Development of Advanced Wear and Corrosion Resistant Systems through Laser Surface Alloying and Materials Simulation

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PRESENTATION OUTLINE

Laser Deposition at Praxair Surface technologies

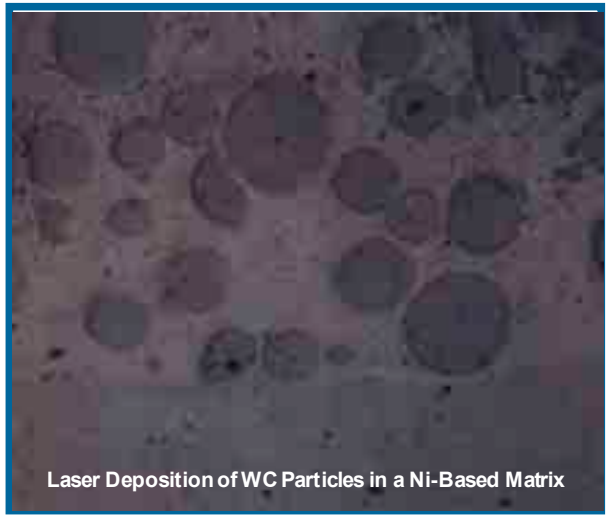
Laser Deposition of Tooling Material at Alvord Polk Corp.

- Background of Program
- Process Technology
- Materials Technology
- Summary

BACKGROUND

Industry Needs

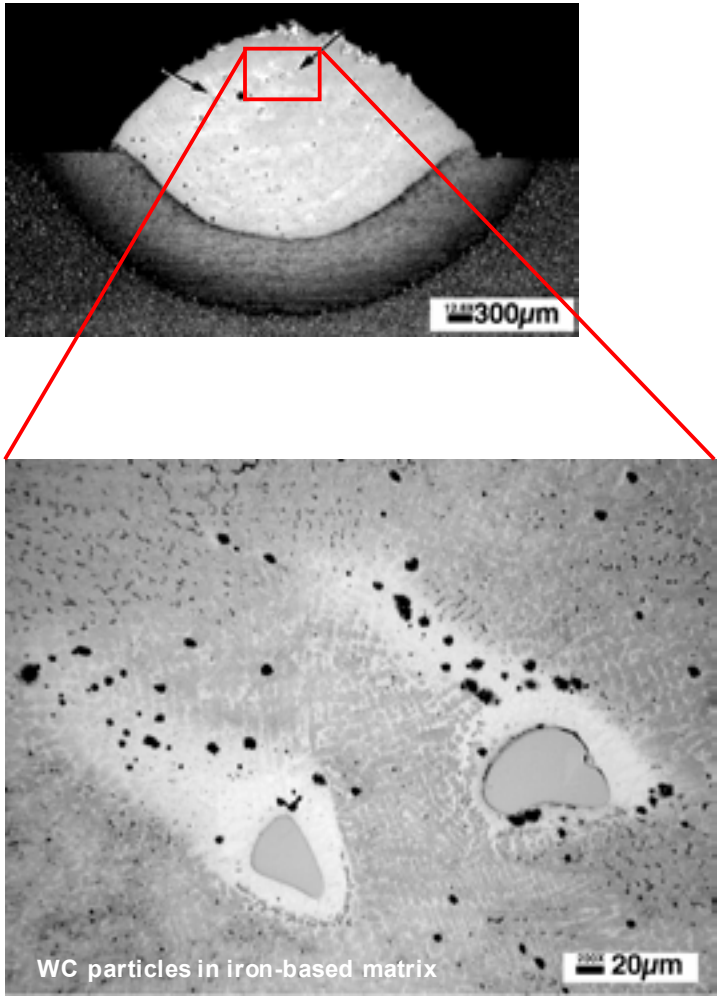
Large Struts that have been Laser Clad


Laser Deposition of WC Particles in a Ni-Based Matrix

- Laser-based deposition processes may be used to impart high wear and corrosion resistance for manufacturing of original components and repair
- Laser deposition using pre-placed powder offers:
  - moderate deposition rates (2- 15 pounds/hour)
  - strong metallurgical bonding to the substrate and refined structure of the deposit
  - low dilution of the substrate (less than 5%) and low thermal distortion
- However, there is a continuing need to increase the wear resistance of materials used for laser deposition

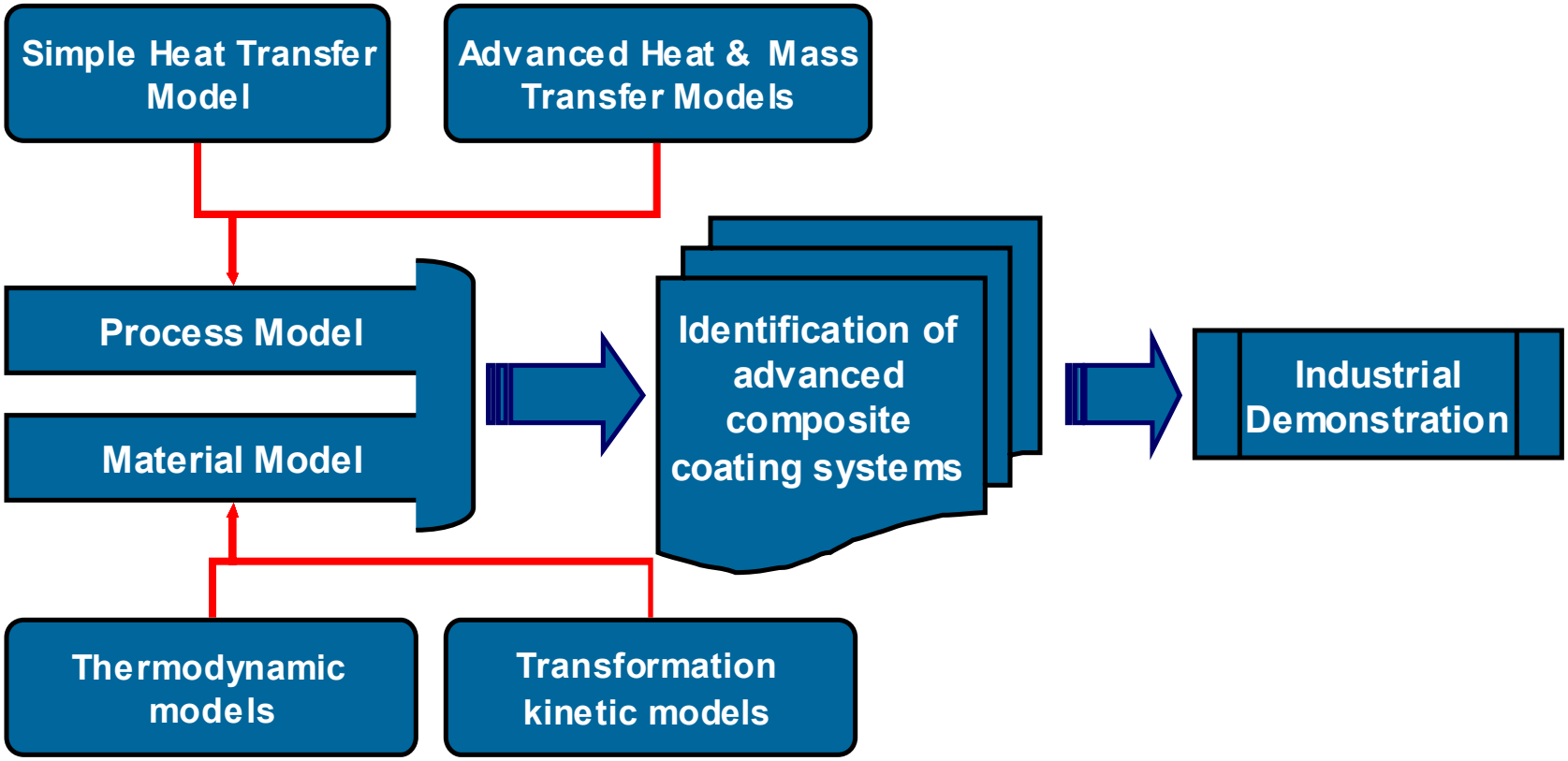
BACKGROUND

Challenges



- Improved wear resistance may be achieved through alloy induced transformations, composite hardening, or a combination of both
- However, the challenge is to dictate the evolved microstructures through process development and material design
- Current process and material development has relied on an inefficient trial-and-error approach

BACKGROUND


Simple Heat Transfer Model
Advanced Heat & Mass Transfer Models
Process Model
Material Model
Identification of advanced composite coating systems
Industrial Demonstration
Thermodynamic models
Transformation kinetic models

BACKGROUND

Program Team

- **ALSTOM Power Inc., Connecticut and Tennessee**
  - wear, fatigue, corrosion, creep and heat resistance surfaces for energy and mining industries
- **Praxair Surface Technologies, Pennsylvania**
  - wear, fatigue, corrosion, creep and heat resistance surfaces for various heavy manufacturing and energy industries
- **Alvord-Polk Corporation, Pennsylvania**
  - tooling grade coatings on low cost substrate materials
- **Spirex Corporation, Ohio**
  - Improved machinery for materials processing
- **NUVONYX Incorporated, Missouri**
  - Laser processing systems for laser deposition
- **Applied Research Laboratory's Laser Processing Consortium:**
  - development and implementation of advanced laser processing technology for the US Navy and industry
- **Oak Ridge National Laboratory**
  - development of advanced materials and processing solutions for US industry

BACKGROUND

Program Goals and Tasks

- Develop processing and material simulation techniques for identifying and developing advanced coating systems for laser assisted surface modifications

