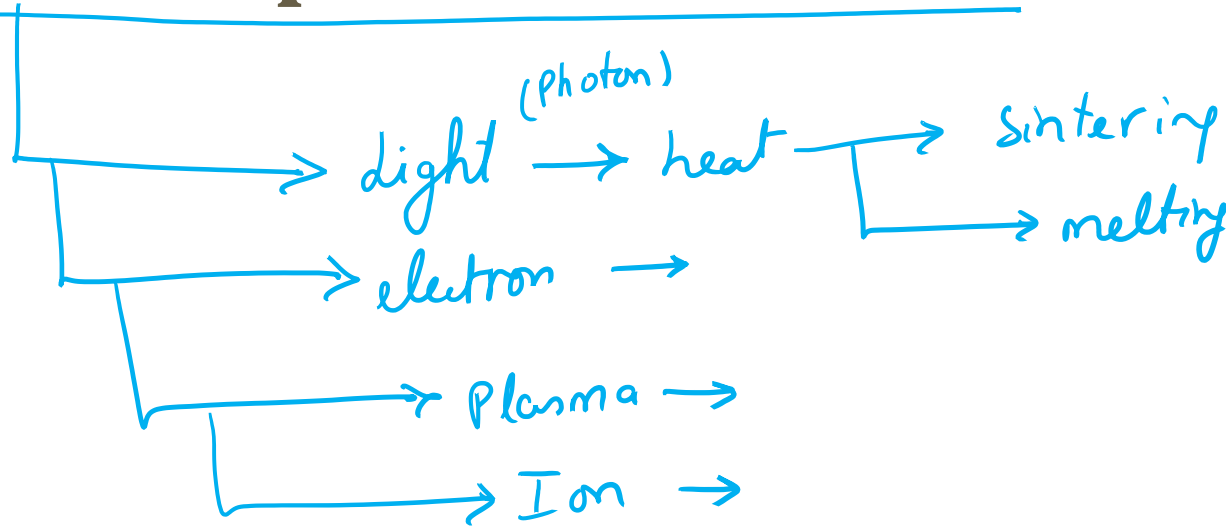


Beam Deposition Processes



Dr. Janakarajan Ramkumar

Professor

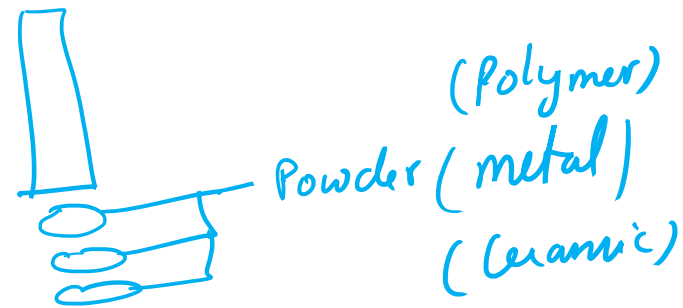
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- **Introduction** ✓
- **Beam Deposition Process** ✓
- **Material Delivery** ✓
- **Wire Feeding** ✓
- **Beam Deposition Systems** ✓
- **Process Parameters** ✓
- **Processing–Structure–Properties relationships** ✓
- **Beam Deposition benefits and drawbacks**

Introduction



- **Beam deposition (BD)** processes enable the creation of parts by melting and deposition of material from powder or wire feedstock.
- Although this basic approach can work for polymers, ceramics, and metal matrix composites, it is predominantly used for metal powders.
 ↳ reinforce → Powder form
- Thus, this technology is often referred to as 'metal deposition' technology.
- To avoid limiting the readers' understanding to just metal build materials, however, we will refer to this category of processes as beam deposition processes.

