ME361A

Additive Manufacturing

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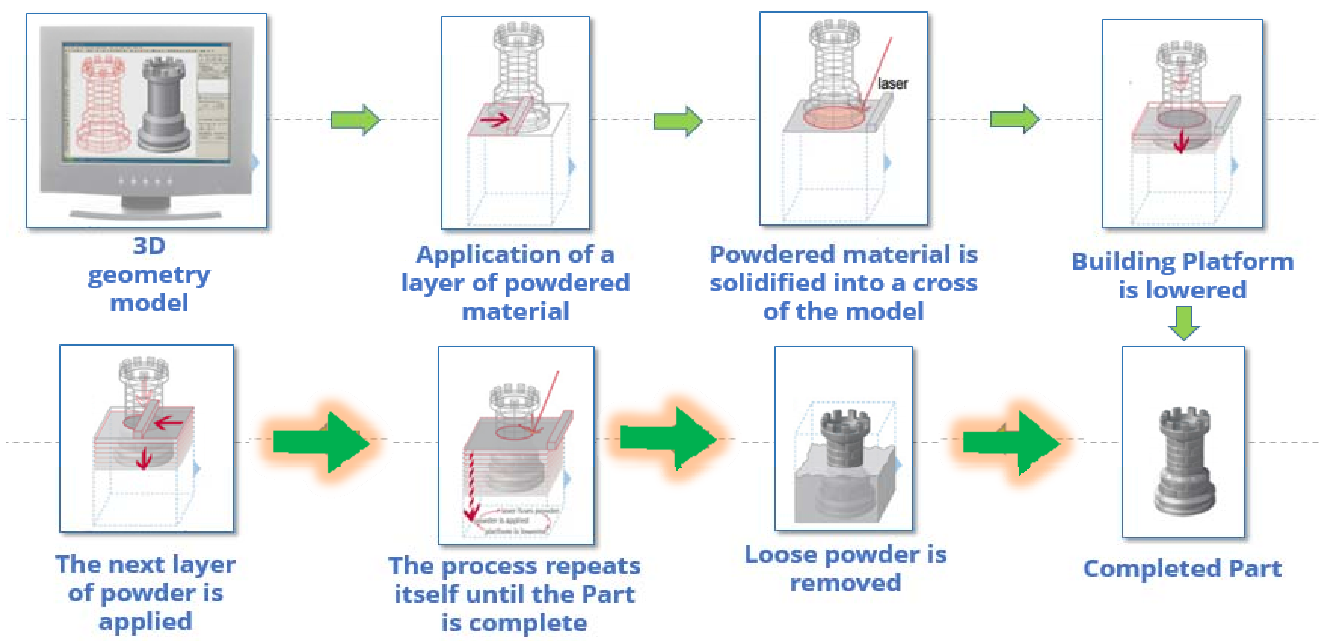
Additive manufacturing: Principle, advantages & possibilities

Digital 3D design data is used to build up a component in layers by depositing material.

A layer by layer build up.
Metals, plastics and composite materials may be used.

AM Process principle and path



AM: Benefits

Freedom of Design
Light Weight

1) Static: Weight of Parts
2) Dynamic: Moving, accelerated parts
3) Lattice Structures

Customization
Individualized Parts

1) Customer specific adaptations
2) Medical Implants

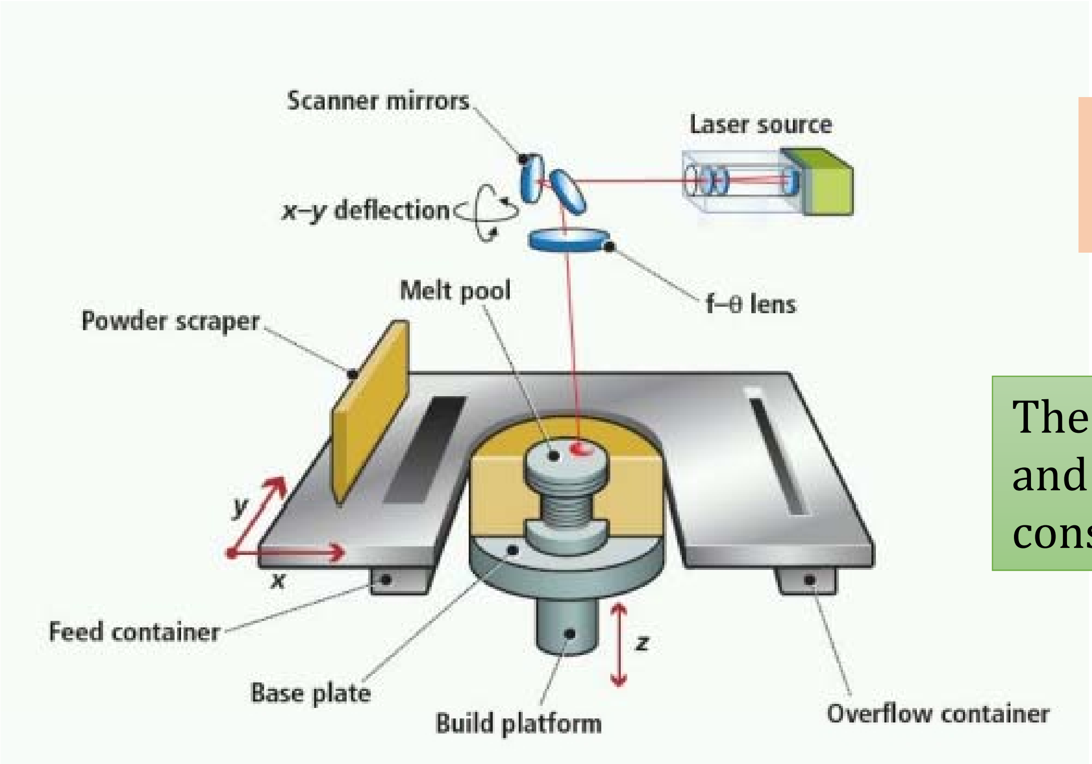
Cost Advantages
Integrated Functionality

1) Embedded Functionality
2) NO Assembly
3) Minimized Stock

Time to Market
Prototyping

1) Fast feasibility feedback by prototyping
2) CAD data to parts
3) Cost efficient small series production

SELECTIVE LASER MELTING (SLM)



A powder bed process , involving the use of laser as a heat source

The heat causes powder particles to melt and form a melt pool which solidifies as a consolidated layer of material.

Full melting of the particles and then re-solidification

SLM produces parts with much higher density and strength

Can process metals, alloys and metal matrix composites (MMCs) like stainless steel, tool steel, cobalt chrome, titanium, Al

Process

- A powder bed process, involving the use of laser as a heat source for manufacturing hard and brittle materials and fabricating complex shapes by layer upon layer techniques.
- Structures that will be fabricated are designed on the computer-aided-design and computer-aided-manufacturing (CAD–CAM) system before being converted to the STL file format
- The STL file is then sliced into numerous cross-sections of a layer thickness pre-defined by the user and input into the SLM computer.
- The fabrication process first begins with a layer of powder of pre-defined thickness, usually 20–50 µm being laid across the base-plate by a recoater.

