

# **Feedstock Material Efficiency Analysis in Laser- based Directed Energy Deposition**

Department of Mechanical and Materials Engineering

Bachelor's thesis

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Feedstock material efficiency plays a crucial role in efficient and cost-effective directed energy deposition. This thesis examines the different process parameters in DED-LB/P relating to powder catchment efficiency and the methods used to determine it. The literature review presents common additive manufacturing processes, processing parameters, powder properties and powder catchment efficiency.

In this study melt pool diameter and particle stream diameter are found to be the main factors in catchment efficiency. It is found that these factors can be altered and in turn catchment can be improved by changing powder size, laser spot size and carrier gas flow rate. Few relatively accurate methods used to determine and predict catchment efficiency are discussed in this study.

**Keywords:** Additive manufacturing, Directed energy deposition, DED-LB/P, Catchment efficiency

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## 1 Introduction

Additive manufacturing (AM) is a technology, where material is added selectively layer by layer in order to create the desired geometry [1]. Because of this AM technologies waste less material in comparison to traditional subtractive manufacturing technologies, where material is removed from a work piece [1]. Directed Energy Deposition (DED) is an Additive Manufacturing technology capable of printing metals, polymers and ceramics. Having applications not just in part fabrication but also in part repair and customisation DED shows promise in becoming a widespread manufacturing technology [1]. DED can also be used for coating by adding a few layers of new material on the surface of an existing part. This process is known as laser cladding and it offers good surface quality, minimal dilution and minimal distortion. Laser cladding is able to produce a much better coating in comparison to conventional processes like arc welding and plasma spraying [2].

In DED processes parts are created by melting feedstock material as it is being deposited [3]. In these processes thermal energy is directed into a narrow region melting the substrate or previously deposited layers and the simultaneously deposited feedstock material [3]. The substrate's melt region is denominated as melt pool [3]. A focused thermal source (usually a laser or an electron beam) is used to melt the added material and build three-dimensional parts [3]. Many different materials can be used, and the feedstock material can be in the form of wire or powder [3].

With DED processes fully dense parts with exceptionally controllable microstructural properties can be produced. The processes also have the capability of changing solidification rate and material composition by adjusting process parameters and mixing different powder feedstocks [3]. The physical attributes of feedstock powders used in additive manufacturing, in particular particle size and size distribution, particle morphology, and powder flowability, are important factors in the manufacturing process as well as the quality of the final product [3]. The most versatile feedstock is powder, and most ceramics and metal materials can be easily found in powder form [4]. However, it has some disadvantages, as not all of the powder is captured in the melt pool [4]. Powder recycling and reconditioning offer a potential solution, but reducing primary powder waste demands a more fundamental approach. In this

regard, the improvement of powder catchment efficiency is crucial for achieving sustainable manufacturing [2].

The objective of this study is to evaluate the powder catchment efficiency by the melt pool of different feedstock materials and powder feeders used in Directed Energy Deposition. In particular the effects of particle size, size distribution and particle morphology on the deposition efficiency is to be investigated. This thesis a literature review based on previous research on the topic. The main sources used for articles and research were Google scholar, UTU Volter, ScienceDirect and Knovel. The findings are summarized and discussed in chapters 3 and 4.

## 2 Literature review

The term additive manufacturing (AM) is used to describe different manufacturing technologies using a layer by layer technique, which starts from a virtual model [5]. AM technologies focus on the production of parts with complex shapes and features that are not feasible to manufacture with conventional subtractive methods. By selectively adding material instead of removing it, the cost of the produced part does not increase with geometric complexity, which offers unparalleled desing freedom and production flexibility [5].

### 2.1 Metal Additive manufacturing methods

Powder bed fusion (PBF) processes were one of the earliest commercially available AM processes [4]. The PBF technique utilizes a thermal source (laser or electron beam for example) to selectively melt powder particles in a powder bed in order to build three-dimensional parts. Metal, polymer or ceramic powders can be used as feedstock in PBF. The molten particles fuse together and solidify to form the printed part [6]. Most PBF processes share a set of characteristics including one or multiple thermal sources that are used to induce fusion between powder particles, a method that controls the fusion to a specific area of each layer and a mechanisms that adds powder and levels the added powder layer [4]. Typically a new layer of powder is added by lowering the powder bed and moving a counter rotating roller across the bed spreading the powder over the previous layers [4]. Basic schematic of a typical powder bed fusion process is shown in Figure 1.