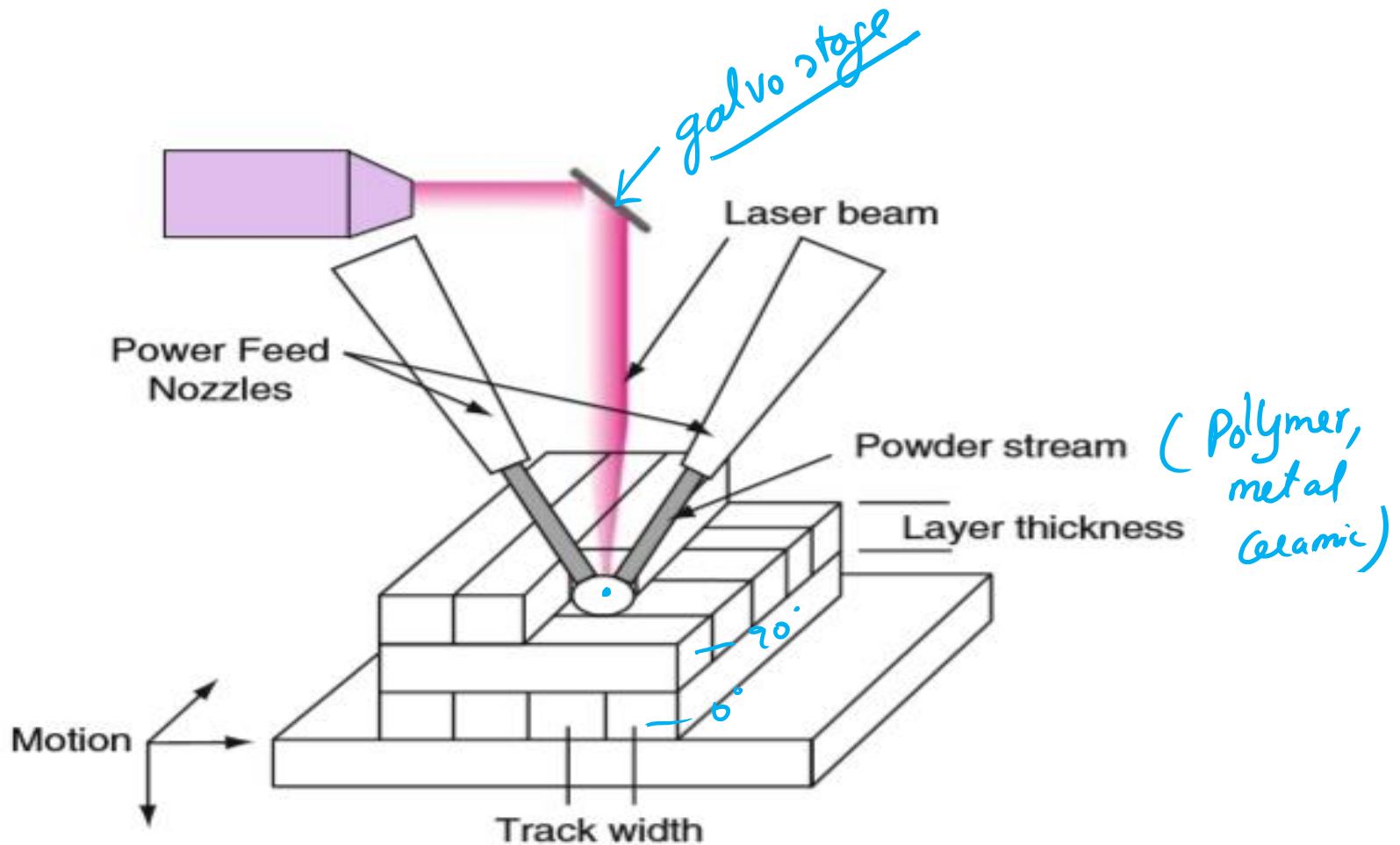
Introduction

- BD processes use some form of energy focused into a narrow region (a beam), which is used to heat a material that is being deposited.
- 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.
- BD processes use a focused heat source (such as a laser, electron beam or plasma arc) to melt the feedstock material and build up 3-dimensional objects in a manner similar to the extrusion-based processes.
- Each pass of the BD head creates a track of solidified material, and adjacent lines of material make up layers.

Introduction

- Complex 3D geometry requires either support material or a multi-axis deposition head.
- A schematic representation of a BD process using powder feedstock material and laser is shown in Figure below.
- Most commercialized BD processes enable complete melting of powders using a focused high-power laser beam as the heat source.
- Research variants include using an electron beam or plasma source in place of the laser beam or the use of a thin metal wire instead of powder as the build material.

Introduction



Introduction

- In many ways, BD techniques can be used in an identical manner to laser cladding and plasma welding machines.
- For the purposes of this chapter, however, BD machines are considered as those which are designed to create depositions of complex 3D shapes directly from CAD files, rather than the traditional welding and cladding technologies, which were designed for repair, joining, or to apply coatings and do not typically use 3D CAD data as an input format.

Introduction

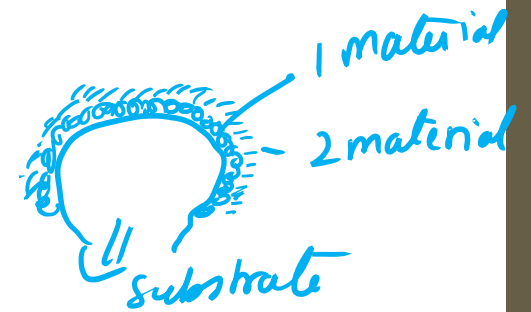
- A number of organizations have developed BD machines using lasers and powder feeders.
- These machines have been referred to as:
 - Laser Engineered Net Shaping (LENS), ✓
 - Directed Light Fabrication (DLF), ✓
 - Direct Metal Deposition (DMD), ✓
 - 3D Laser Cladding, ✓
 - Laser Generation, ✓
 - Laser-Based Metal Deposition (LBMD), ✓
 - Laser Freeform Fabrication (LFF), ✓
 - Laser Direct Casting, ✓
 - LaserCast, ✓
 - Laser Consolidation, ✓
 - LasForm and others. ✓

Introduction

- 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).