- Year 1 Tasks:
  - identify performance requirements and potential material systems
  - construct material model
  - modify existing process model
  - validate models through controlled experiments
  - develop advanced coating systems

- Year 2 Tasks:
  - demonstrate and confirm predictive capability through industrial trials
  - confirm enhanced performance characteristics
  - extend advanced laser modification technology to other applications

BACKGROUND

Benefits

- **Industries of the Future:** Components of steel, mining, chemical, mineral processing, agricultural, pulp and paper, foundry and primary metal processing industries with improved wear and corrosion resistance

- **Economic benefit:** Increased performance through life extension, decreased down time, superior wear performance over a wide environmental range and low cost replacement of metallurgical coatings. With 5% applicability and 1% improvement estimated savings for wear and corrosion application is 8.8 million dollars

- **Energy Efficiency:** Improved process efficiency, reduced down time associated with repair and refurbishment of wear and corrosion critical components. Estimated energy savings due to advanced coating technology is 31 million Btu/year

- **Environmental Benefits:** Minimize Cr plating, minimize leaks due to corrosion, minimization of process waste, reduction of scrap due to increased life, recycling with better selection of raw materials, increased efficiency will reduce greenhouse gas emissions

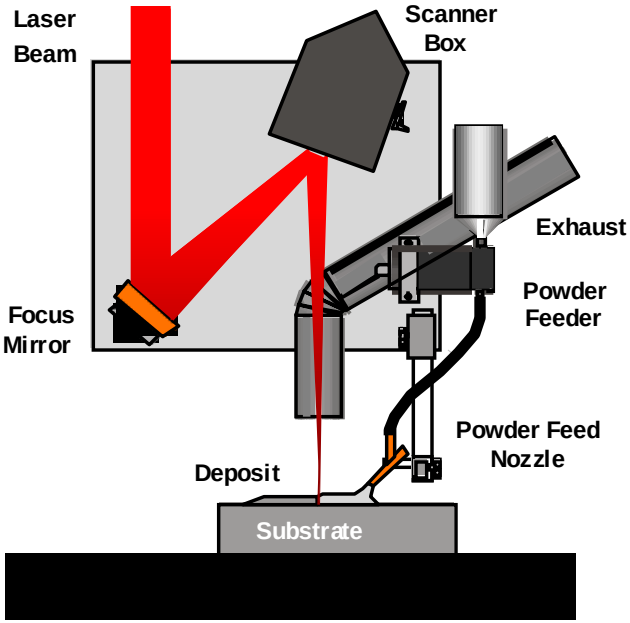
BACKGROUND

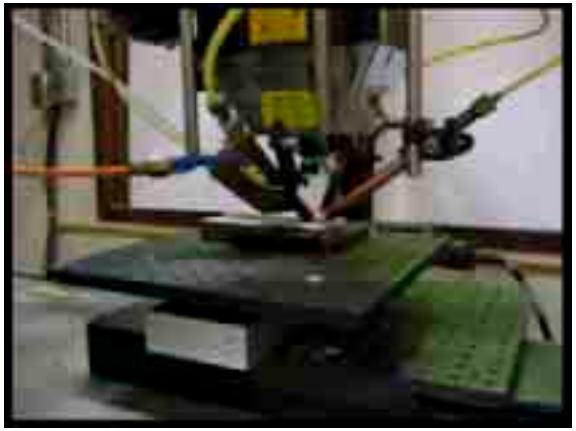
Technical Barriers

- Lack of availability of thermodynamic data for non-stoichiometric compounds at elevated temperature and interfacial energy values
  - thermodynamic software libraries and extensive literature survey
- Accurate representation of thermal cycles as a function of process parameters
  - accurate simulation methods require parameters that are currently unknown
  - experimental measurements used to obtain critical parameters and calibrate process model
- Difficult to obtain high coating rates with complex parts and uniform deposition
  - precursor technology being applied to new materials

PROCESS TECHNOLOGY

Process Description

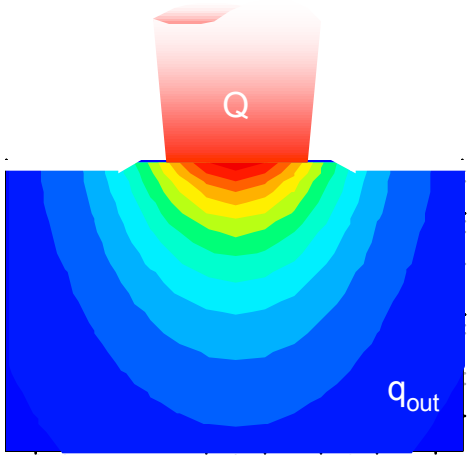


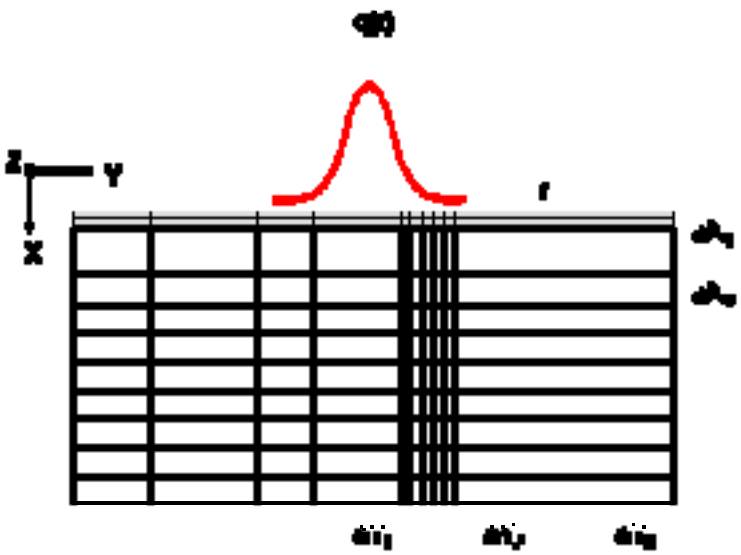


- Moderate power densities are provided to the substrate
  - stationary or scanned beam
- Additions are added to the point of beam and material interaction
  - powder or solid wire
  - heterogeneous combinations may be made through multiple feed nozzles or powder blends
- Significant absorption of the beam occurs within the powder layer, which in turn causes melting of the substrate and fusion

PROCESS TECHNOLOGY

Energy Balance





The energy balance is:

$$\frac{\partial \mathbf{H}}{\partial \mathbf{t}} = \nabla \cdot (\mathbf{k} \nabla \mathbf{T}) + \mathbf{Q}$$

with enthalpy defined as:

$$\mathbf{H} = \rho(\mathbf{C_p T} + \mathbf{L})$$

Certain conditions are imposed:

1) $\mathbf{d}\Delta \mathbf{I} - \gamma^2 \mathbf{I} = \mathbf{0}$ and $\int_\Omega I(x)dx = q_{in} = A_b Q$

2) $\mathbf{q_{out}} = \mathbf{h_{eff}}(\mathbf{T} - \mathbf{T_\infty})$ where

$$\mathbf{h_{eff}} = \mathbf{h_c} + \sigma\, \mathbf{e}\left(\mathbf{T}^3 + \mathbf{T}^2\mathbf{T_\infty} + \mathbf{T}\mathbf{T_\infty}^2 + \mathbf{T_\infty}^3\right)$$

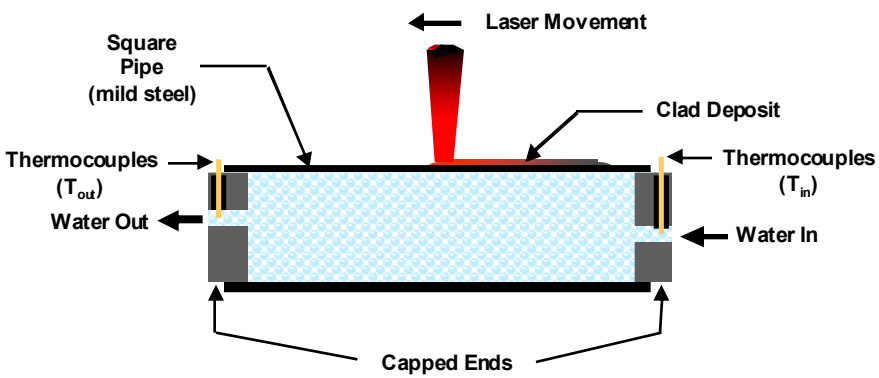
3) $\mathbf{k_1}(\mathbf{k} \nabla \mathbf{T})_{i,1} = \mathbf{k_2}(\mathbf{k} \nabla \mathbf{T})_{i,2}$

Solution may be approximated through explicit finite differencing

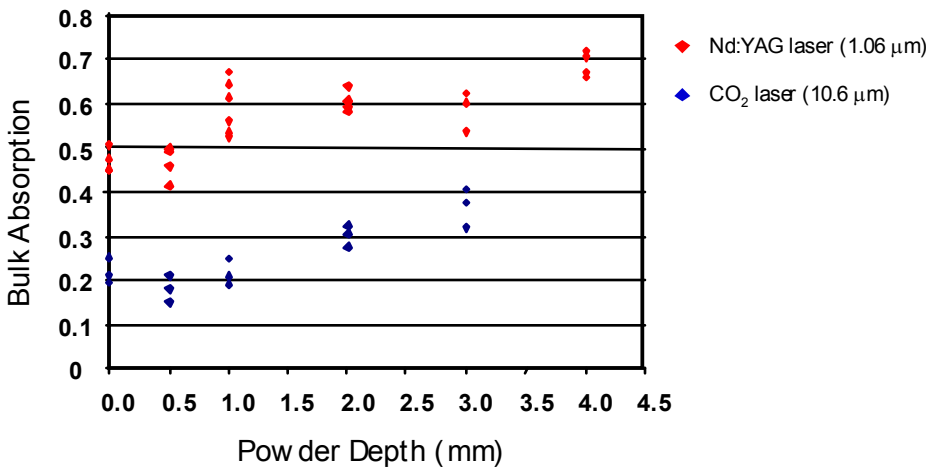
PROCESS TECHNOLOGY

Bulk Absorption

Process Calorimeter



Bulk Absorption of Fe Powder



The bulk absorption (A_b) may be defined as the ratio of energy presented to the substrate (Q) to the energy absorbed by the substrate (q_{in})