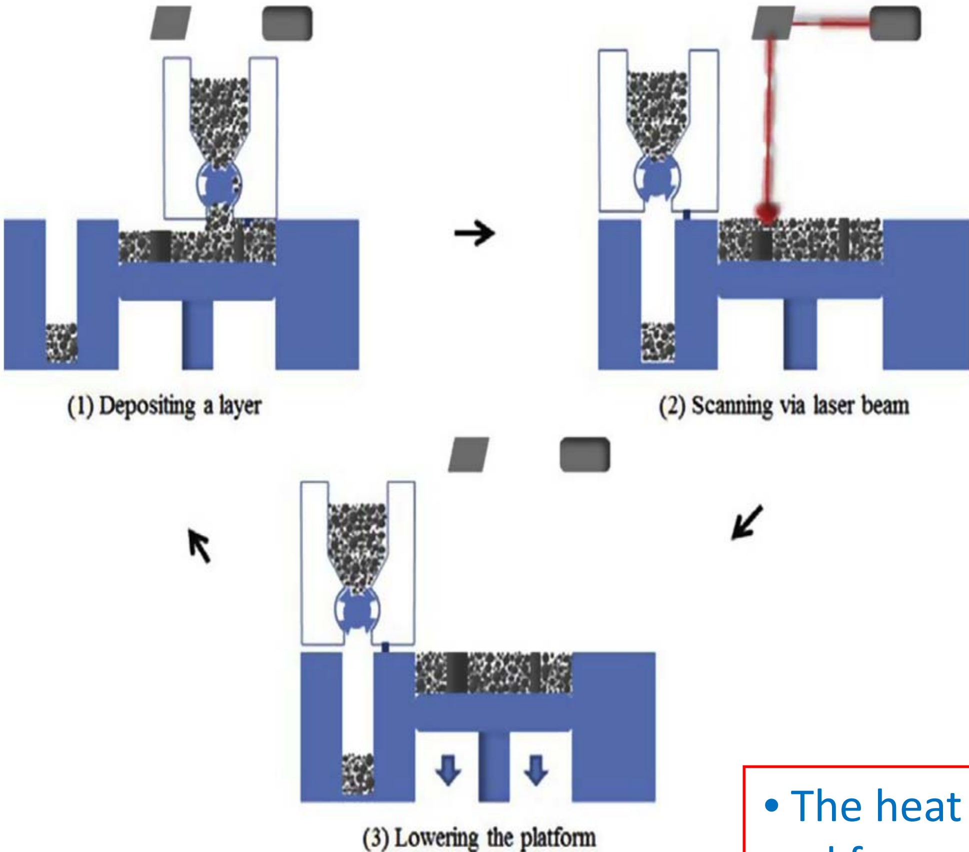


Fig. 1. Schematic of the SLM process

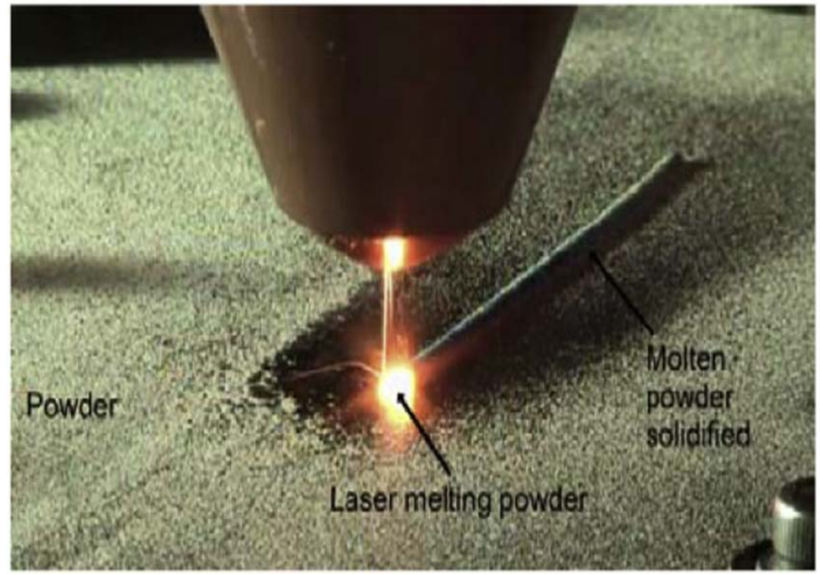


Fig. 2. Laser beam melting powder in the SLM process

- The heat generated causes powder particles to melt and form a melt pool which solidifies as a consolidated layer of material.

- SLM is very similar to SLS in terms of equipment but uses a much higher energy density, which enables full melting of the powders. Therefore, the fabricated parts exhibit a density very close to the theoretical one.

Process…Contd

- After a layer of powder is laid, the Yb:YAG fibre laser beam scans the powder-coated base-plate according to the first cross-section defined by the input STL file.
- When the scanning of first cross-section is complete, the building platform will move several microns down, a distance equivalent to the pre-defined layer thickness of 50 µm. This is the end of a cycle.
- After which, the recoater will once again move across the base-plate, laying another 50 µm layer of powder and the process repeats as described.
- Areas that have been scanned by the laser will become solid while those not scanned by the laser will remain in powder form and serve as support material. The entire fabrication process occurs generally in inert environment.
- To prevent oxidation, degradation and interaction of the molten material with the surroundings argon gas environment is used.
- After the entire fabrication process is complete the supporting powder will be collected and sieved for reuse.

Process…Contd

- The temperature experienced by the powder under it rises and eventually melts when the melting point is exceeded.
- The energy density deposited has to be sufficient in order to ensure not only the melting of the powder but also the underlying base-plate as both have to fuse together to avoid weak bonding.
- Weak bonding between layers are the source of cracking and are undesirable.
- During melting, the powder layer will shrink in volume as the molten metal seeps through pores.
- Volume shrinkage is equivalent to the initial powder porosity.
- If the energy density deposited is high, the temperature of the molten metal will continue to rise and evaporation will occur when the boiling point is exceeded.
- The evaporated material is removed by the flow of argon gas and as the laser beam moves away, the remaining molten metal cools rapidly and solidifies.
- The presence of pores in SLM fabricated parts could be possible due to the inherent trapping of gas in the melt pool, recoil pressure experienced by the molten material as the material evaporates and reduction in the dissolved element solubility during the rapid melting and cooling process.

Process...Contd

- Subsequent annealing and heat treatment can produce mechanical properties comparable to wrought materials.
- Hot Isostatic Pressing (HIP)?   Densification?

Advantages

- Complete melting of powder in SLM could produce parts with much higher density and strength.
- Negligible waste of material (unused powders can be recycled).
- Possibility of producing complicated shapes (e.g., a steel mold with curved internal cooling channels, which is common to other AM methods).
- Ability to process a wide variety of metals and their mixtures (due to the powder-based nature of SLM).
- No need for any distinct binders or melt phases.

Disadvantages

- SLM suffers from melt pool instabilities leading to imperfections such as low-quality down-facing surfaces, greater upper-surface roughness, and the risk of internal pores.
- The coarse and grainy surface finish may require a secondary machining or polishing process.
- The high temperature gradients in SLM increase the risk of delamination and distortion due to large thermal or residual stresses.
- From an economical aspect, the high cost of a high-power laser source, long processing times, and a small palette of available materials are the main obstacles.

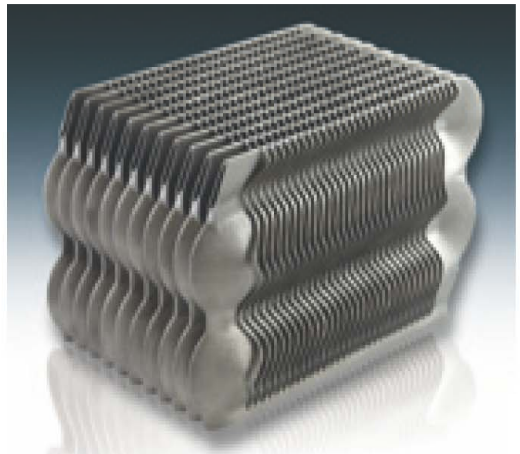
Materials

- Stainless steel
- Cobalt-Chrome alloys
- Titanium alloys
- Bronze-nickel alloys
- Tool steels
- Nickel based super alloys
- Composites
- Plastics and polymer

Material name	Material type	Typical applications
Stainless Steel	1.4404 (316L) stainless steel	functional prototypes
Tool Steel	1.2344 (H13) tool steel	Injection moulding tooling; functional prototypes
CpTi	Commercially Pure Titanium	Implants and medical devices
Ti64	Ti6Al4V	Implants and high performance functional components
Ti6Al7Nb	Ti6Al7Nb	Implantable devices
Aluminium	Aluminum Silicon Alloy	Functional prototypes and series parts;
Cobalt Chrome	CoCrMo superalloy	Functional prototypes and series parts; medical, dental

However the production of metal parts via SLM has some open challenges:

- To fully liquefy material from a powder bed.
- High heat input often causes an increase in material vaporization and spatter generation during processing.
- Surface roughness is another SLM issue that is influenced by particle melting, melt pool stability and re-solidifying mechanisms

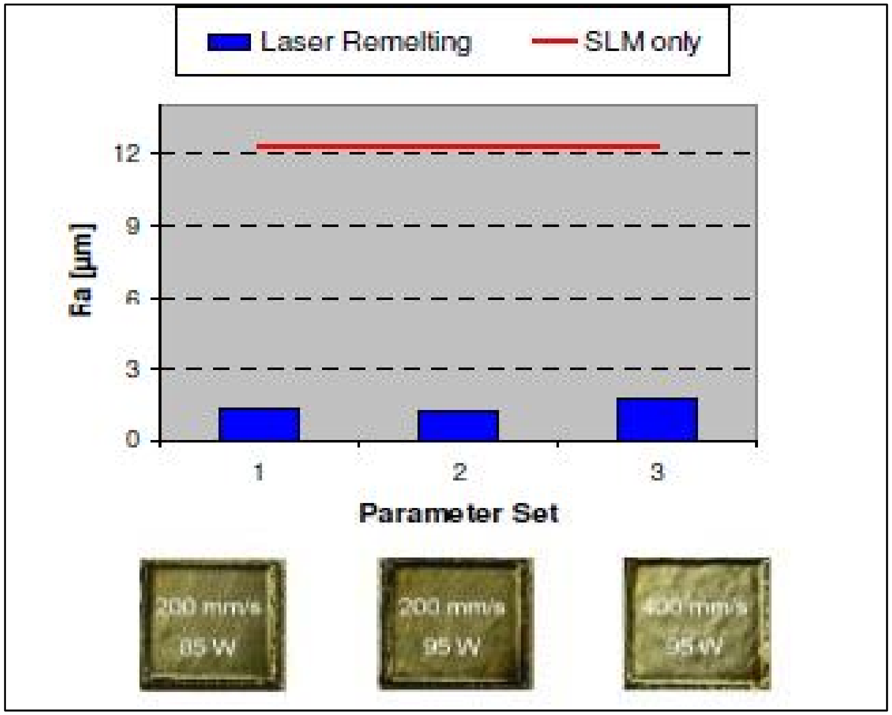


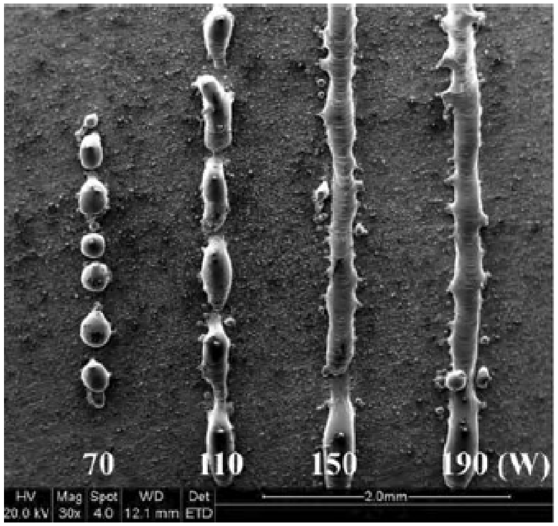
Selective laser melting, SLM. Internally cooled pin for injection molds, left (Source: Concept Laser GmbH); micro cooler made from AlSi10Mg, right (Source: EOS GmbH)