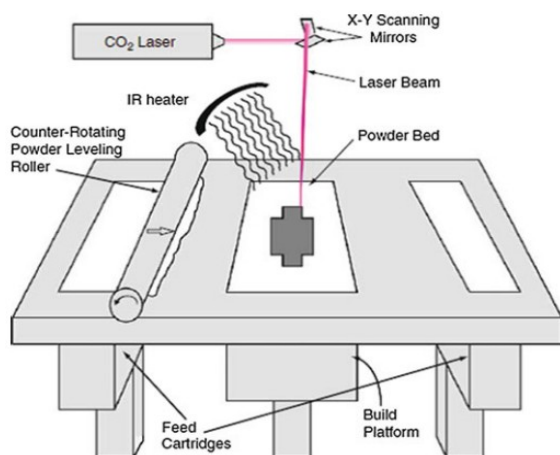


Figure 1. Schematic of powder bed fusion (Modified from Gibson et al. [4])

Binder jetting techniques deposit droplets of liquid binder onto powder feedstock using one or more inkjet printheads [6]. The liquid binder glues the powder particles together to build three dimensional objects. Similar to PBF, the powder feedstock is in a powder bed and can consist of metal, polymer or ceramic [6]. A single or multi-pass printing strategy can be used to deposit the droplets [6]. The binder droplets form spherical masses of powder particles and binder liquid, which bonds to previous layers [4]. The powder bed is lowered after each printed layer and a fresh layer of powder is spread on top of it. The recoating methods are typically similar to ones used in PBF processes [4]. A schematic of a typical binder jetting process is shown in Figure 2.

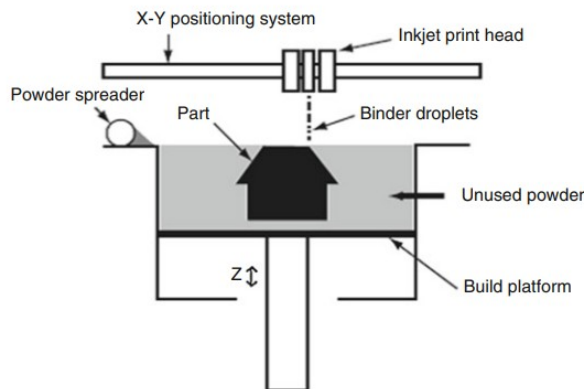


Figure 2. Schematic of binder jetting process (Modified from Gibson et al. [4])

Sheet lamination is a process where thin sheets are stacked and laminated to fabricate 3D objects through different bonding and cutting strategies [6]. The sheets can be made of different materials such as metal sheets, paper, ceramic tapes, woven fiber sheets and thermoplastic foils. Adhesive bonding, thermal bonding and ultrasonic welding can be used to bond the sheets together. The bonded sheets can be cut to shape by sawing, milling or laser cutting for instance [6]. An example of sheet lamination process where material is first cut to shape and stacked and then thermally bonded is shown in Figure 3 [4].

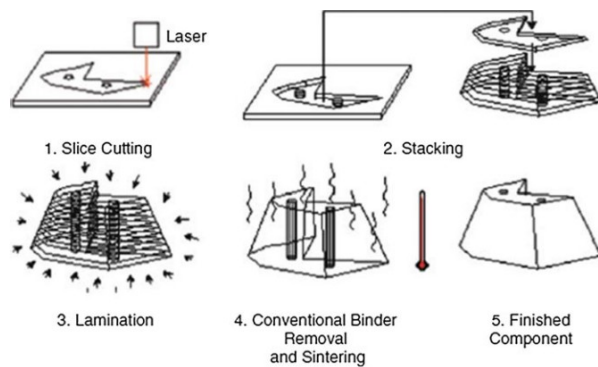


Figure 3. Schematics of sheet lamination process steps (Modified from Gibson et al. [4])

Directed energy deposition (DED) is an AM technology where a focused thermal energy joins materials simultaneously as it is being deposited [7]. The main energy sources used for the process are laser beam, electron beam, and plasma arc. The energy source is selected based on the deposited material [7]. A selection of different materials such as ceramics, polymers and wide range of metal alloys can be used as feedstock which can be in the form of powder, pellet or wire [4,7]. Figure 4. depicts a typical DED process where laser and powder feedstock is used.