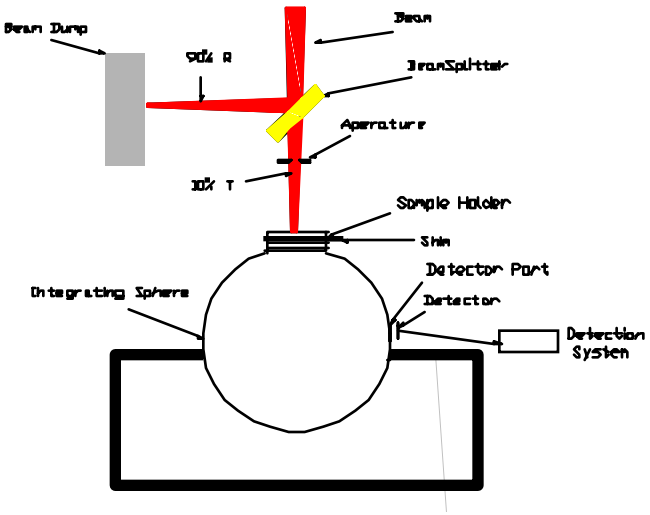
Knowing the amount of energy provided to the process calorimeter, bulk absorption may be obtained by measuring the amount of energy absorbed.

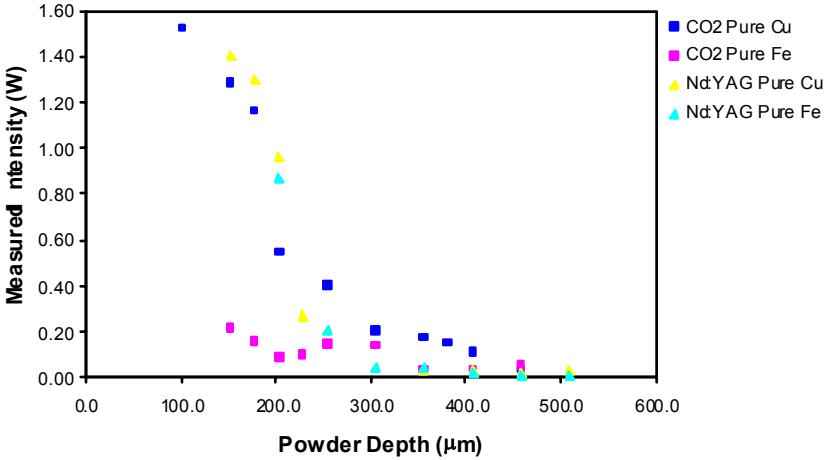
The bulk absorption coefficient may be used to simulate energy transfer to the surface of the powder layer.

PROCESS TECHNOLOGY

Laser Absorption

Absorption Experiments





Typical optical properties are not appropriate for describing the energy transmitted to the porous powder layer

The amount of energy absorbed in the powder layer due to scattering may be generically described by the absorption coefficient (γ):

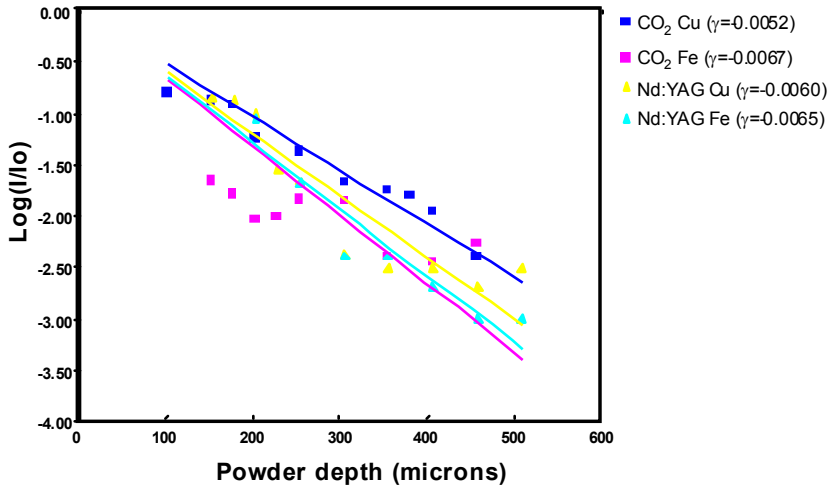
$$I(x) = I_o \exp(-\gamma x)$$

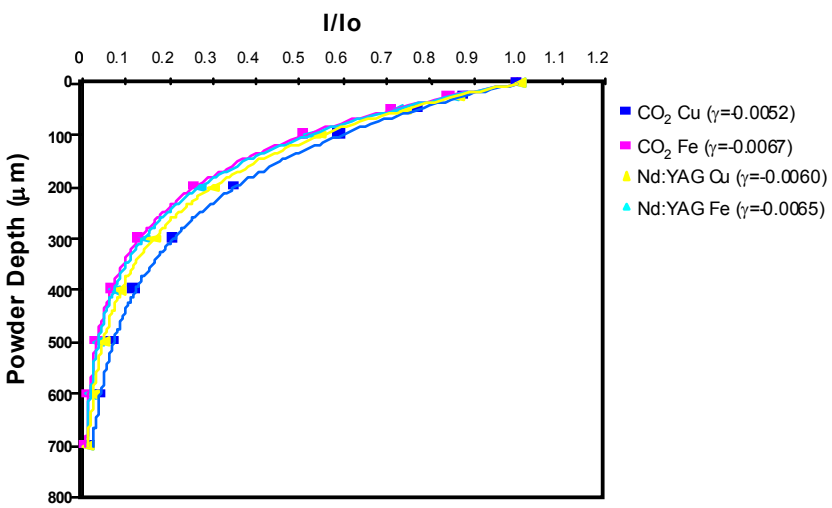
where $\gamma = \frac{4k}{\lambda}$, with λ being wavelength and k being referred to as the extinction coefficient.

These values have been measured by controlled experiments.

PROCESS TECHNOLOGY

Absorption Coefficients



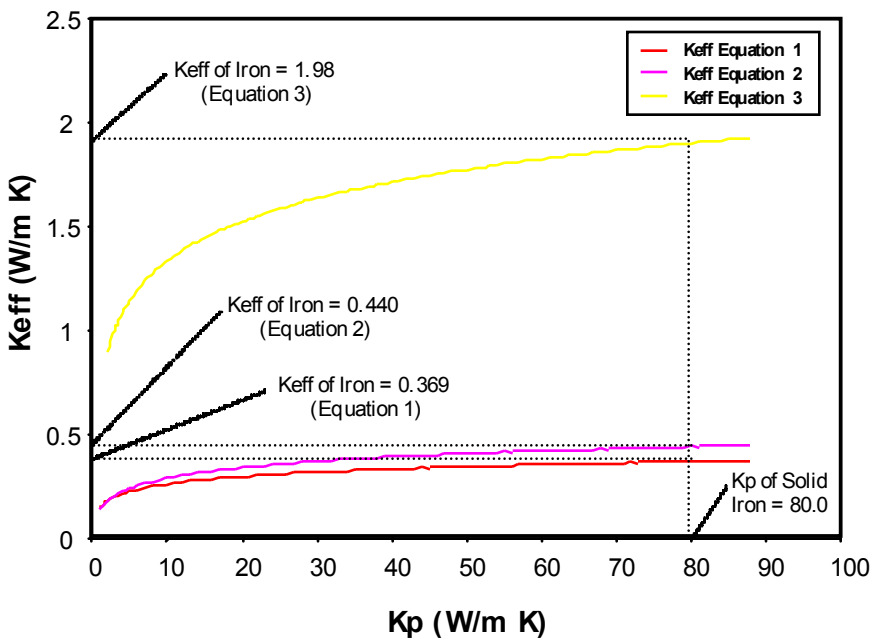


The results of absorption measurements for pure iron and pure copper powders during CO_2 (λ=10,600 nm) and Nd:YAG (λ=1064 nm) laser irradiation may be fitted to:

$$\log\left(\frac{I}{I_o}\right) = -\gamma x$$

which allows γ (the absorption coefficient) to be estimated.

The absorption coefficient may be utilized to represent energy transfer to the porous powder layer in three-dimensions.



The thermal conductivity of the porous powder (k_{eff}) layer is significantly less than that of solid material.

Thermal conductivity of the powder may be described using an effective conductivity, such as[1,2]:

1) $$k_{eff} = \frac{2k_{air}}{1-(k_{air}/k_{powder})}\left[\frac{\ln(k_{powder}/k_{air})}{1-(k_{air}/k_{powder})}-1\right]$$

2) $$\log\left(\frac{k_{eff}}{k_{air}}\right) = \left(0.280 - 0.757\log(\alpha) - 0.057\log\left(\frac{k_{powder}}{k_{air}}\right)\right) * \log\left(\frac{k_{powder}}{k_{air}}\right)$$

3) $$\frac{k_{eff}}{k_{air}} = V_s N_c * 2\ln\left(\frac{k_{powder}}{k_{air}}\right)$$

[1] Rohsenow, W.M., Hartnett, J.P., Cho, Y.I., Handbook of Heat Transfer, McGraw-Hill, New York, 13.11 (1998).