Selective laser sintering, SLS (3D Systems), polyamide; exhaust gas device, prototype (left); fan, final product (right) (Source: CP-GmbH)

CHALLENGES

- Surface finish
- Residual Stress
- Density Issue
- Balling

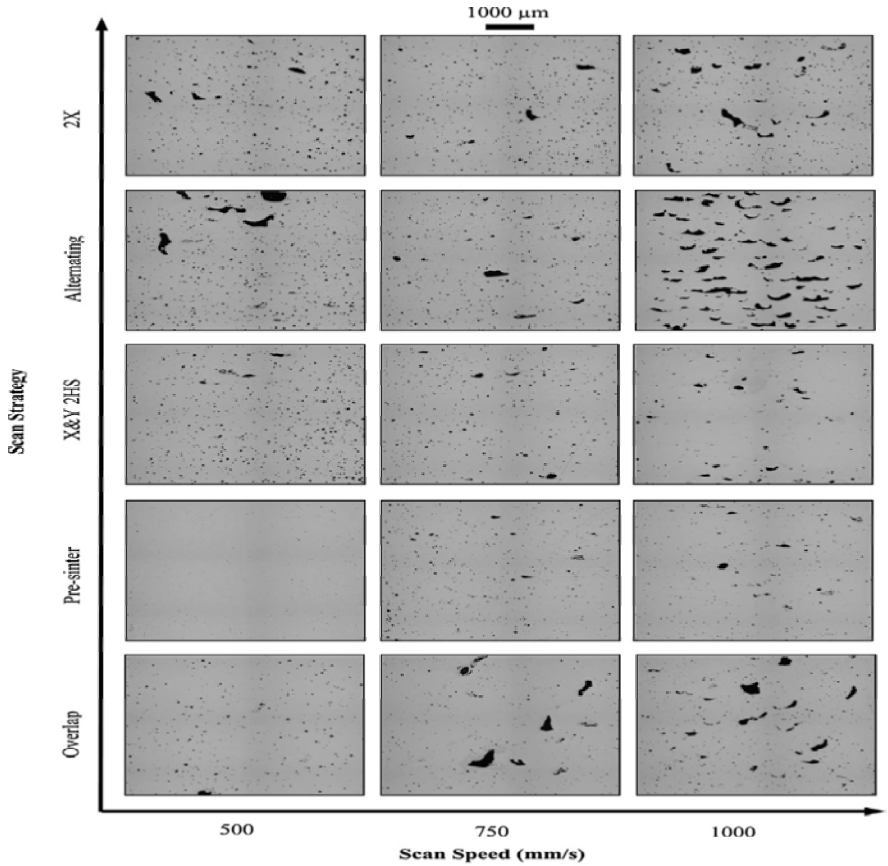




Potential Defects

Porosity

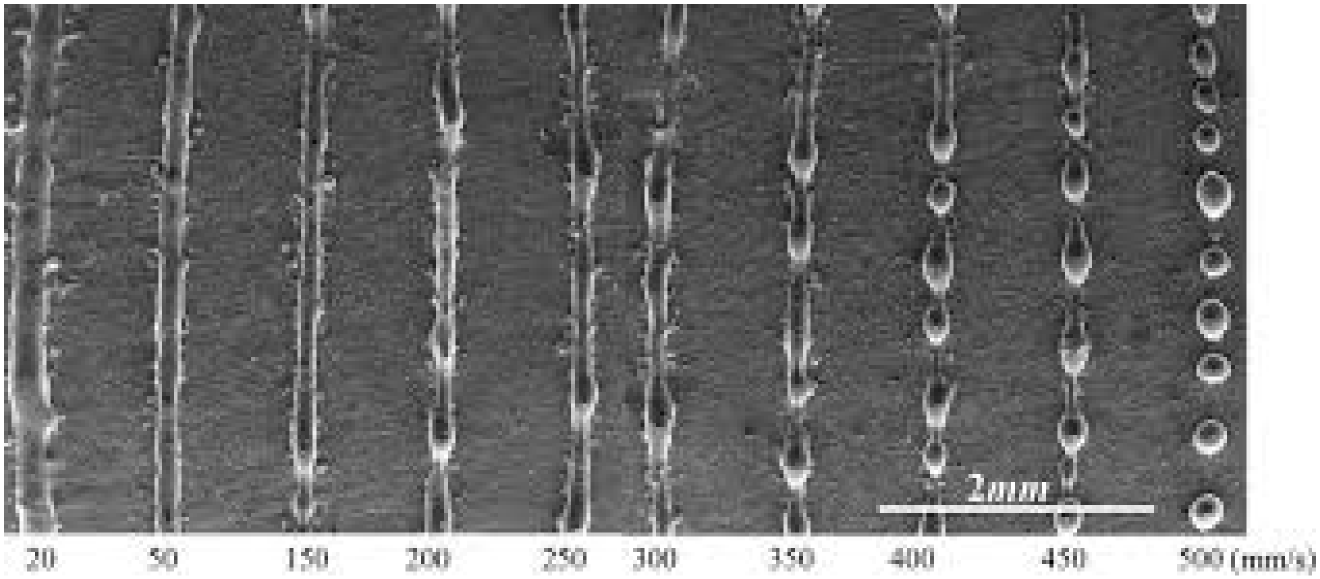
Porosity is a common defect in SLM products because the powder consolidation process is driven only by temperature changes, gravity, and capillary forces, without the application of external pressure. Porosity can be found as large irregular pores due to a lack of melting, shrinkage micropores due to a lack of feeding within interdendritic zones, spherical pores caused by trapped gas, etc. Adjustments of the laser processing parameters can improve the densification



Porosity evolution in AlSi10Mg samples processed using different combinations of scan speeds and scan strategies.

Balling

Balling occurs when the molten material fails to wet the underlying substrate (due to the surface tension), spheroidizing the liquid. This results in a rough and bead-shaped scan track, increasing the surface roughness and increasing the porosity. Generally, both material properties and processing variables can influence wettability and consequently balling. Because liquid metals do not wet surface oxide films in the absence of a chemical reaction, it is very important to avoid oxidation and contamination. Another possibility to improve wetting is the addition of certain alloying elements, such as phosphorous in selective laser melting of iron-based powder.



Balling characteristics of single scan tracks under different scan speeds.

Residual Stress

SLM is known to introduce large amounts of residual stresses due to the large thermal gradients that intrinsically exist in the process. The residual stress originates partly from the cooling and shrinkage of the newly molten layer and partly from strain-induced stresses in the solid layers on the substrate underneath the newly applied layer. This imposes tensile stresses on the newly deposited layer and creates compressive stresses at the bottom. The residual stresses will be partially relieved after cutting the part from the base plate, causing some deformation. The stress is usually tensile at the top or bottom and compressive in the center of the part.

Cracks

Cracks commonly originate from the high temperature gradient between the melt pool and surrounding solids leading to excessive thermal stress and rupture. Compositional segregations in some alloys may intensify the cracking. Alloys that are prone to hot cracking and solidification cracking have been proven difficult to process by SLM.