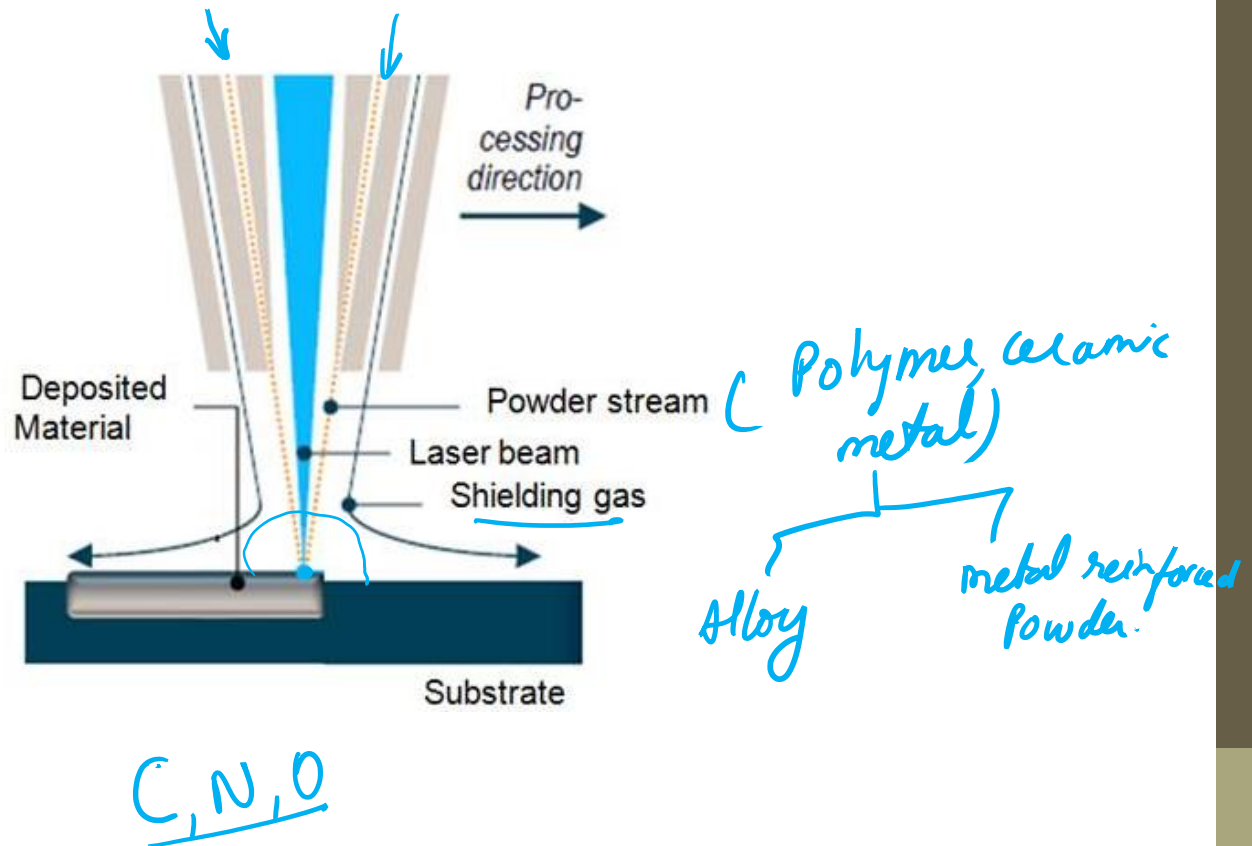


Beam Deposition Process

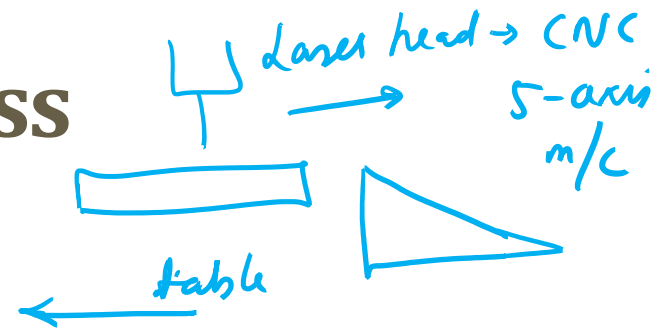


- As the most common type of beam deposition system is powder-based laser deposition system optimized for metals, a typical **Laser-Based Metal Deposition (LBMD)** process can be mentioned as the paradigm process.
- In LBMD, a “deposition head” is utilized to deposit material onto the substrate.
- A deposition head is typically an integrated collection of laser optics, powder nozzle(s), inert gas tubing, and in some cases, sensors.
- The substrate can be either a flat plate on which a new part will be fabricated or an existing part onto which additional geometry will be added.

Beam Deposition Process

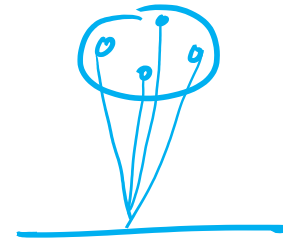


Beam Deposition Process



- Deposition is controlled by relative differential motion between the substrate and deposition head.
- This differential motion is accomplished by moving the deposition head, by moving the substrate, or by a combination of substrate and deposition head motion.
- 3-axis systems, whereby the deposition occurs in a vertical manner, are typical.
- However, 4- or 5-axis systems using either rotary tables or robotic arms are also available.

Beam Deposition Process

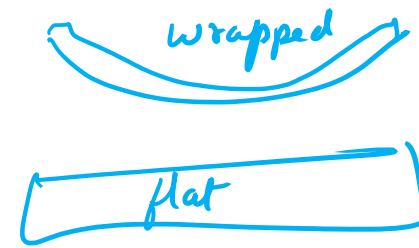


- ★ • The kinetic energy of powder particles being fed into the melt pool is greater than the effect of gravity on these powders during flight.
- ★ • As a result, nonvertical deposition is just as effective as vertical deposition. Multi-axis deposition head motion is therefore possible and, indeed quite useful.
- In particular, if the substrate is very large and/or heavy, it is easier to accurately control the motion of the deposition head than the substrate.
- Conversely, if the substrate is a simple flat plate, it is easier to move the substrate than the deposition head.

Beam Deposition Process

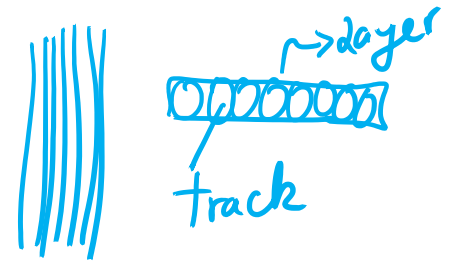
- Thus, depending on the geometries desired and whether new parts will be fabricated onto flat plates or new geometry will be added to existing parts, the optimum design of a LBMD apparatus will change.
- In LBMD, the laser generates a small molten pool (typically 0.25–1 mm in diameter and 0.1–0.5 mm in depth) on the substrate as powder is injected into the pool.
- The powder is melted as it enters the pool and solidifies as the laser beam moves away. 
- Under some conditions, the powder can be melted during flight and arrive at the substrate in a molten state; however, this is atypical and the normal procedure is to use process parameters that melt the substrate and powder as they enter the molten pool.

Beam Deposition Process



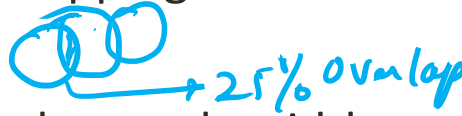
- The typical small molten pool and relatively rapid traverse speed combine to produce very high cooling rates (typically 1,000–5,000°C/s) and large thermal gradients.
- Depending upon the material or alloy being deposited, these high cooling rates can produce unique solidification grain structures and/or nonequilibrium grain structures which are not possible using traditional processing.
- At lower cooling rates (when using higher beam powers or lower traverse speeds), the grain features grow and look more like cast grain structures.

Beam Deposition Process



- The passing of the beam creates a thin track of solidified metal deposited on and welded to the layer below.

- A layer is generated by a number of consecutive overlapping tracks.

- The amount of track overlap is typically 25% of the track width (which results in re-melting of previously deposited material) and typical layer thicknesses employed are 0.25–0.5 mm.


- After each layer is formed, the deposition head moves away from the substrate by one layer thickness.

Material Delivery

Powder Feeding

- BD processes can utilize both powder and wire feedstock material.
- Each has limitations and drawbacks with respect to each other.
- Powder is the most versatile feedstock, and most metal and ceramic materials are readily available in powder form.
- However, not all powder is captured in the melt pool (e.g., less than 100% powder capture efficiency), so excess powder is utilized and care must be taken to ensure this excess powder is recaptured in a clean state if recycling is desired.