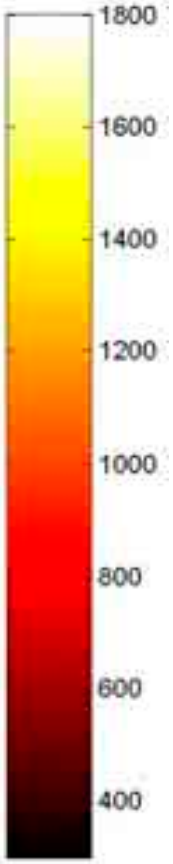
[2] Batchelor, G.K., O'Brien, R.W., Thermal or Electrical Conduction Through a Granular Boundary, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 1682, 313-333 (1977).

PROCESS TECHNOLOGY

Effect of Source

Simulation of 3.0 kW Nd:YAG (d=5.0 mm) with 2.0 mm Thick and 10.0 mm Wide Layer of Iron Powder on 12.7 mm Thick Mild Steel Substrate

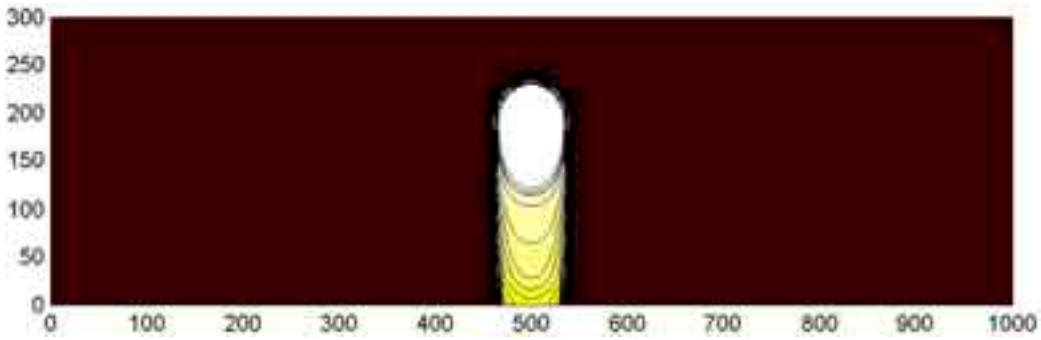
Simulation of 4.0 kW Direct Diode Laser (a=12 mm and b=0.8 mm) with 2.0 mm Thick and 20.0 mm Wide Layer of Iron Powder on 12.7 mm Thick Mild Steel Substrate



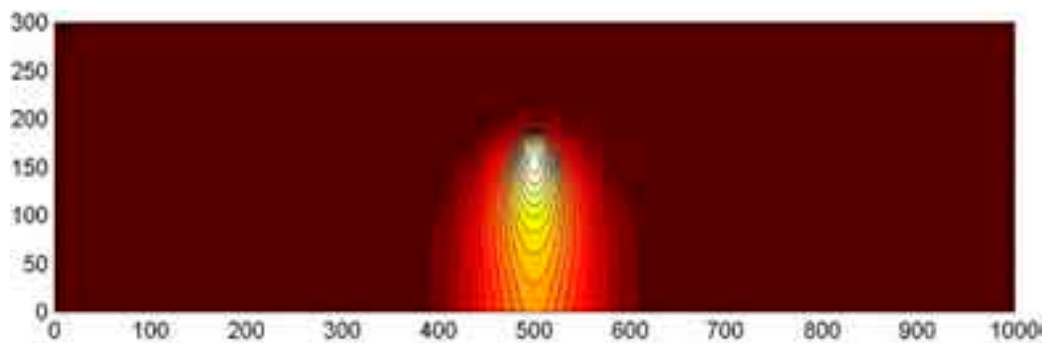
PROCESS TECHNOLOGY

Conduction in Powder and Substrate

Simulation of 3.0 kW Nd:YAG (d=5.0 mm) with 2.0 mm Thick and 10.0 mm Wide Layer of Iron Powder on 12.7 mm Thick Mild Steel Substrate



Isotherms on Top Surface of Powder Layer

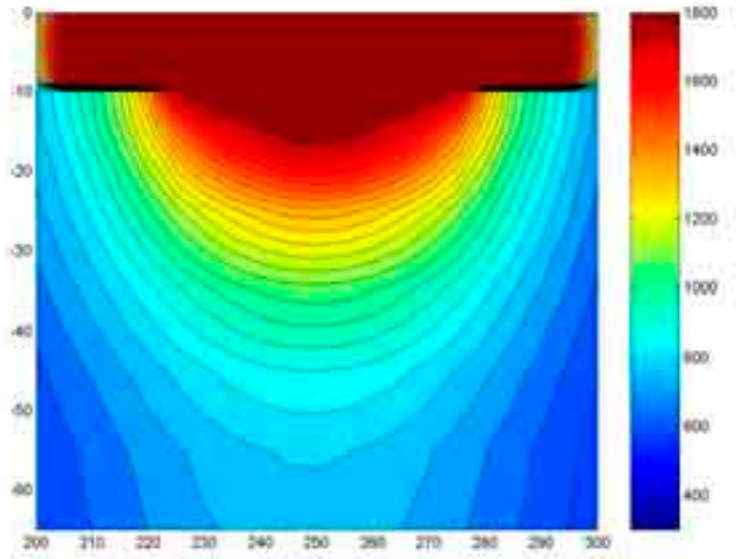


Isotherms at Powder/Substrate Interface

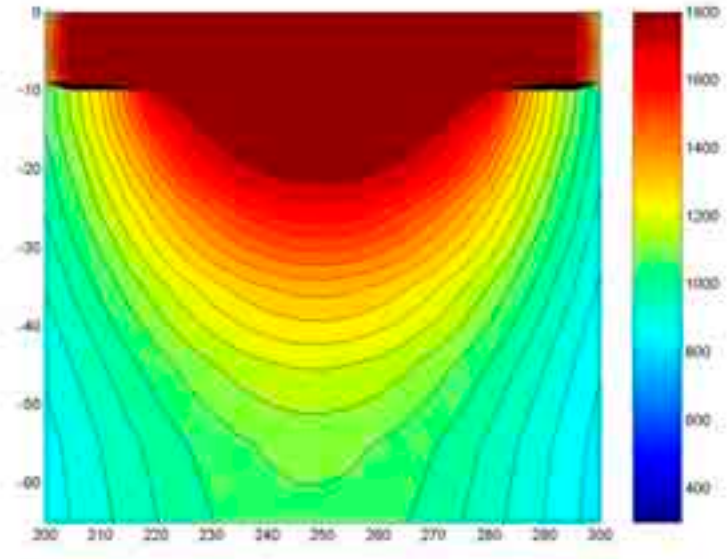
PROCESS TECHNOLOGY

Effect of Velocity

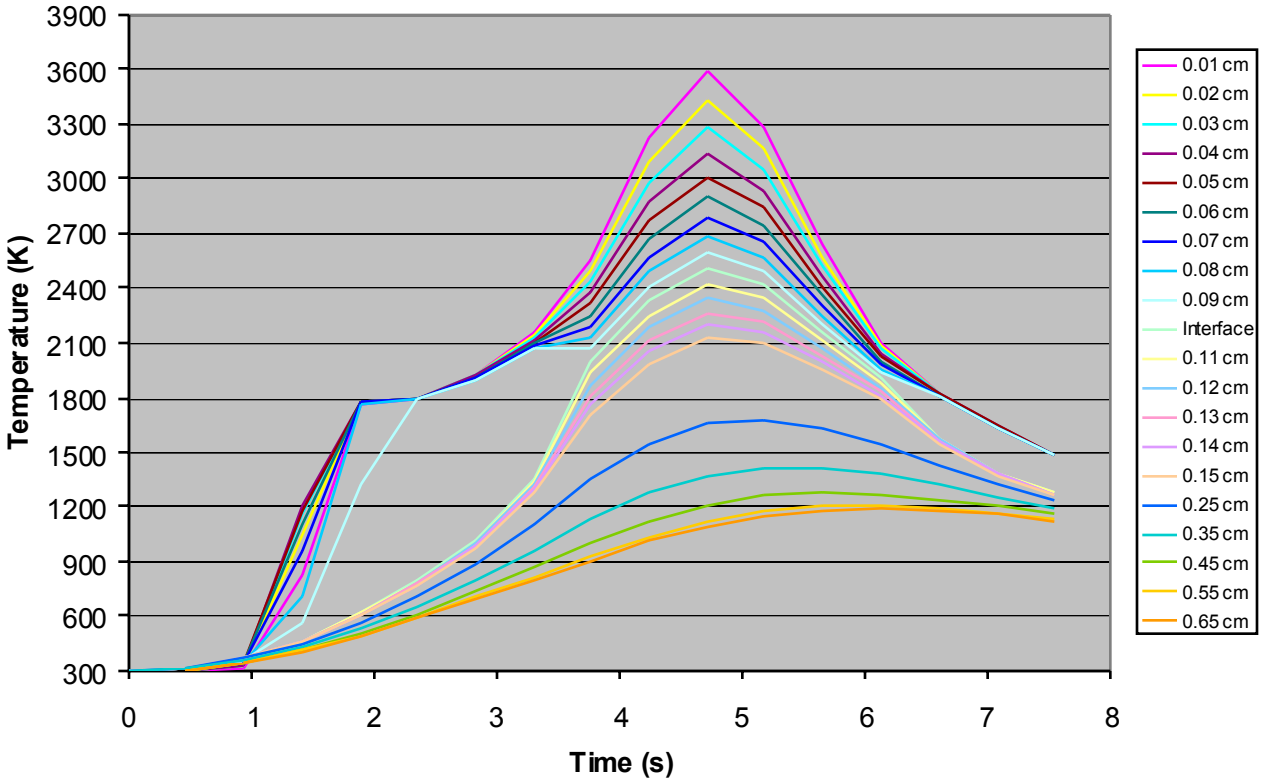
Power = 2430 watts
Velocity = 4.23 mm/s
Beam Diameter = 0.5 mm
Nickel Powder Thickness = 1.0 mm