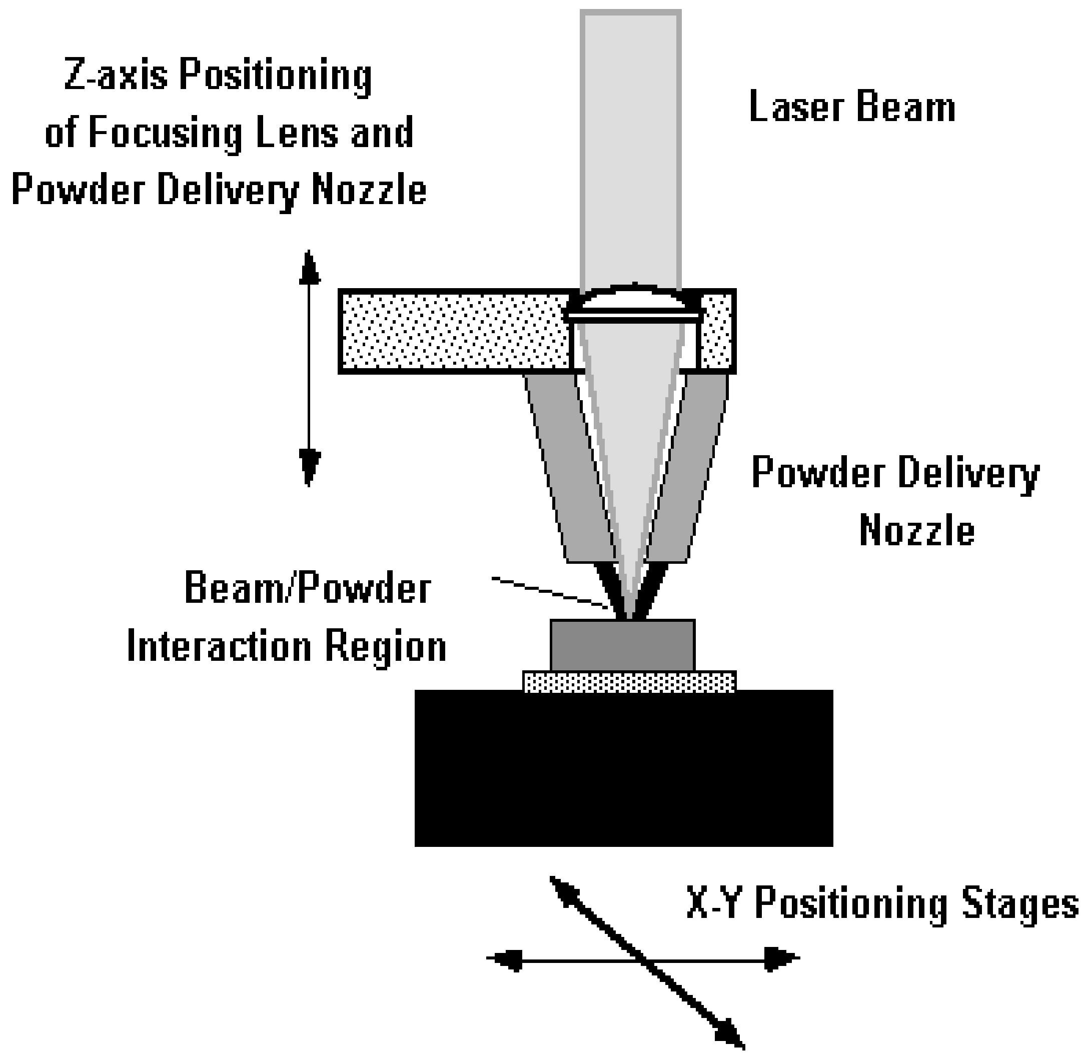
Research opportunities in SLM

- Melt pool formation and solidfification
- Investigating mechanisms of residual stress build up and finite element modeling
- Measurement of ‘as built’ residual stress
- Parameter development for increase build rate
- Parameter development for improved down facing surface finish
- Mechanical property validation together with build position and parameter effects
- Microstructural evolution and modeling
- Manufacture and quantification of complex net structures
- Deposition of new and novel materials

LASER ENGINEERED NET SHAPING (LENS)

a type of Beam Deposition (BD) Process

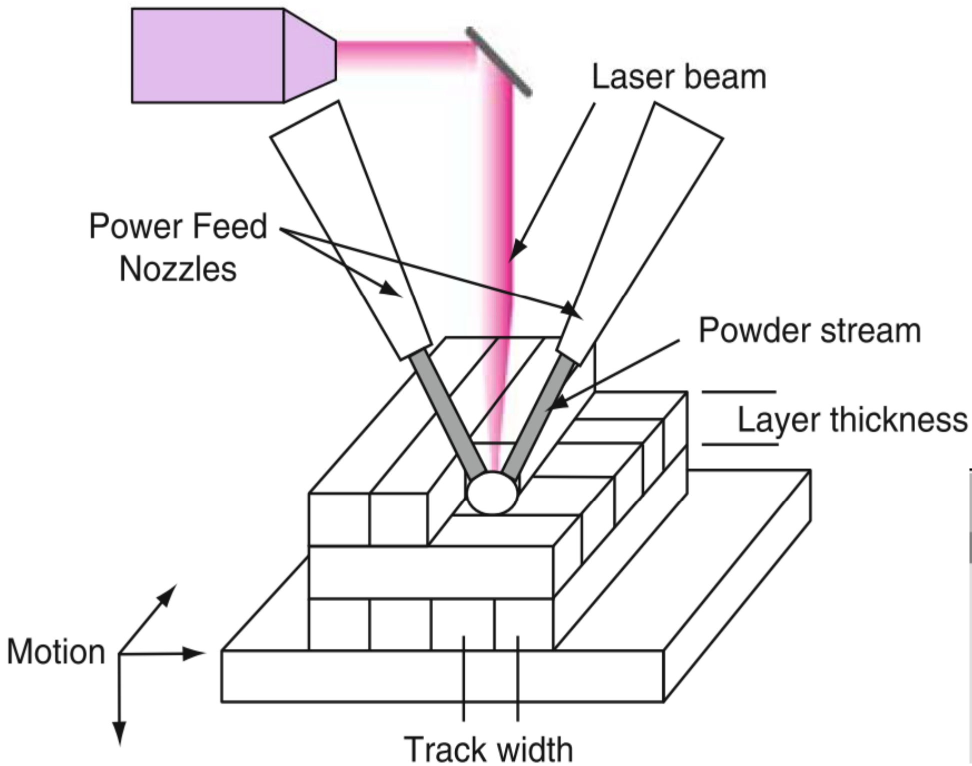
Schematic of LENS Process

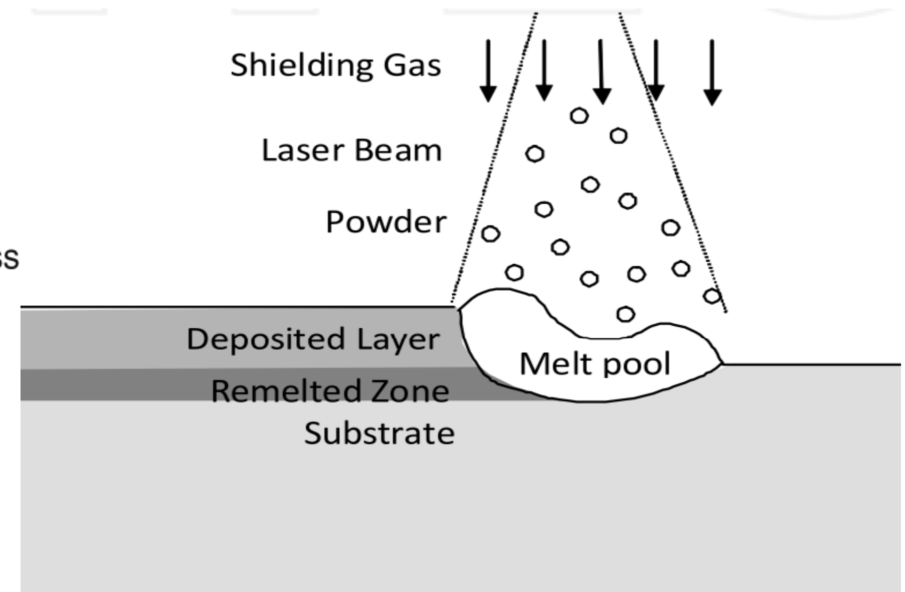


- This machine employs powder delivery through a nozzle placed above the part.
- The powder is melted where the material converges with the laser and the substrate.

- Unlike the powder bed fusion techniques discussed, BD processes are NOT used to melt a material that is pre-laid in a powder bed but are used to melt materials as they are being deposited.
- Energy focused into a narrow region (a beam, such as a laser, electron beam or plasma arc), which is used to heat a material that is being deposited.
- Each pass of the beam deposition head creates a track of solidified material, and adjacent lines of material make up layers.
- This approach allows the process to be used to add material to an existing part, which means it can be used for repair of expensive metal components that may have been damaged, like chipped turbine blades and injection mold tool inserts.

Complex 3-dimensional geometry requires either support material or a multi axis deposition head.