Material Delivery

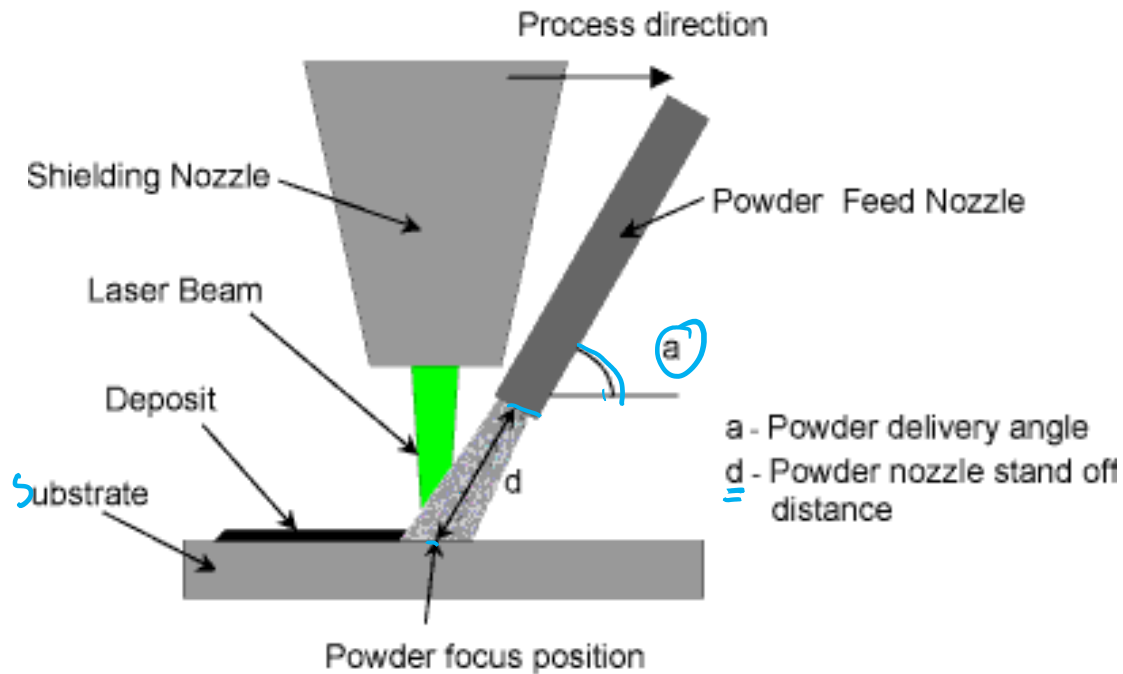
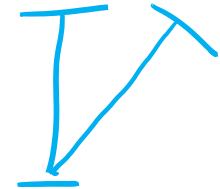
Powder Feeding

- Excess powder feeding, however, is not necessarily a negative attribute, as it makes BD processes geometrically flexible and forgiving.
- This is due to the fact that excess powder flow enables the melt pool size to dynamically change.
- (As described below, BD processes using powder feeding can enable overlapping scan lines to be used without the swelling or overfeeding problems inherent in extrusion-based processes.)

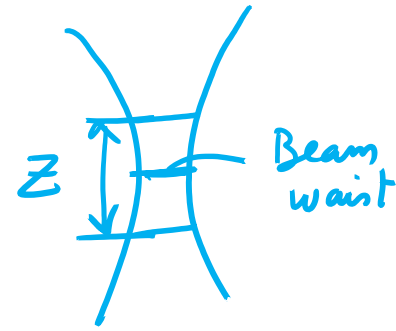
adv of BD with EP

Material Delivery

Powder Feeding



Material Delivery



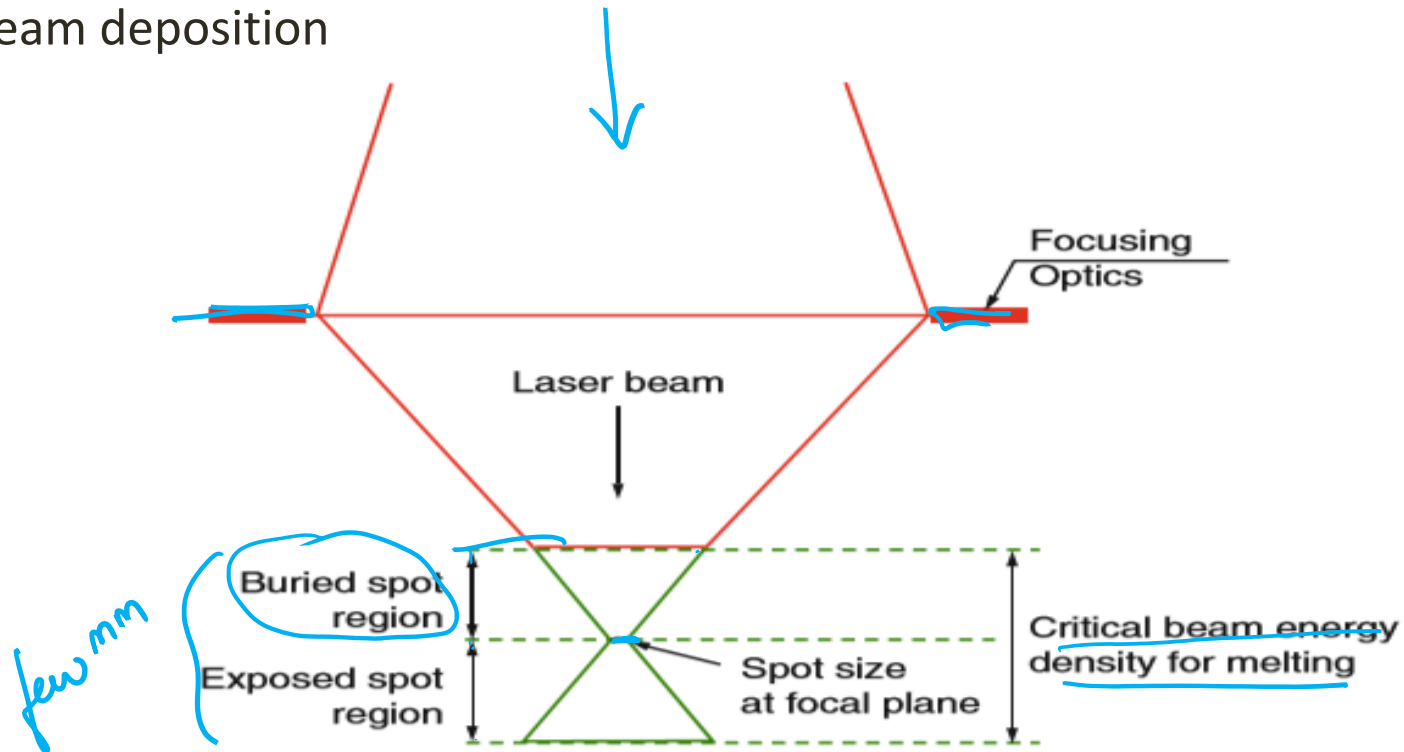
Powder Feeding

- In BD, the energy density of the beam must be above a critical amount to form a melt pool on the substrate.
melting (handwritten note with an arrow pointing to 'melt pool')
- 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. This region is labeled in Figure below.
⇒ flux density ↑ (handwritten note with an arrow pointing upwards)
- If the substrate surface is either too far above or too far below the focal plane, no melt pool will form. Similarly, the melt pool will not grow to a height that moves the surface of the melt pool outside this region.