Power = 2430 watts
Velocity = 2.12 mm/s
Beam Diameter = 0.5 mm
Nickel Powder Thickness = 1.0 mm



Temperature Versus Time at Various Depths in Deposit and Substrate

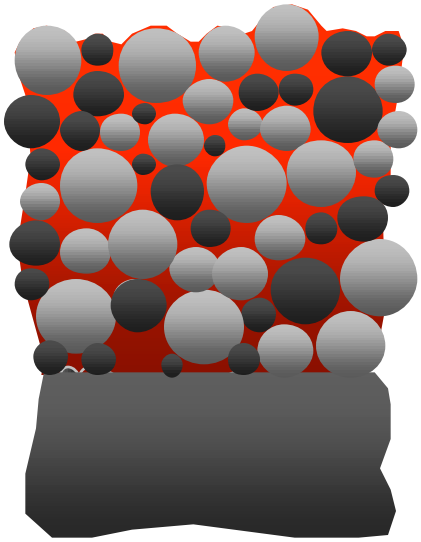


Power = 2430 watts, velocity = 2.12 mm/s, beam diameter = 0.5 mm, and nickel powder thickness = 1.0 mm

PROCESS UNDERSTANDING

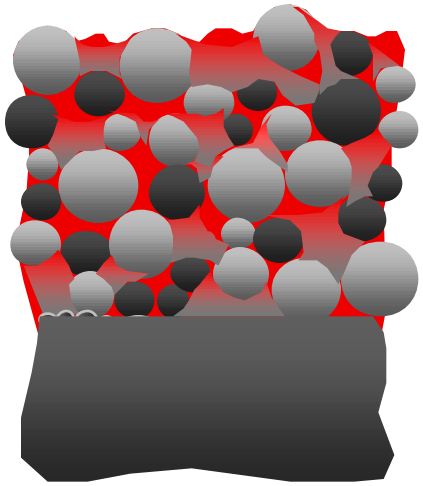
Time Dependence During Irradiation

Initial Irradiation of Powder Layer ($A_b = A_b^P$)



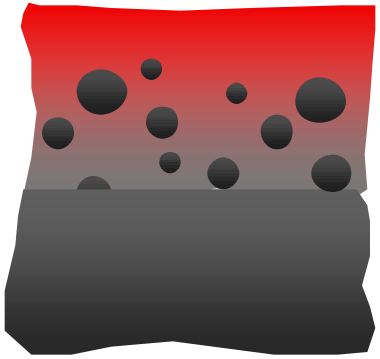
Absorption in powder through scattering with low thermal conductivity

Rapid Formation of Two Phase Mixture



Initial melting of powder layer and coalescence

Irradiation of Liquid Pool ($A_b = A_b^L$)



Complete melting of matrix, consolidation, and wetting of substrate with high thermal conductivity

Matrix Particles Hard Particles

PROCESS UNDERSTANDING

Powder Absorption Model

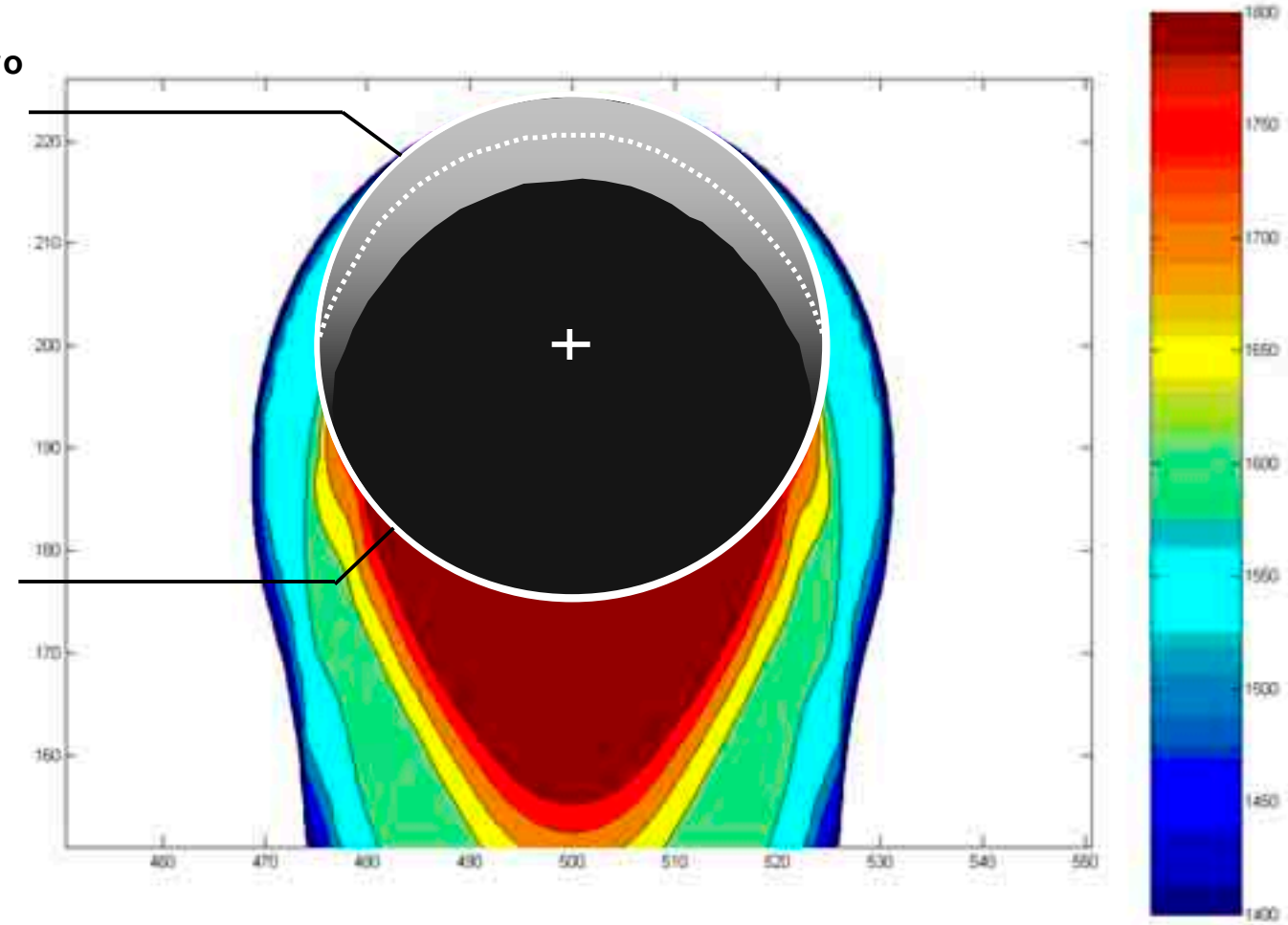
Simulation of Inconel Powder and Nd:YAG Irradiation of 1500 W at 4 cm/s

Powder and two phase region under beam

(A_b^P=0.55)

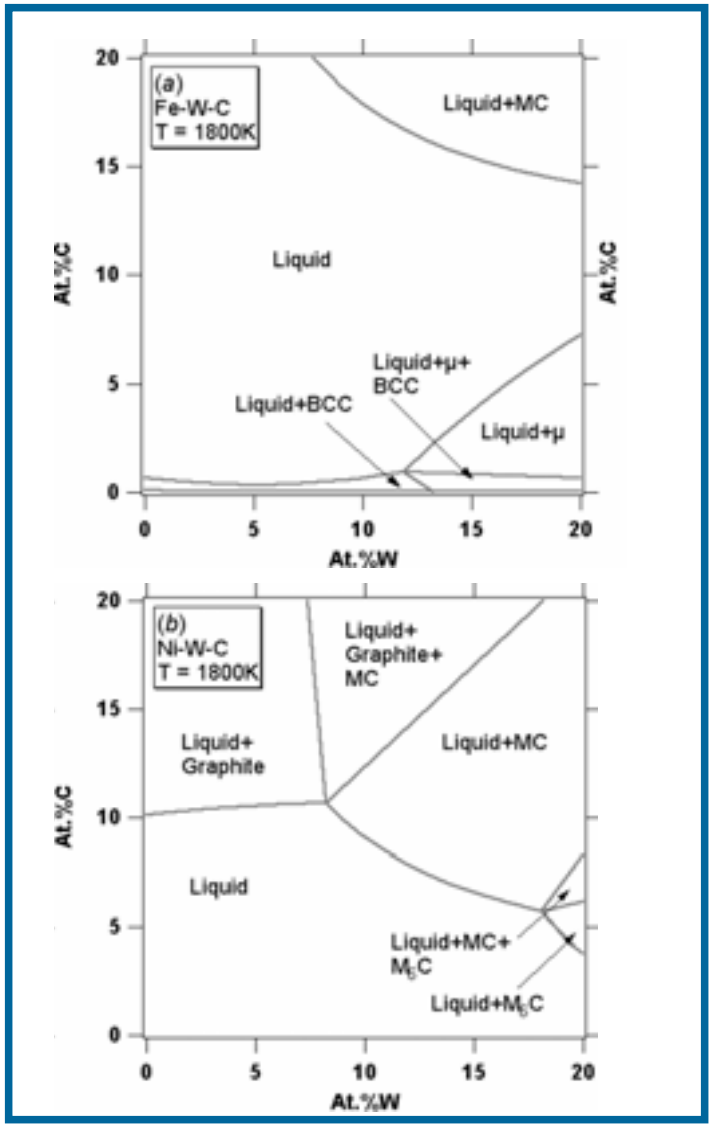
Area under the beam

(A_b^L=0.48)