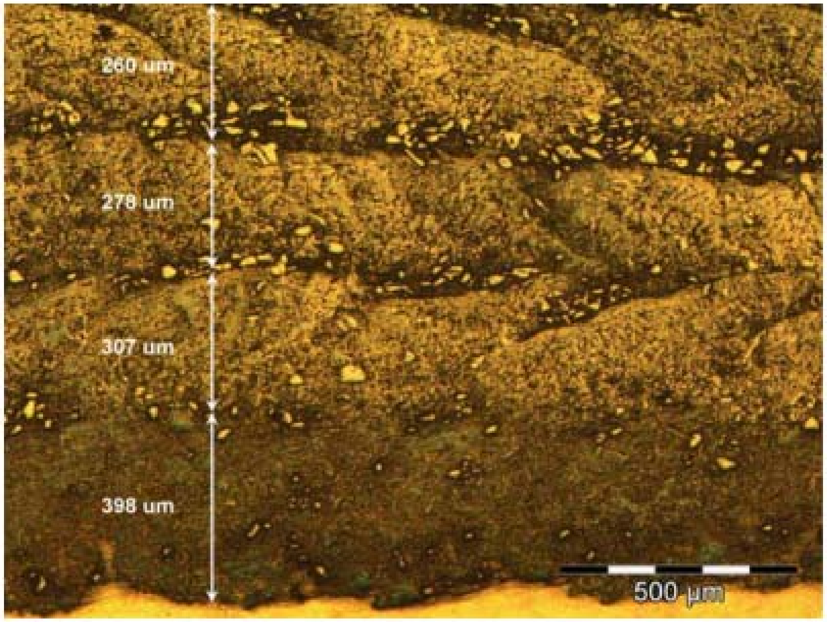




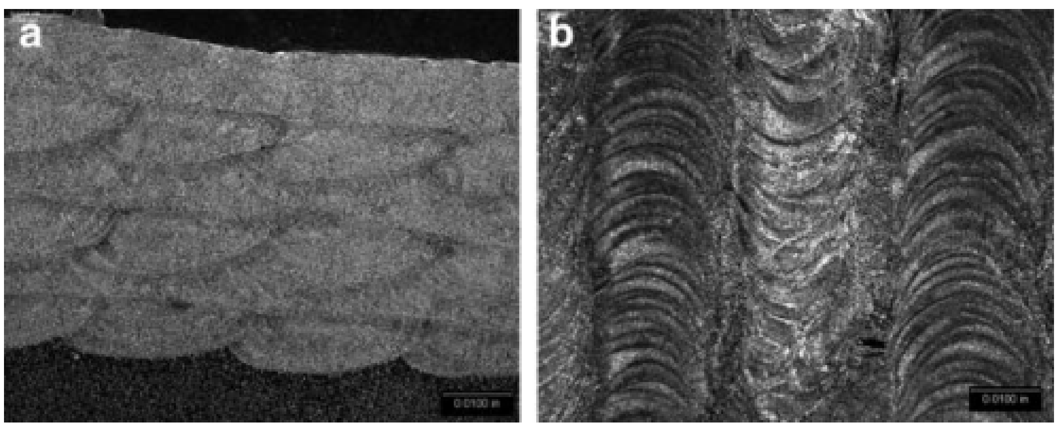
- These machines have been referred to as Laser Engineered Net Shaping (LENS), Directed Light Fabrication (DLF), Direct Metal Deposition (DMD), 3D Laser Cladding, Laser Generation, Laser-Based Metal Deposition (LBMD), Laser Freeform Fabrication (LFF), Laser Direct Casting, LaserCast, Laser Consolidation, LasForm and others.

- Although the general approach is the same, differences between these machines commonly include changes in laser power, laser spot size, laser type, powder delivery method, inert gas delivery method, feedback control scheme, and/or the type of motion control utilized.

- Because these processes all involve deposition, melting and solidification of powdered material using a traveling melt pool, the resulting parts attain a high density during the build process (although the surface often has porosity due to adhered partially molten particles).

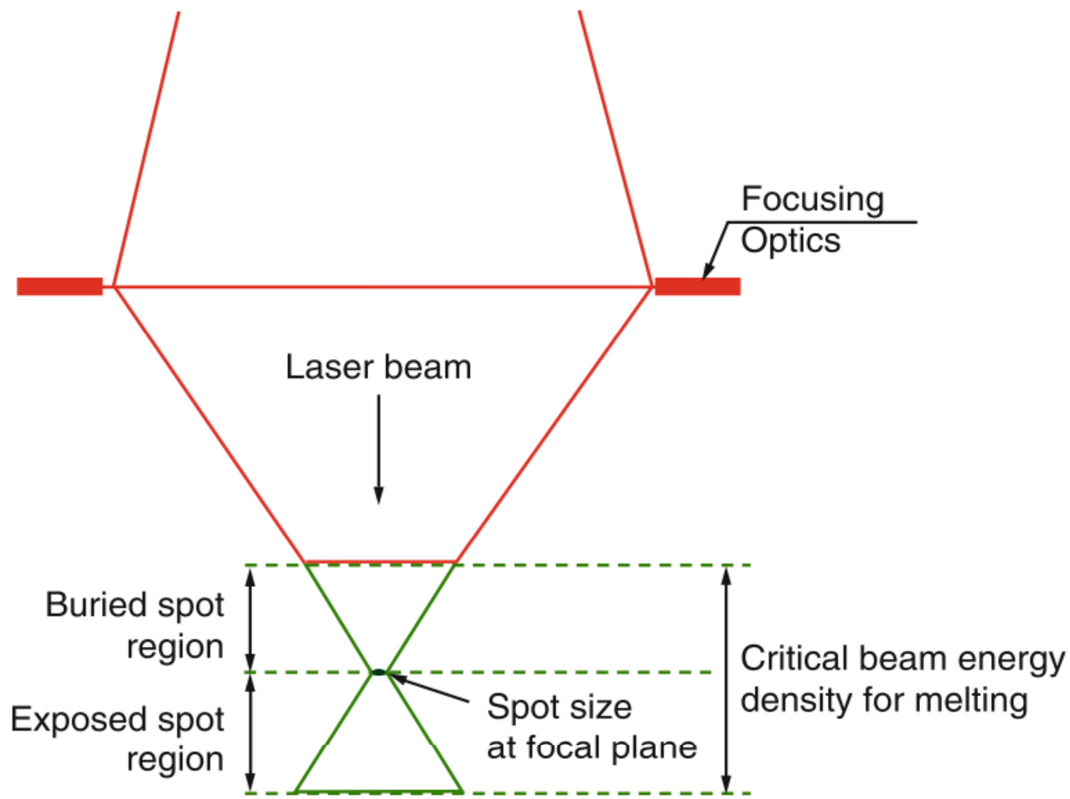


LENS-deposited Ti/TiC metal matrix composite structure (4 layers on top of a Ti substrate)



CoCrMo deposit on CoCrMo: (a) side view (every other layer is deposited perpendicular to the previous layer using a 0,90,0 pattern); and (b) top view of deposit

- When a laser is focused to a small spot size, there is a region above and below the focal plane where the laser energy density is high enough to form a melt pool.
- If the substrate surface is either too far above or too far below the focal plane, no melt pool will form.



MATERIALS

- Process also allows fabricating multiple materials structures with gradient or stepped material transitions.
- These processes can involve extremely high solidification cooling rates, from 10^3 to as high as 10^5 ºC/s. This can lead to several microstructural

  advantages, including:

(a) suppression of diffusion controlled solid-state phase transformations

(b) formation of supersaturated solutions and nonequilibrium phases

(c) formation of extremely fine microstructures with dramatically reduced elemental segregation

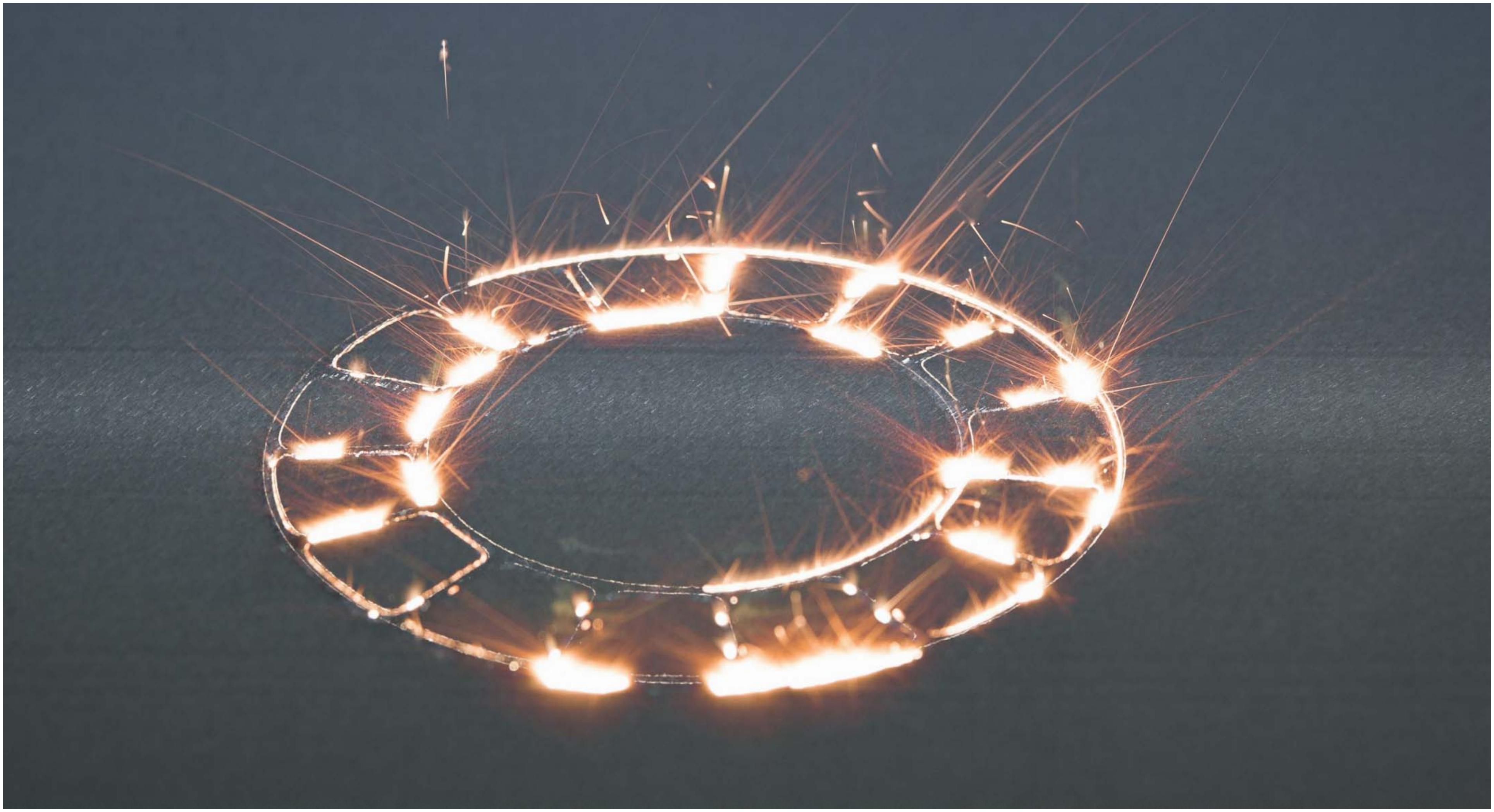
(d) formation of very fine secondary phase particles (inclusions, carbides, etc.)