Material Delivery

Powder Feeding

Schematic illustrating laser optics and energy density terminology for beam deposition



Source: Gibson et al. Additive manufacturing Technologies, 2010

Material Delivery

Powder Feeding

- Within this critical beam energy density region, the height and volume of the deposit melt pool is dependent upon melt pool location with respect to the focal plane, scan rate, laser power, powder flow rate, and surface morphology.
- Thus, for a given set of parameters, the deposit height approaches the layer thickness offset value only after a number of layers of deposition.
- This is evident, for instance, in the Figure, where a constant layer thickness of 200 mm was used as the deposition head z-offset for each layer.

Material Delivery

Powder Feeding

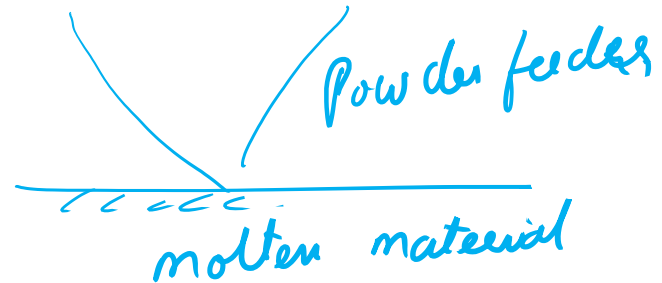
- The substrate was initially located within the buried spot region, but not far enough within it to achieve the desired thickness for the layers shown (i.e., the laser power, scan rate and powder flow settings caused the deposit to be thicker than the layer thickness specified).
- Thus, deposit thickness approached the layer thickness z-offset as the spot became effectively more “buried” during each subsequent layer addition.
- In the Figure, however, too few layers were deposited to reach the steady-state layer thickness value.

Material Delivery

Powder Feeding

- If the laser and scanning parameters settings used are inherently incapable of producing a deposit thickness at least as thick as the layer thickness z-offset value, subsequent layers will become thinner and thinner.
- Eventually, no deposit will occur when scanning for the next layer starts outside the critical energy density region (i.e., when the substrate starts out below the exposed spot region, there is insufficient energy density to form a melt pool on the substrate).
- In practice, when the first layer is formed on a substrate, the laser focal plane is typically buried below the surface of the substrate approximately 1 mm.

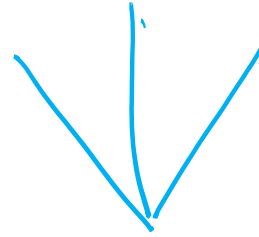
Material Delivery



Powder Feeding

- In this way, a portion of the substrate material is melted and becomes a part of the melt pool.
- The first layer, in this case, will be made up of a mixture of melted substrate combined with material from the powder feeders, and the amount of material added to the surface for the first layer is dependent upon process parameters and focal plane location with respect to the substrate surface.
- If little mixing of the substrate and deposited material is desired, then the focal plane should be placed at or above the substrate surface to minimize melting of the substrate – resulting in a melt pool made up almost entirely of the powdered material.

Material Delivery



Powder Feeding

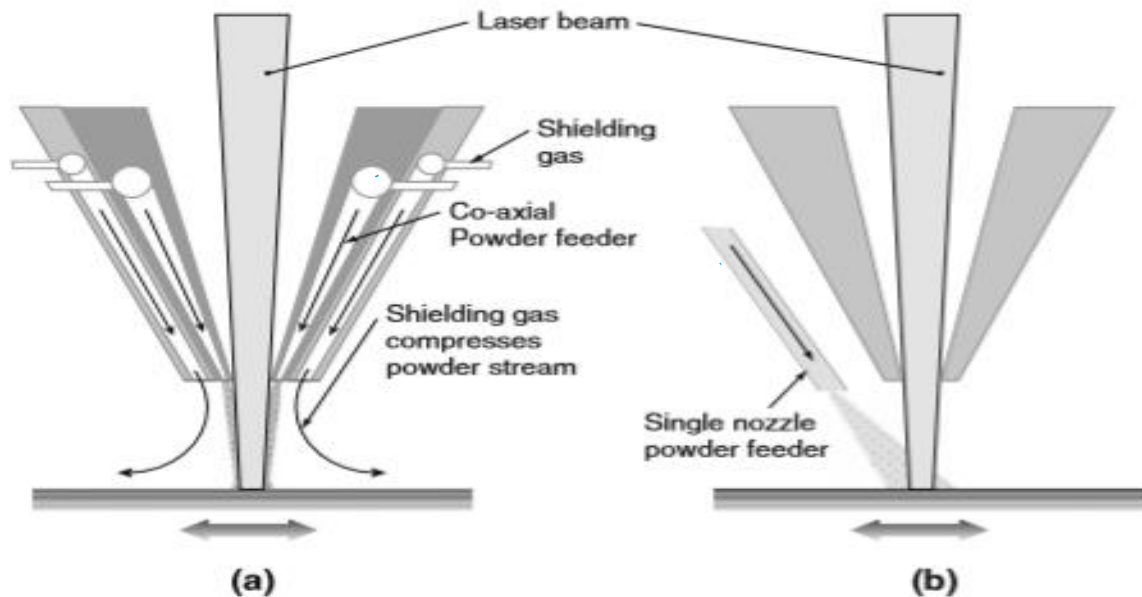
- Powder is typically fed by first fluidizing a container of powder material (by bubbling up a gas through the powder and/or applying ultrasonic vibration) and then using a pressure drop to transfer the fluidized powder from the container to the laser head through tubing.
- Powder is focused at the substrate/laser interaction zone using either co-axial feeding, 4-nozzle feeding, or single nozzle feeding.
- In the case of co-axial feeding, the powder is introduced as a toroid surrounding the laser beam, which is focused to a small spot size using shielding gas flow, as illustrated in the next Figure

Material Delivery

Powder Feeding

Illustration of powder nozzle configurations:

- (a) co-axial nozzle feeding; and
- (b) single-nozzle feeding

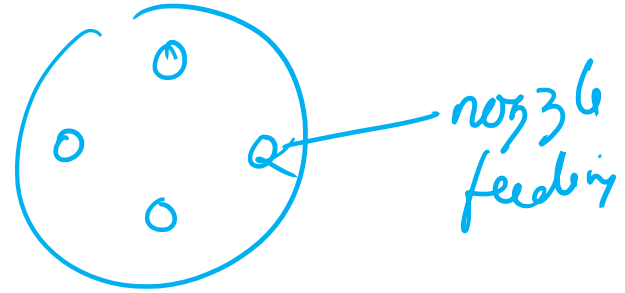


Material Delivery

Powder Feeding

- The two main benefits of co-axial feeding are that
 1. it enables a higher capture efficiency of powder, and
 2. the focusing shielding gas can protect the melt pool from oxidation when depositing in the presence of air.
- Single nozzle feeding involves a single nozzle pointed at the interaction zone between the laser and substrate.
- The main benefits of single nozzle feeding are
 1. the apparatus simplicity (and thus lower cost),
 2. a better powder capture efficiency than 4-nozzle feeding, and
 3. the ability to deposit material into tight locations (such as when adding material to the inside of a channel or tube).