MATERIALS TECHNOLOGY

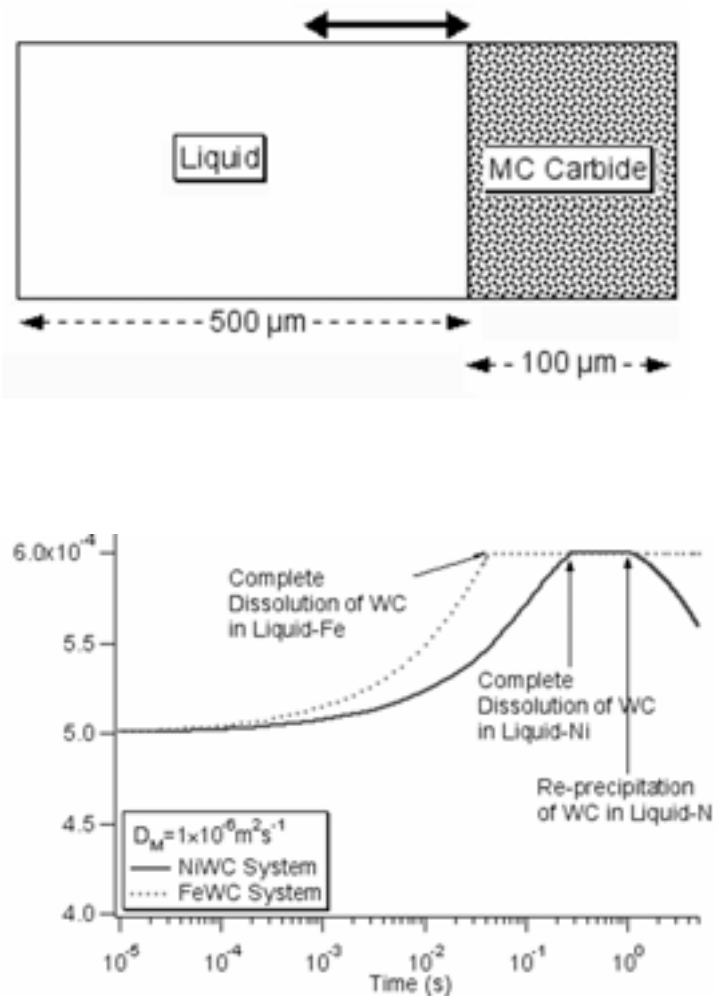
Stability Diagrams



- Material simulations are conducted through the use of computational thermodynamics and kinetic analyses under non-isothermal conditions representing the process
- Computational thermodynamics provides stability diagrams that are utilized to initially identify composite systems that provide the ability of the hard particles to be retained in various matrix materials
- Although useful for screening of material systems, stability diagrams do not consider the kinetics of particle dissolution, re-precipitation, nor growth

MATERIALS TECHNOLOGY

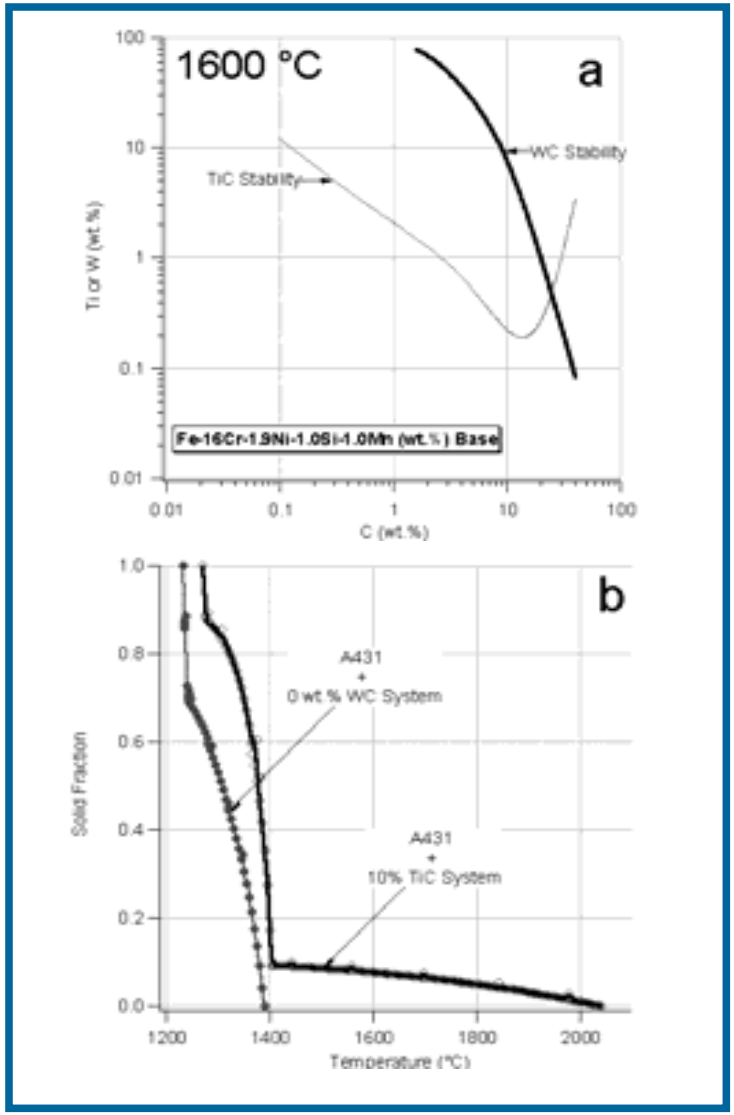
Kinetic Analysis



- Kinetic calculations consider dissolution and precipitation as a function of thermal cycle and composition
  - assumes local equilibrium at the interface
  - considers the diffusion in the liquid and rapid thermal cycles
- These calculations will eventually be coupled to energy and mass transfer models
- The simple kinetic model may also be extended to particle and precipitate arrays

MATERIALS TECHNOLOGY

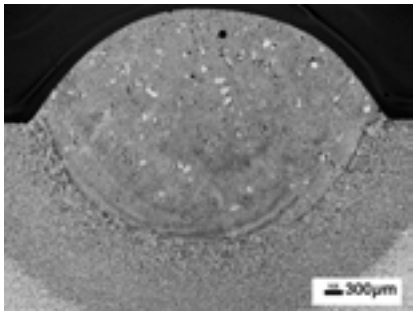
Coatings Design

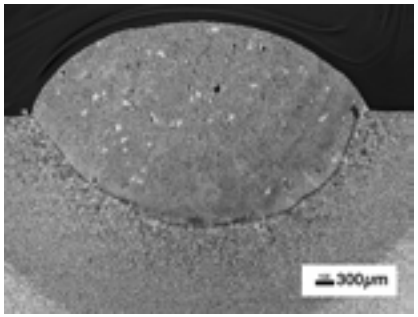


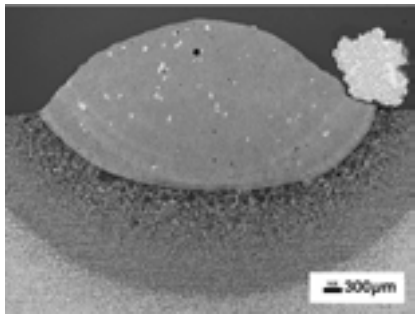
- Simulations have been used to identified materials systems for addition to a martensitic grade matrix alloy (alloy 431):
  - TiC
  - TiC and TiN with reactive shielding
  - ferro-titanium with reactive shielding
  - BN
- These systems rely on composite strengthening and re-precipitation of fine, stable particles
- The theoretical predictions are being validated by laser experiments

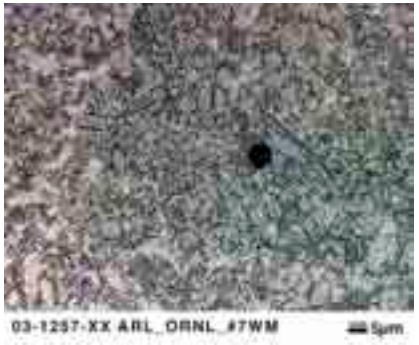
20 w/o TiC in a Martensitic Grade of Stainless Steel (Alloy 431)