Applications

- Build mold and die inserts
- Producing titanium parts in racing industry
- Fabricate titanium components for biological implants
- Produce functionally gradient structures

Research and Development

- Embedded structures.
- Thermally conductive materials.
- Gradient materials.
- Metal matrix composites.
- Mold repair and modification
- Ways to increase deposition rate.

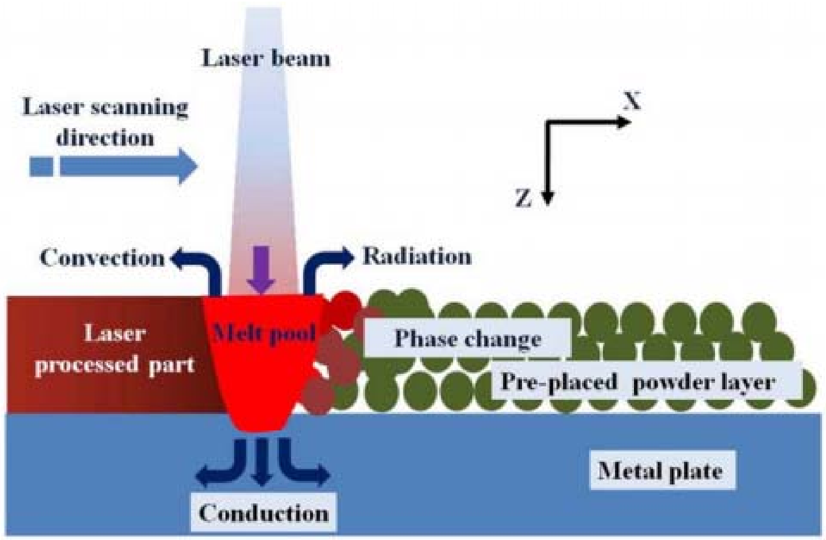


Transport Phenomena in
Selective Laser Melting
(Metal Additive Manufacturing)

Context : Scientific issues

Physical mechanisms involved

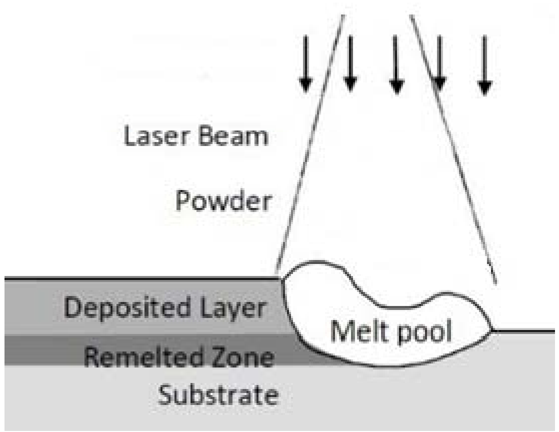
- Multi-mode phase change (melting, solidification, evaporation, and remelting
- Melt pool/powder interaction (splashing, mass addition), mass, heat and species transport
- Surface tension and density gradient driven flows, sensible heating/ thermal cycling

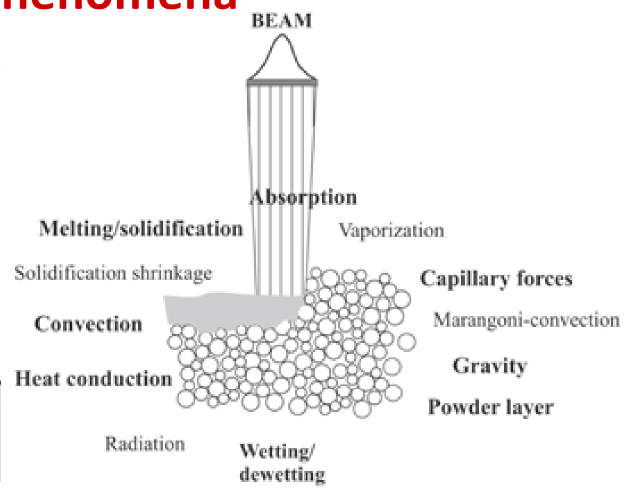


Outstanding scientific issues

- Transport phenomena in molten pool and solidification
- Inter layer bonding
- Temperature gradients and thermal stresses
- Microstructure formation and mechanism

Physical phenomena

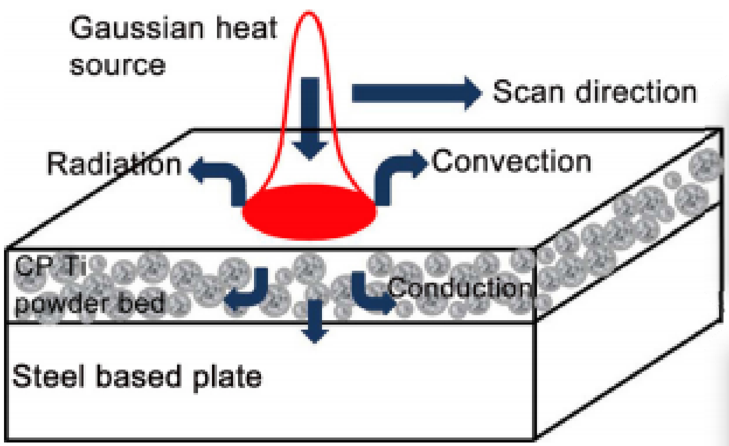




Macro scale **Micro scale**

Key Results of the Previous Work

Many important phenomena that influence the melt pool geometry were neglected in the past studies



1 Melting of solid powder not attended in detail

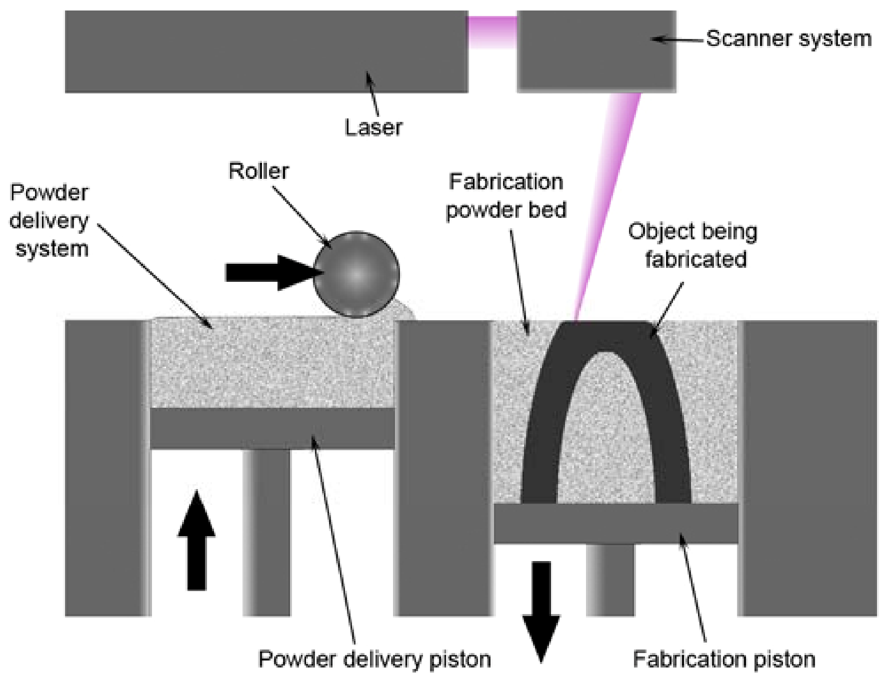
2 Melting of powder to liquid leads to volume shrinkage