Material Delivery



Powder Feeding

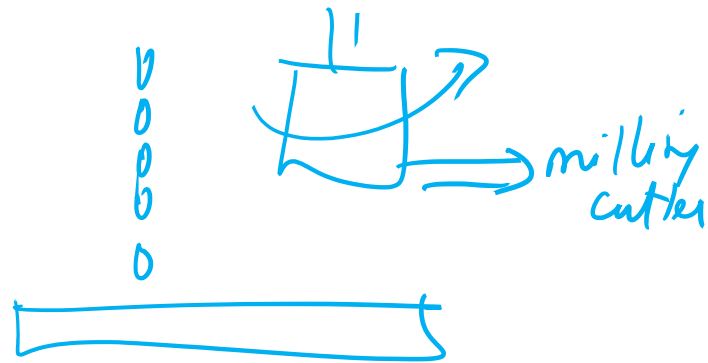
- 4-nozzle feeding involves 4 separate nozzle heads equally spaced at 90 degree increments around the laser beam, focused to intersect at the melt pool.
- The main benefit of a 4-nozzle feeding system is that the flow characteristics of 4-nozzle feeding gives more consistency in build height for complex and arbitrary 3D geometries that involve combinations of thick and thin regions.

Material Delivery

Wire Feeding

- In the case of wire feeding, the volume of the deposit is always the volume of the wire that has been fed, and there is 100% feedstock capture efficiency.
- This is effective for simple geometries, coating of surfaces, and/or deposits where porosity is acceptable.
- However, when complex, large, and/or fully dense parts are desired, geometry-related process parameters (such as hatch width, layer thickness, wire diameter, and wire feed rate) must be carefully controlled to achieve a proper deposit size and shape.
- Just as in extrusion-based processes, large deposits with geometric complexity must have porosity designed into them to remain geometrically accurate.

Material Delivery



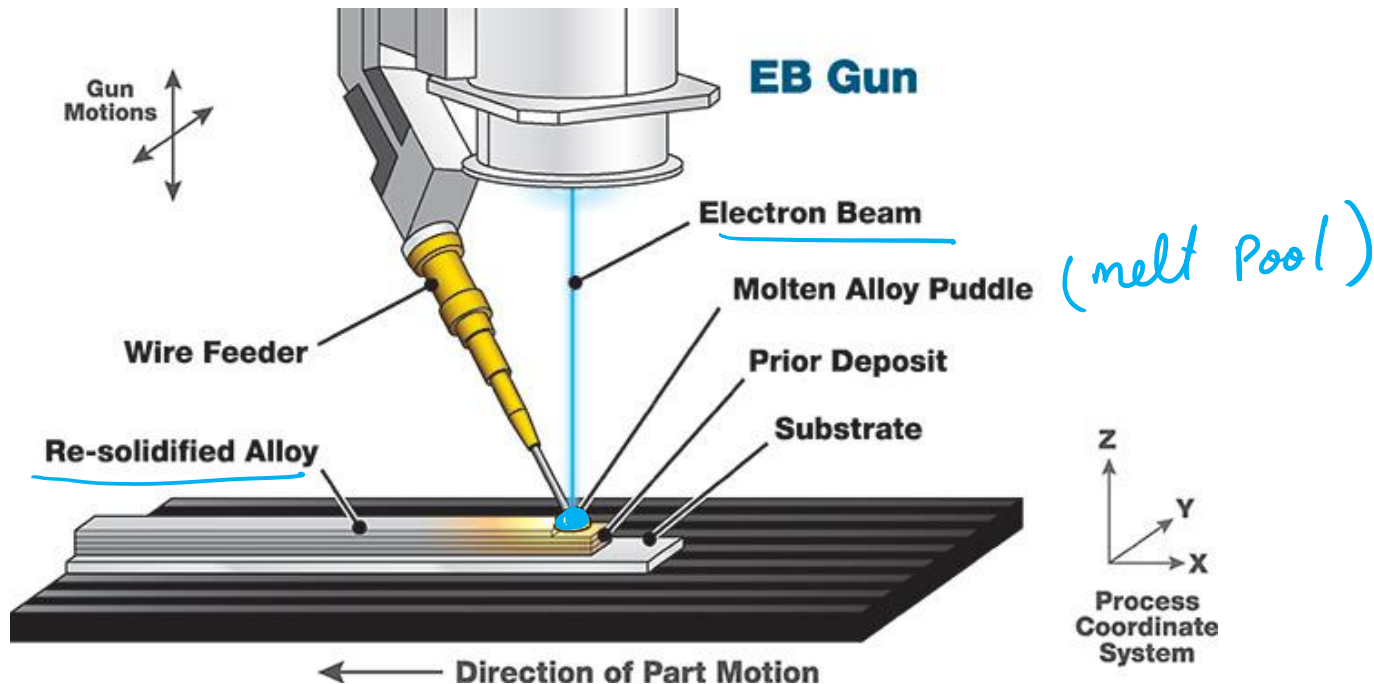
Wire Feeding

- For certain geometries, it is not possible to control the geometry-related process parameters accurately enough to achieve both high accuracy and low porosity with a wire feeder unless periodic subtractive processing (such as CNC machining) is done to reset the geometry to a known state.
- Thus, the selection of a wire feeding system versus a powder feeding system is best done after determining what type of deposit geometries are required and whether a subtractive milling system will be integrated with the additive deposition head.

Material Delivery

Wire Feeding

*metal
cladding*



BD Systems



CAD ✓
↓
STL ✓
↓
Layer ✓
↓
Part geometry
↓
Post Processing.