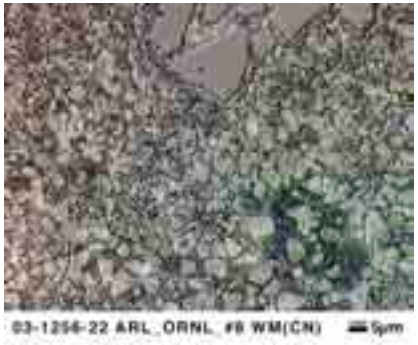
20 Ar	18 Ar – 2 N_2	Air



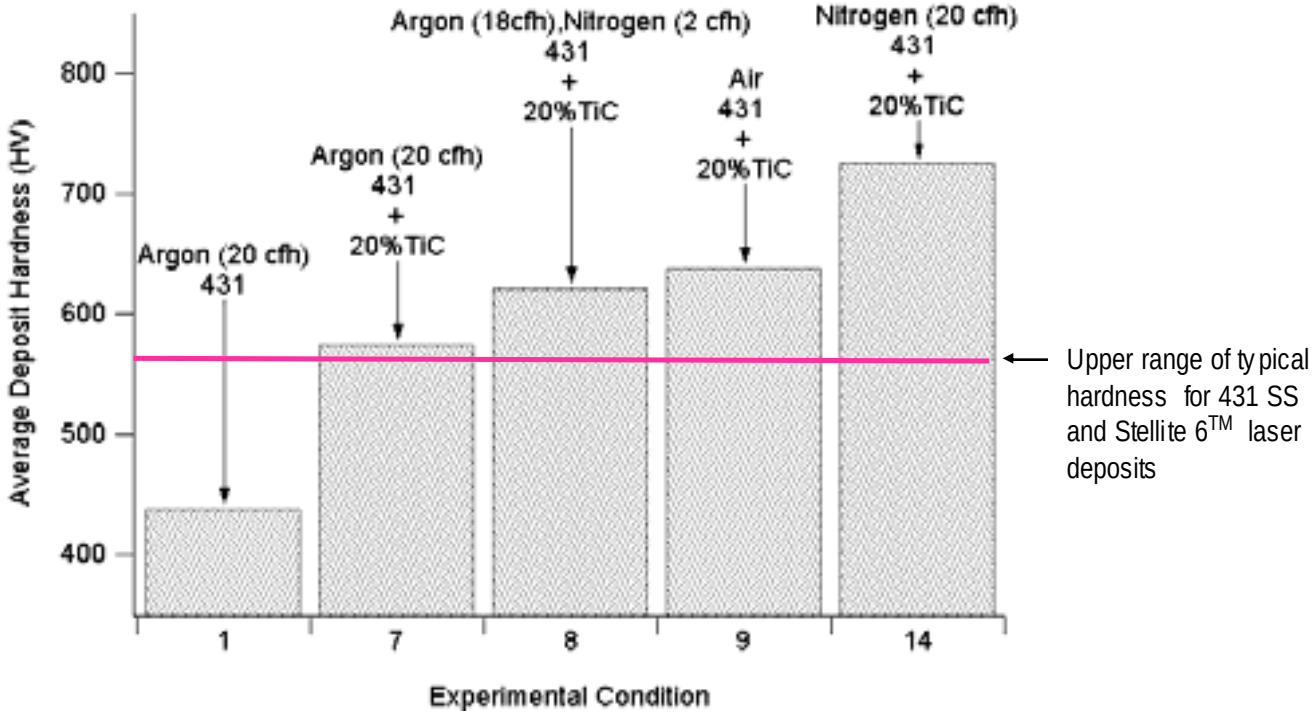




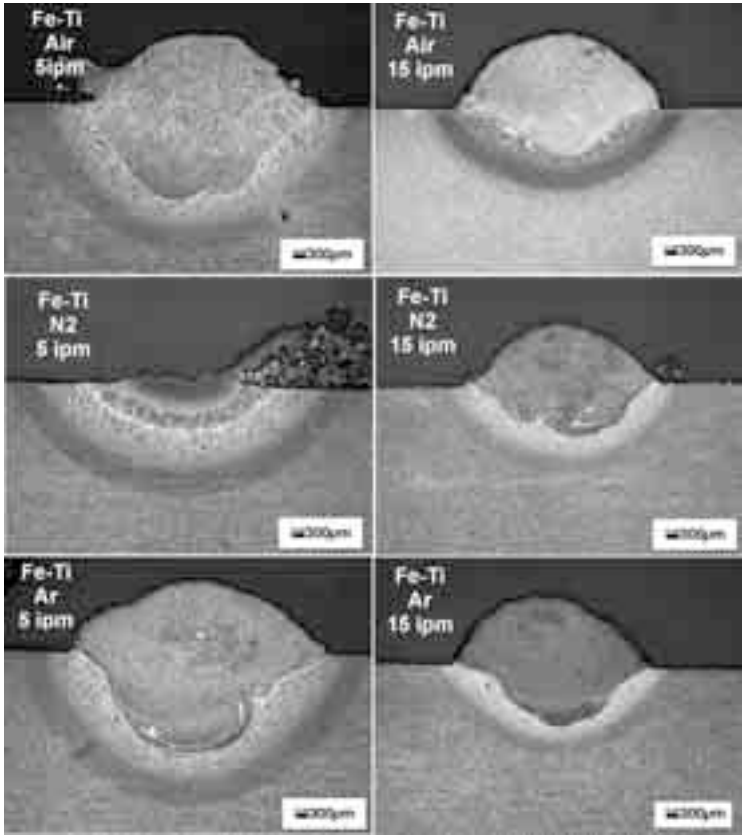


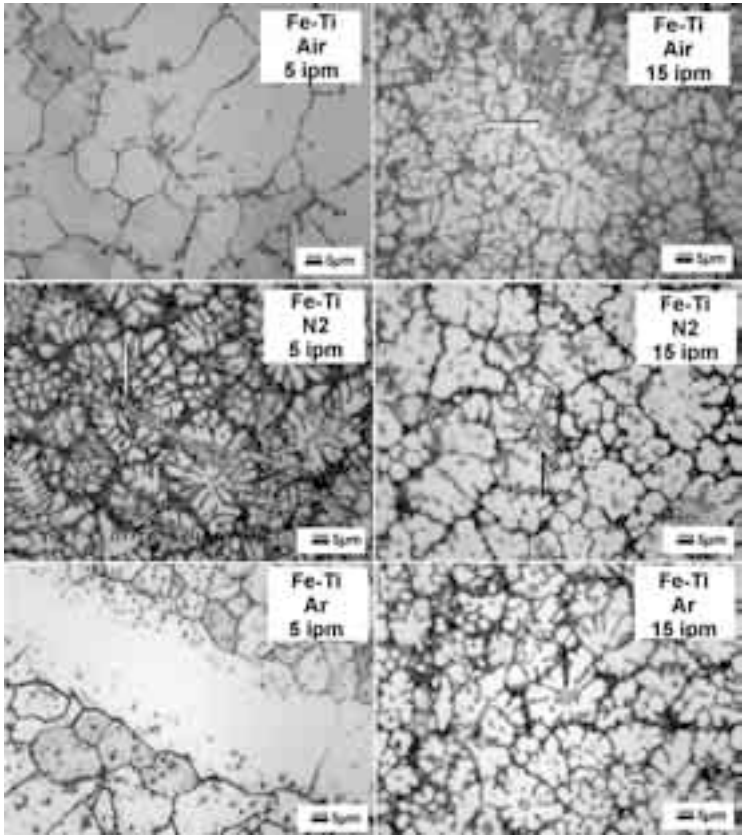


Hardness of SS 431 and 20 % TiC Deposits With Reactive Shielding



Laser Deposits of Ferro-Titanium and Stainless Steel Alloy 431

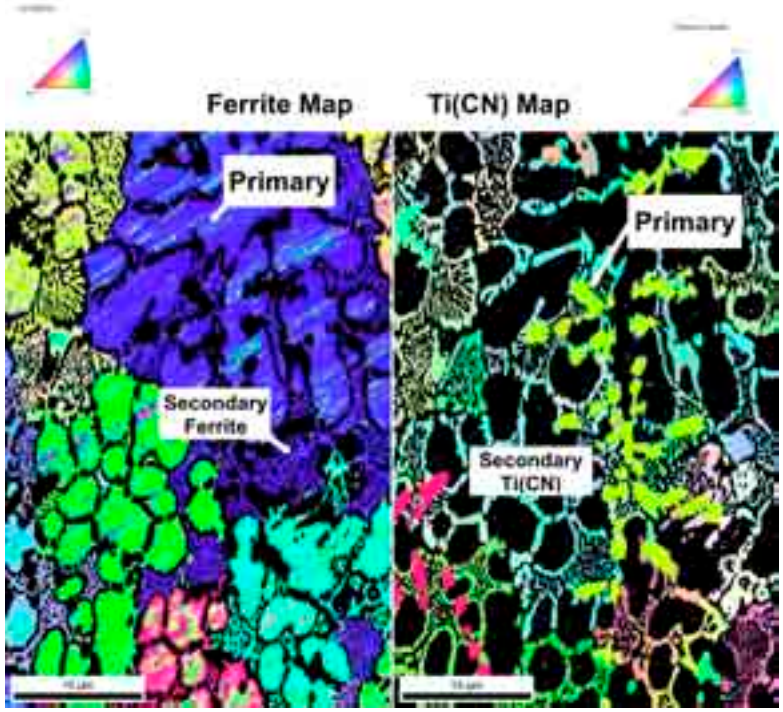




MATERIALS TECHNOLOGY

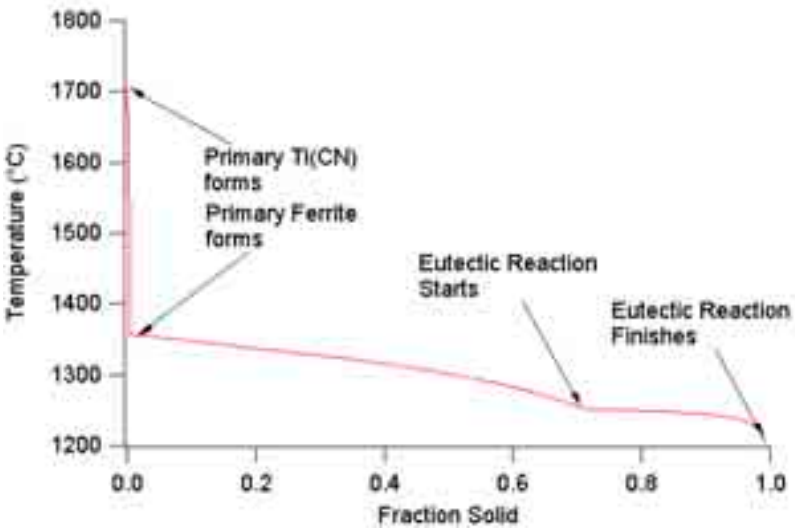
Coatings Design

Orientational Images of Ferro-Titanium and SS Deposits Showing Ferrite as BCC and Ti(CN) as FCC



The primary Ti(CN) appear as dendritic and the primary ferrite appear as equiaxed ferrite grains.