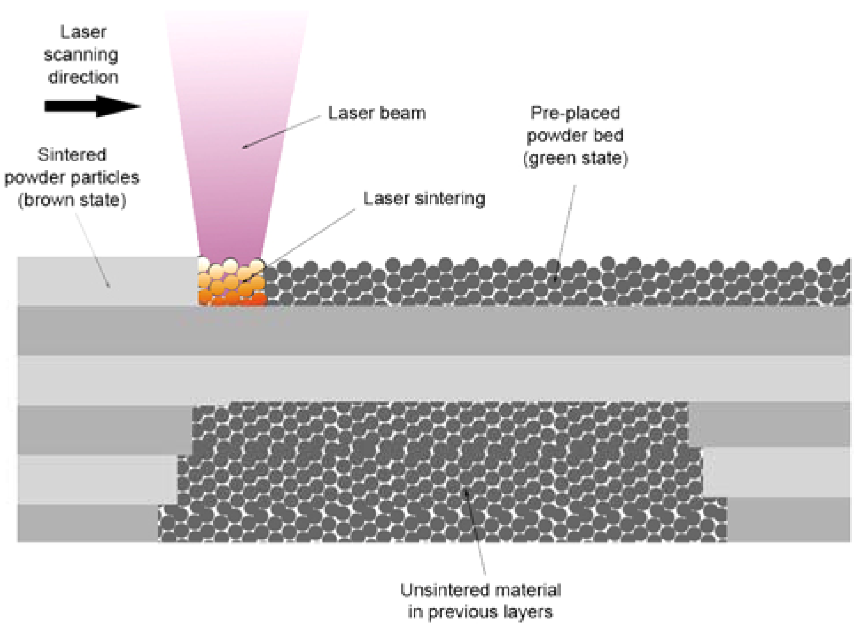
3 Deformation of surface of powder after melting

New model for Selective Laser Melting (SLM) process should consider:

I. Volume contraction of porous powder layer during melting and the transition of powder-liquid-solid phase change

II. Fluid flow in the melt pool – Marangoni and natural convection





Modelling

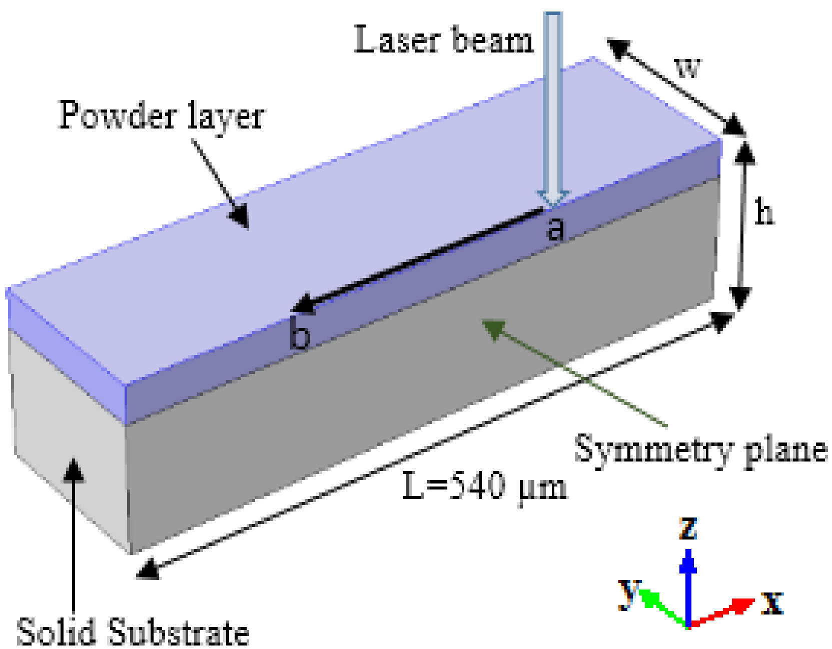
Only half domain is simulated because of symmetry in the x-z plane.
Gaussian Laser beam traverses from point *a* to *b.*

Both the powder layer and the substrate are of Ti-6Al-4V material.

Assumptions:

(1) Powder layer is homogeneous with uniform material properties.

(2) Laminar flow, incompressible Newtonian fluid.



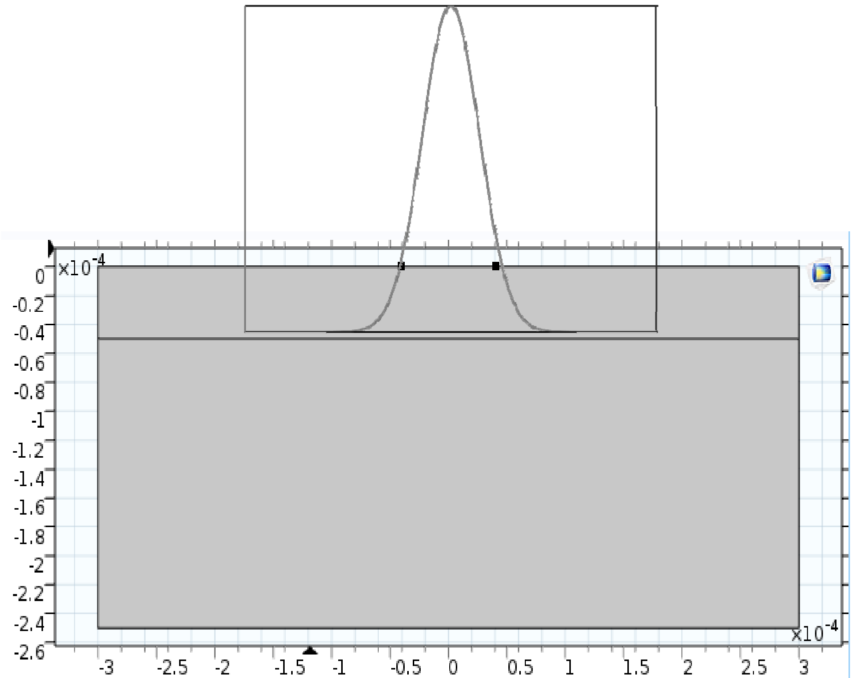
Powder and solid metal properties

Accounting the power porosity in the powder layer is a very crucial factor in determining the accuracy of the simulated results. Thummler and Oberacker proposed the thermal conductivity of a powder bed by the following relationship

$$k_{powder} = k_{solid}(1 - \varphi)$$

$$\rho_{powder} = \rho_{solid}(1 - \varphi)$$

Model Set-Up



Material Properties of Ti6Al4V

Physical Properties	Value
Liquidus temperature (K)	1923.0
Solidus temperature (K)	1877.0
Evaporation temperature (K)	3533.0
Solid specific heat ($J\ kg^{-1}\ K^{-1}$)	$\begin{cases} 483.04 + 0.215T & T \le 1268K \\ 412.7 + 0.1801T & 1268 < T \le 1923 \end{cases}$
Liquid specific heat ($J\ kg^{-1}\ K^{-1}$)	831.0
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	$\begin{cases} 1.2595 + 0.0157T & T \le 1268K \\ 3.5127 + 0.0127T & 1268 < T \le 1923 \\ -12.752 + 0.024T & T > 1923 \end{cases}$
Solid density ($kg\ m^{-3}$)	4420 – 0.154 (T – 298 K)
Liquid density ($kg\ m^{-3}$)	3920 – 0.68 (T – 1923 K)
Latent heat of fusion ($J\ kg^{-1}$)	2.86×10^{5}
Latent heat of evaporation ($J\ kg^{-1}$)	9.83×10^{6}
Dynamic viscosity ($N\ m^{-1}\ s^{-1}$)	3.25×10^{-3} (1923K) 3.03×10^{-3} (1973K) 2.66×10^{-3} (2073K) 2.36×10^{-3} (2173K)
Radiation emissivity	$0.1536+1.8377\times10^{-4}\ (T - 300.0\ K)$
Surface tension ($N\ m^{-1}$)	$1.525 - 0.28\times10^{-3}(T - 1941K)^{a}$
Thermal expansion coefficient (K^{-1})	1.1×10^{-5}
Laser absorption coefficient	0.4
Ambient temperature (K)	300
Convective coefficient ($W\ m^{-2}\ K^{-1}$)	10

Determination of thermal parameters

- The effective thermal conductivity of the loose powder bed is an important material property determining the accuracy of SLM simulation results.
- Effective thermal conductivity of a powder bed was controlled by gas-filled pores and depended on the solid fraction and particle size.
- Effective thermal conductivity of a powder bed could be defined by the following simplified generic relationship:

$$k_{\mathrm{p}} = k_{\mathrm{s}}(1 - \phi),$$

- Where *k*p and *k*s are the thermal conductivity of the powder bed and solid material, respectively, and ϕ is the porosity of the powder bed, which can be expressed as

$$\phi = \frac{\rho_{\mathrm{s}} - \rho_{\mathrm{p}}}{\rho_{\mathrm{s}}},$$

- Where ρs and ρp are the density of the solid and the powder bed , respectively. It is normally assumed that the porosity varies from ϕ = 0.40 for the powder state to ϕ = 0 for the solid state.