BD Systems

LENS → laser Engineered
near net Shaping

- In a typical BD system, an oxygen removal, gas recirculation system is used to keep the oxygen concentration in the gas (typically argon) near or below 10 ppm oxygen.
- The inert gas chamber, laser type, and 4-nozzle feeder design utilized by Optomec make their LENS machines some of the most flexible platforms for BD, as many materials can be effectively processed with this combination of laser type and atmospheric conditions.
- Most LENS machines are 3-axis and do not use closed-loop feedback control, however Optomec now offers a 5-axis "laser wrist" system that can enable deposition from any orientation, and systems for monitoring build height and melt pool area can be used to dynamically change process parameters to maintain constant deposit characteristics.

5 axis → Rolling, yawing
Pitch

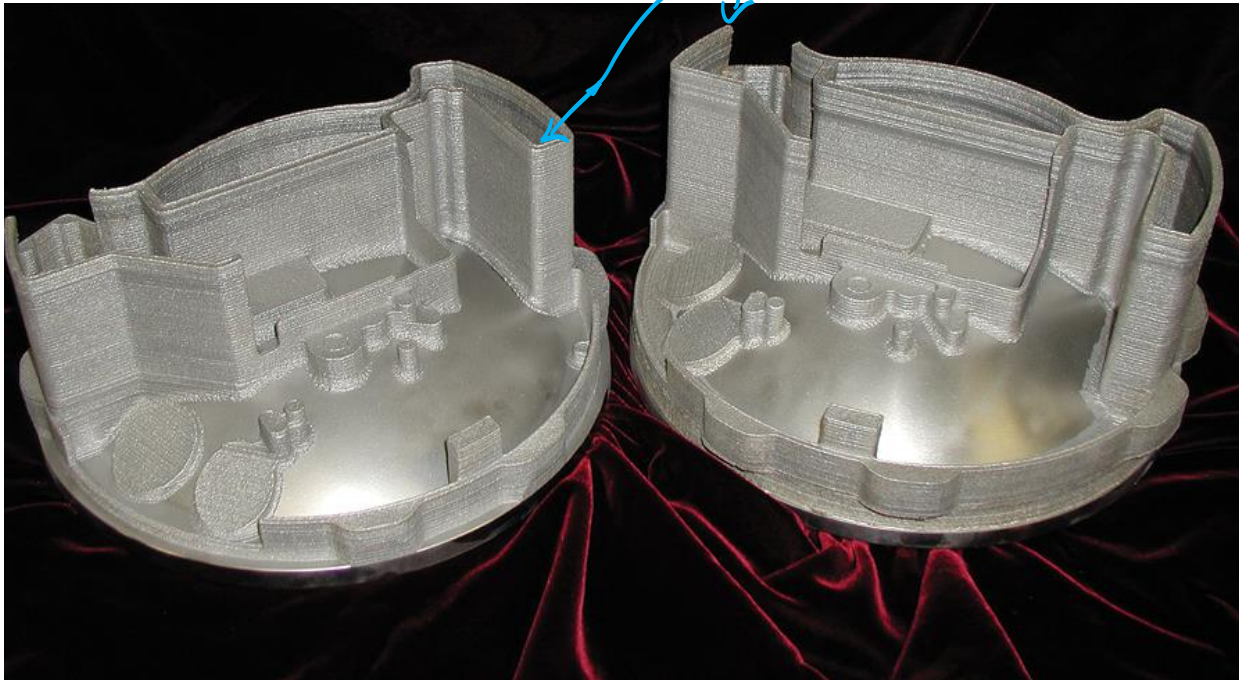
BD Systems

- As BD technologies become accepted in the aerospace industry, a similar system will likely become commercialized again.
- The benefits behind adding features to simple shapes to form aerospace and other structures with an otherwise poor “buy-to-fly” ratio makes sense.
- The term buy-to-fly refers to the amount of wrought material that is purchased as a block that is required to form a complex part.
- In many cases, 80% or more of the material is machined away to provide a stiff, lightweight frame for aerospace structures.

↳ Al-alloy → frame

BD Systems

A metal satellite housing built with the hybrid process is shown; the base was machined from billet stock and thin wall structures were added with the LENS DED process



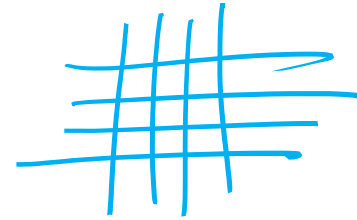
Process Parameters

- Unlike SLA, FDM and SLS, which come pre-programmed with optimized process parameters for materials sold by the machine vendors, BD machines are sold as flexible platforms; and thus BD users must identify the correct process parameters for their application and material.
- Optimum process parameters are material dependent and application/geometry dependent. Important process parameters include track scan spacing, powder feed rate, laser traverse speed, laser power, and laser spot size.
- Powder feed rate, laser power and traverse speed are all interrelated; for instance, an increase in feed rate has a similar effect to lowering the laser power.

Process Parameters

- Likewise, increasing laser power or powder feed rate and decreasing traverse speed all increase deposit thickness.
- From an energy standpoint, as the scan speed is increased, the input laser energy decreases because of the shorter laser dwell time, resulting in a smaller melt pool on the substrate and more rapid cooling.
- Scan pattern also plays an important role in part quality.

Process Parameters



- As mentioned previously, it may be desirable to change the scan orientation from layer to layer to minimize residual stress build-up.
- Track width hatch spacing must be set so that adjacent beads overlap, and layer thickness settings must be less than the melt pool depth to produce a fully dense product.
- Sophisticated accessory equipment for melt pool imaging and real-time deposit height measurement has been developed for accurately monitoring the melt pool and deposit characteristics.

Process Parameters

- It is possible to monitor the melt pool size, shape and temperature to maintain the desired pool characteristics. $\propto$ defect
- To control deposit thickness, travel speed can be dynamically changed based upon sensor feedback.
- Similarly to control solidification rate, and thus microstructure and properties, the melt pool size can be monitored and then controlled by dynamically changing laser power.

Processing–Structure–Properties

- Parts produced in beam deposition processes exhibit cast microstructures.
- Processing conditions influence the solidification microstructure in ways that can be predicted in part by rapid solidification theory.
- For a specific material, solidification microstructure essentially depends on the local solidification conditions, specifically the solidification rate and temperature gradient at the solid/liquid interface.
- By calculating the solidification rate and thermal gradient, the microstructure can be predicted based upon calibrated “solidification maps” from the literature.