Predicted Solid Fraction Showing Primary Solidification of Ferrite and Ti(CN) Followed by Eutectic Decomposition of the Remaining Liquid



Calculations assume the Scheil additivity law.

IMPLEMENTATION

Application of Technology

- Year 2 entails implementation
- Industrial partners are beginning evaluations of recently developed processes and materials
  - Spirex Corporation conducting evaluations on high WC precursor deposit with annular heat source
  - Alvord Polk Corporation evaluating Fe-Co-Mo matrix with WC and TaC
  - Praxair Surface Technologies interested in Co and Fe-Co-Mo matrices with various hard particles (WC, TiC, HfC, and TaC)
- Evaluations include deposition on mock-ups or components, material characterization, and various wear tests

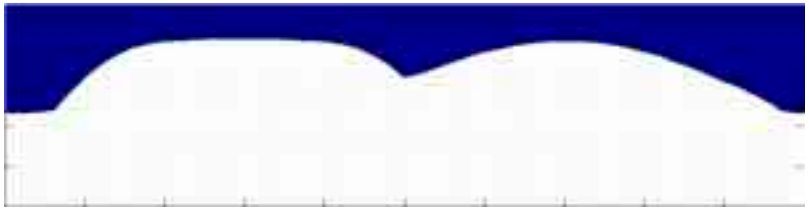
SUMMARY

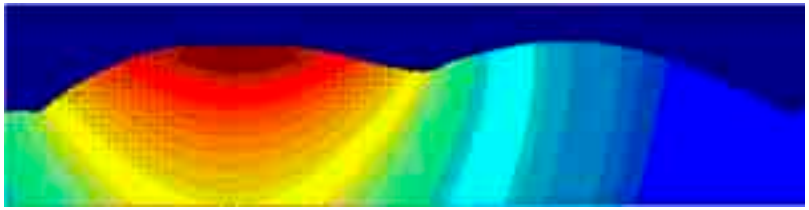
- Laser based deposition is a highly versatile technology that may be used to effectively modify surface properties for improved wear and corrosion resistance
- The integration of process and materials simulation techniques have enabled the efficient development of new process techniques and coating materials specifically designed for laser processing
  - precursor formulations
  - composite coatings
  - re-precipitation reactions
  - reactive gas processing
- These new coatings exhibit improved properties and show significant promise for enhancing performance over current materials

PROCESS SIMULATION

Phase Field Model

Simulation of Multi-Pass Deposition Using a 2.7 kW Nd:YAG Laser (d=5.0 mm) with 1.2 mm Thick and 5.0 mm Wide Layer of Iron Powder on 10.0 Thick Mild Steel Substrate



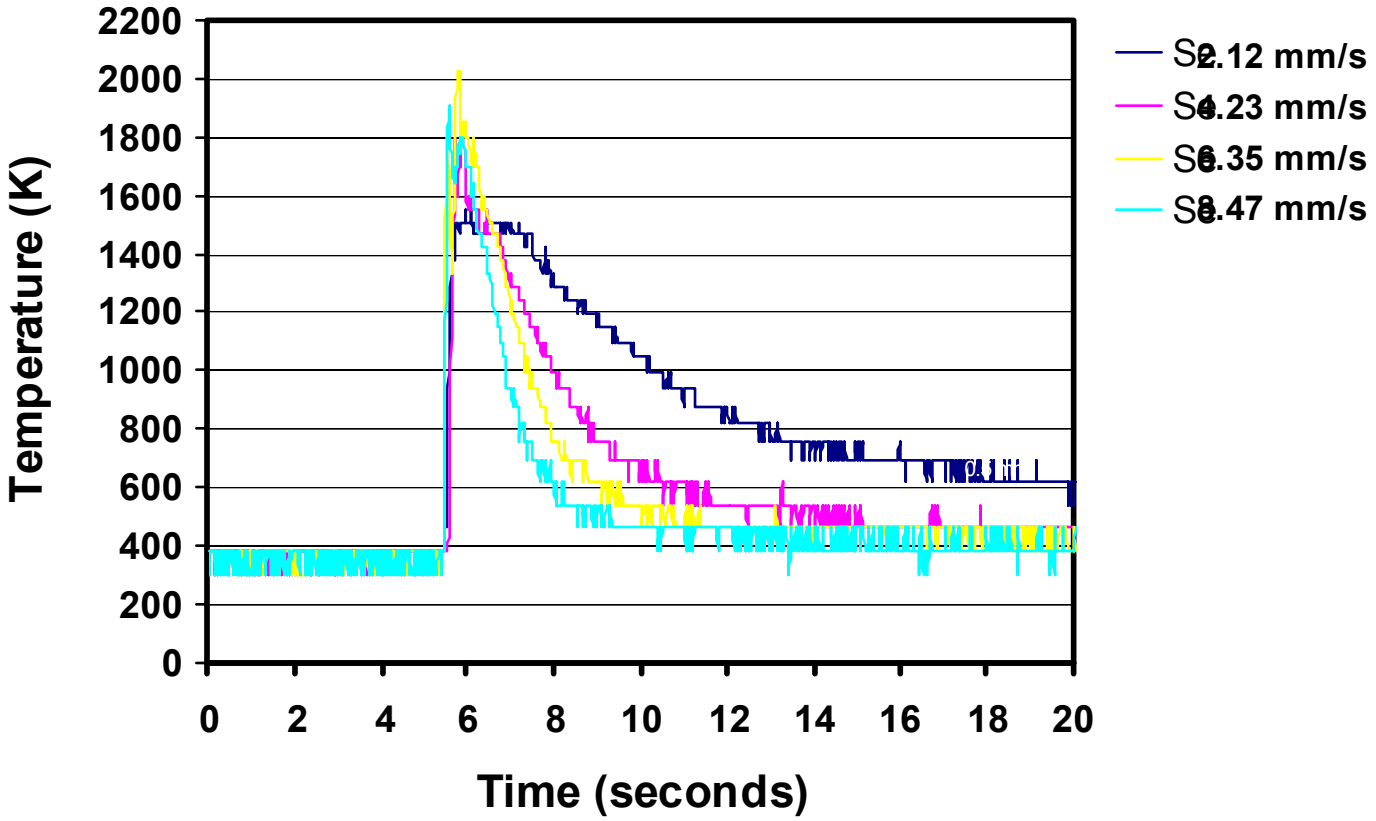


Naber, A. and Martukanitz, R., Simulation of Laser Cladding Through Approximation Using the Finite Element Method and a Variable Phase Field, Proceedings of the 23rd International Congress on Applications of Lasers & Electro Optics, LIA (2004).

MODEL VALIDATION

Experimental Results

Measured Temperatures at the Deposit and Substrate Interface Obtained During Processing at Four Traverse Velocities

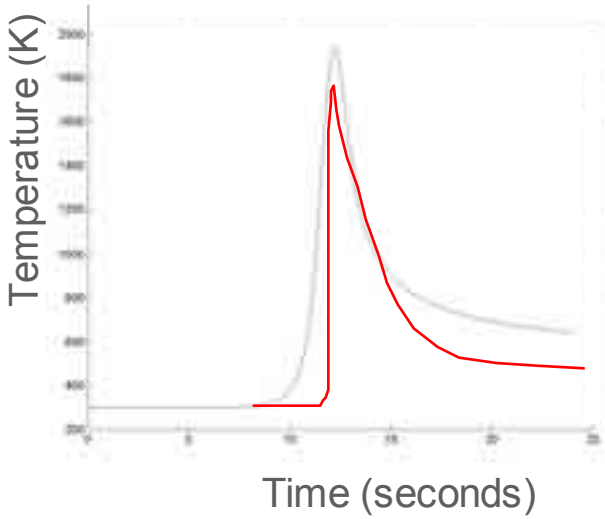
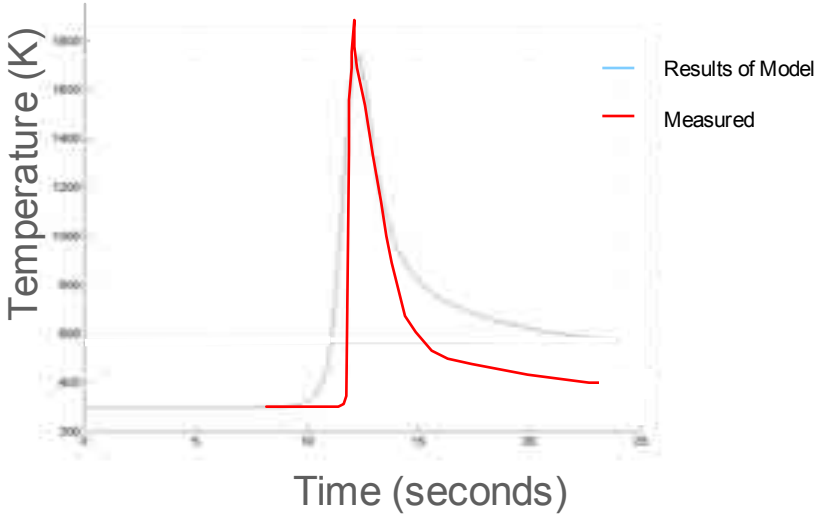


MODEL VALIDATION

Experiment VS Simulation

Comparison of Interface Temperature for Processing at 4.23 and 6.35 mm/s

4.23 mm/s



6.35 mm/s