Governing transport equations and Boundary conditions

Energy conservation:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \vec{u} \,.\, \nabla T = \nabla.(k\nabla T) \quad (1)$$

Momentum conservation:

$$\rho \frac{\partial \vec{u}}{\partial t} + (\rho \,\vec{u} \,.\, \nabla)\vec{u} = -\nabla p + \nabla.(\mu(\nabla \vec{u} + (\nabla \vec{u})^T) + \vec{F} \quad (2)$$

$$\vec{F} = \overrightarrow{F_S} + \overrightarrow{F_N} \quad (3)$$

$$\overrightarrow{F_S} = \frac{(1-\beta)^2}{\beta^3 + b} C\vec{u} \quad (4)$$

Governing transport equations and Boundary conditions

Natural convection: The buoyant flow is included in this model with the help of Boussinesq approximation. The source term F_N in Eq. (3) is given as

$$\overrightarrow{F_N} = \rho\vec{g}\beta_T(T - T_{ref}) \qquad (6)$$

where β is coefficient of thermal expansion.

Marangoni convection: The following equations describes the forces that the Marangoni convection induces on the interface at the free surface

$$\tau_{xz} = -\mu\left(\frac{\partial u}{\partial z}\right) = \gamma\left(\frac{\partial T}{\partial x}\right) \qquad (7)$$

$$\tau_{yz} = -\mu\left(\frac{\partial v}{\partial z}\right) = \gamma\left(\frac{\partial T}{\partial y}\right) \qquad (8)$$

where μ and γ are viscosity and surface tension coefficient, respectively.

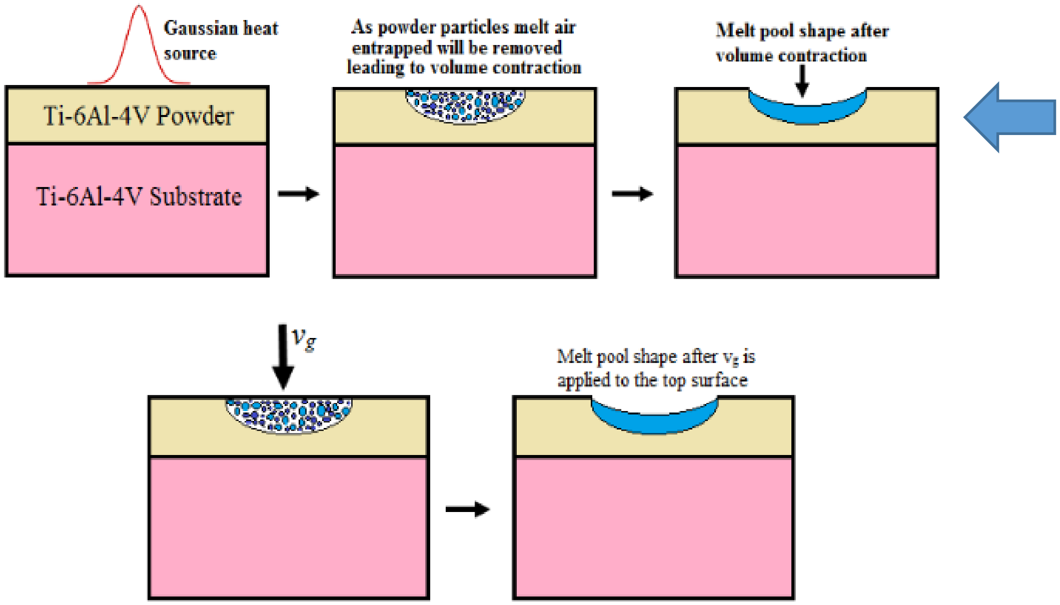
Boundary Conditions: The heat flux from the laser beam in the SLM process can be approximated by a Gaussian distribution & heat flux on powder bed is given by following expression

$$q = \frac{2AP}{\pi R^2}\, exp\left(-\frac{2r^2}{R^2}\right) \qquad (9)$$

Energy balance at the top surface leads to the following boundary equation:

$$\frac{\partial T}{\partial n} = q - h_c(T - T_\infty) - \varepsilon\sigma\left(T^4 - {T_\infty}^4\right)$$

Volume contraction



Upon melting the powder particles remove pores initially present between them. This causes the volume of the powder layer to contract.

Results

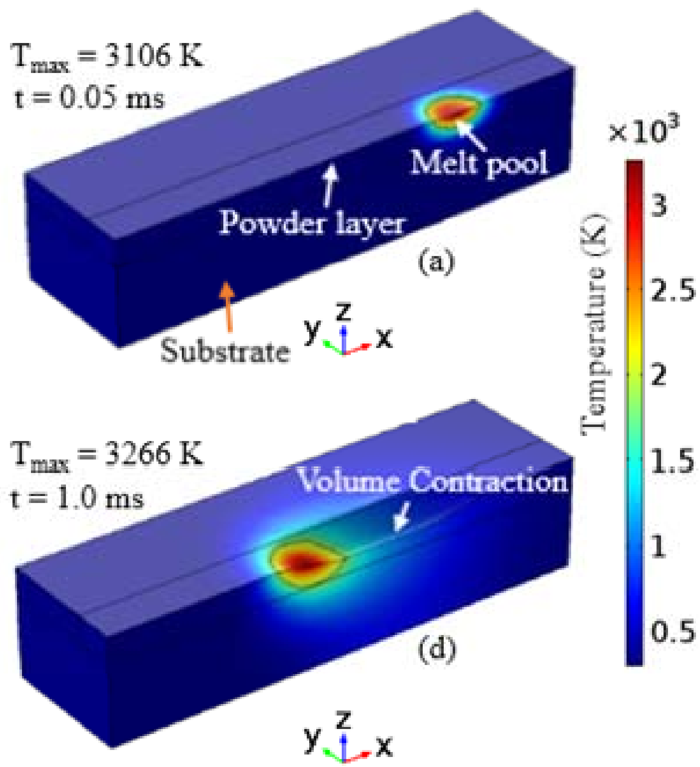


Fig. 1: Evolution of melt pool temperature with time for P = 20 W

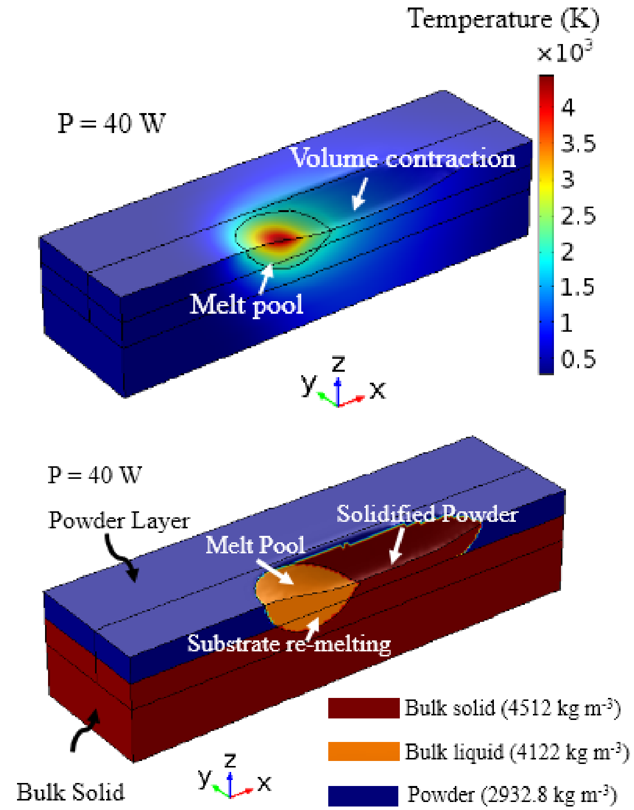
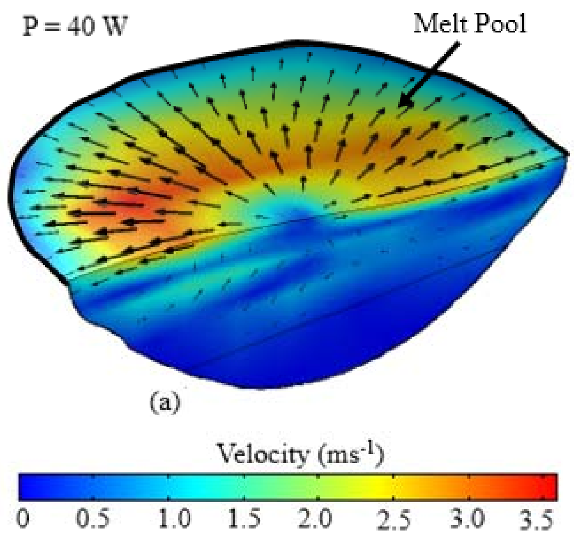


Fig. 2: Powder – Liquid – Solid transition

Substrate remelting phenomenon and flow in remelted portion are also possible to simulate. The remelting is known to create a good interlayer metallurgical bonding.

Results: Convective flows



Marangoni convection strongly governs the melt pool geometry, its thermal and flow behavior.