Processing–Structure–Properties

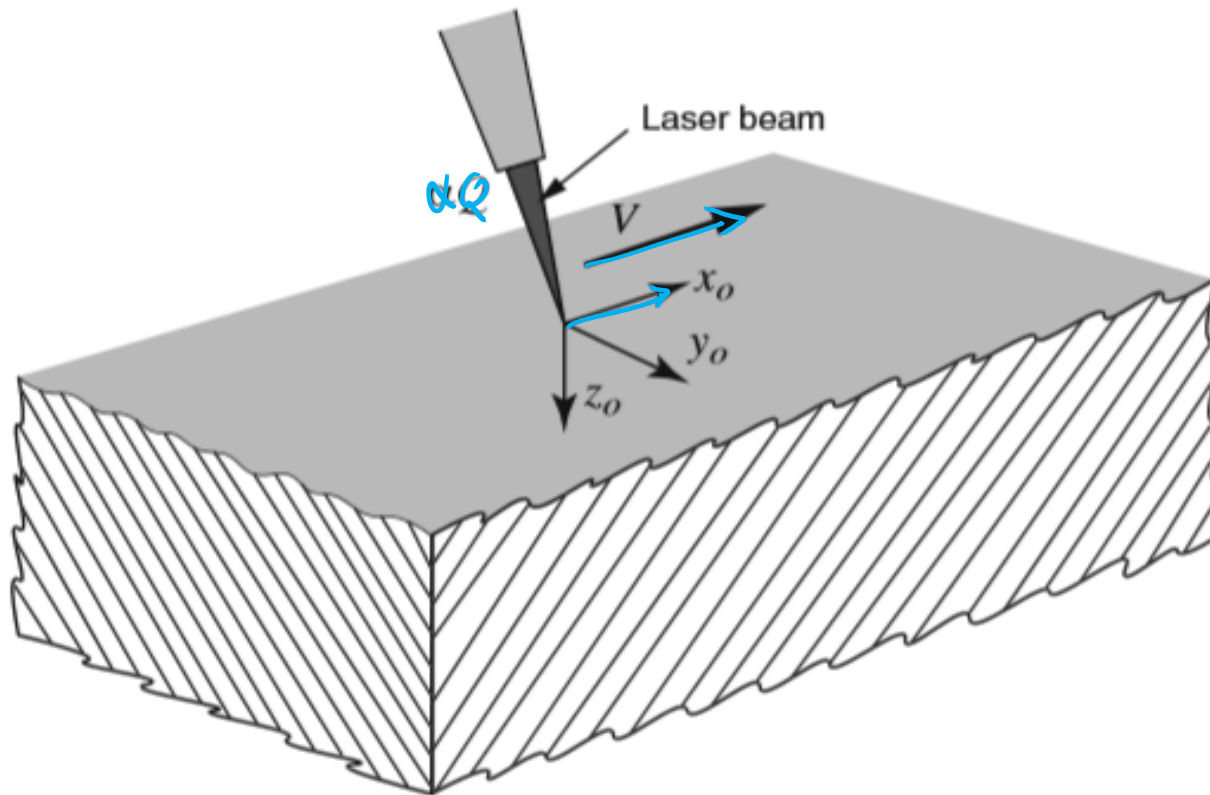
- To better understand solidification microstructures in beam deposition processes, Beuth and Klingbeil have developed procedures for calculating thermal gradients, G , and solidification rates, R , analytically and numerically.

G , R

- These calculated G and R values can then be plotted on solidification maps to determine the types of microstructures which can be achieved with different beam deposition equipment, process parameters, and material combinations.
- Solutions for both thinwalls and bulky deposit have been described. For brevity's sake, the latter work by Bontha et al. based upon the 3D Rosenthal solution for a moving point heat source on an infinite substrate will be introduced here (Figure below).

Processing-Structure-Properties Relationships

3D Rosenthal geometry considered



Source: Gibson et al. Additive manufacturing Technologies, 2010

Processing-Structure-Properties Relationships

laser interacting with material

- In this simplified model, material deposition is ignored.
- The model considers only heat conduction within the melt pool and substrate due to a traveling heat source moving at velocity, V .
- ★ The fraction of impinging energy absorbed is αQ , which is a simplification of the physically complex temperature-dependent absorption of the beam by regions of the melt pool and solid, absorption of energy by powder in flight, and other factors.
- Thus a single parameter, a , represents the fraction of impinging beam energy power absorbed.

*• absorb
• reflection
• transmission*

Beam Deposition

- benefits and drawbacks

- BD processes are capable of producing fully-dense parts with highly controllable microstructural features.
- These processes can produce functionally graded components with composition variations in the X, Y and Z directions.
- The main limitations of beam deposition processes are poor resolution and surface finish.
- An accuracy better than 0.25 mm and a surface roughness of less than 25 μm (arithmetic average) are difficult with many processes.

Beam Deposition

- benefits and drawbacks

- Slower build speed is another limitation.
- Build times can be very long for these processes, with typical deposition rates as low as 25–40 g/h.
- To achieve better accuracies, small beam sizes and deposition rates are required.
- Conversely, to achieve rapid deposition rates, degradation of resolution and surface finish result.
- Changes in laser power and scan rate to achieve better accuracies or deposition rates may also affect the microstructures of the deposited components, and thus finding an optimum deposition condition necessitates tradeoffs between build speed, accuracy and microstructure.

Beam Deposition / Beam delivery

- benefits and drawbacks

- Examples of the unique capabilities of beam deposition include:
- BD offers the capability for unparalleled control of microstructure. G R
- The ability to change material composition and solidification rate by simply changing powder feeder mixtures and process parameters gives designers and researchers tremendous freedom.
- BD is capable of producing directionally solidified and single crystal structures.
- BD can be utilized for effectively repairing and refurbishing defective and service damaged high-technology components such as turbine blades.

Beam Deposition

- benefits and drawbacks

- As a result of the combined strengths of BD processes, practitioners of BD primarily fall into one of several categories.
- First, BD has been highly utilized by research organizations interested in the development of new material alloys and the application of new or advanced materials to new industries.
- Second, BD has found great success in facilities that focus on repair, overhaul, and modernization of metallic structures.

Beam Deposition

- benefits and drawbacks

- **Third**, BD is useful for adding features and/or material to existing structures to improve their performance characteristics.
- In this third category,
 - BD can be used to improve the life of injection molding or die casting dies by depositing wear-resistant alloys in high-wear locations;
 - it is being actively researched by multiple biomedical companies for improving the characteristics of biomedical implants; and
 - it is used to extend the wear characteristics of everything from drive shafts to motorcycle engine components.

To recapitulate

- **What is Material Delivery in BD?**
- **Describe briefly General Beam Deposition Process Description.**
- **Explain Powder Feeding, and Wire Feeding.**
- **Describe BD Systems.**

Thank you