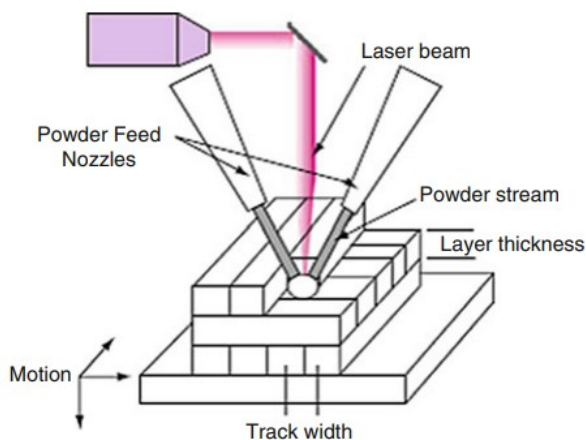


Figure 4. A schematic of a typical DED-LP process (Modified from Gibson et al. [4])

DED has three distinguishable subsystems which accomplish a unique but essential part of the manufacturing process. These include a focused thermal source, a feedstock delivery unit and a substrate [1]. The substrate can be a flat plate or an existing part depending on whether a new part is being made or features are being added [4]. Typically the melt pool in combination with a relatively fast scanning speed produce large thermal gradients and high cooling rates [4]. Such cooling rates can

generate solidification grain structures and nonequilibrium grain structures with unique properties that cannot be produced by traditional processing methods [4].

Laser-powder Directed Energy Deposition (DED-LB/P) is an AM process capable of printing metals in a medium- to largescale near-net shape for producing and repairing parts. In this process a melt pool is produced with the use of a laser and a nozzle is used to transport feedstock powder into the melt pool via carrier gas [8]. Compared to wire-based DED, DED-LB/P has more control over material composition, and has the ability to produce metal matrix composites and functionally graded materials via discrete control of powder delivery [8]. Most DED units use inert gas for powder feedstock transportation [1]. The inert gas (usually argon) acts as a shielding gas for the melt pool which can improve the quality of the laid bead.

Some of the important process parameters of DED-LB/P include stand off distance, powder feed rate, scanning speed, laser power and laser beam spot size [4]. Powder feed rate, laser power, and scanning speed are connected and have an effect on each other. For example, increasing feed rate or lowering laser beam power have similar effect on the deposition [4]. Laser power, scanning speed and powder flow rate have the greatest effect on the produced deposition and its properties (microstructure, porosity and residual stresses) [9].

Powder catchment efficiency is known to vary with the size of the powder stream distribution, size of the melt pool, powder size distribution, powder mass flow rate, carrier gas flow rate, nozzle geometry and nozzle standoff distance [8]. From a processing standpoint, the powder catchment efficiency is an important parameter to consider since only part of the feedstock powder is added to the substrate, causing a large amount of the feedstock to be recycled or wasted. Therefore it is important to recognise how the powder properties and different process parameters affect the catchment efficiency at the melt pool in order to avoid powder waste [10].

## **2.2 Powder properties**

Powder properties form the basis AM-processes, and the quality of the powder influences the printability and performance of the final parts [6]. Powder particle size has a crucial part in the additive manufacturing process. The specific application and

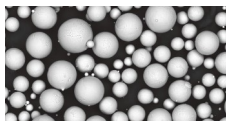


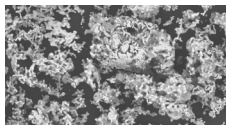
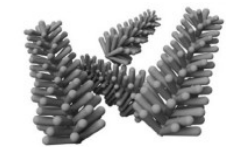


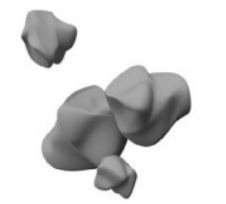
the type of manufacturing process usually influence the optimal particle size [5]. Typically the particle sizes range from 15 to 150  $\mu\text{m}$  [5].

In most DED-LB/P setups, powder particles are larger in comparison to powder bed fusion [1]. For PBF powder particle diameters usually ranges from 10 to 50  $\mu\text{m}$  while for DED it ranges between 50 to 150  $\mu\text{m}$  [1]. Larger particles used in DED can offer a better flowability and have a higher possibility of breaking the melt pools surface tension on impact in comparison to smaller particles [1]. The smaller particles on the other hand offer a larger surface area, increasing energy absorption and radiation scattering, which eases fusion between powder layers as well as improves surface quality and density of the final part [5]. However the using excessively small particle size may decrease powder flowability and promote agglomeration, causing challenges in stable powder feeding during the deposition process. With high carrier gas flow rates smaller particles are also more likely to be blown away instead of incorporating in the melt pool. In contrast, larger particles can lead to deficient powder fusion and lower density unless controlled appropriately [5].

### 2.3.1 Particle morphology

The British Standards Institute created a standard glossary (British Standards 2955 Glossary of Terms Relating to Powders) that can be used to determine the morphology of powder particles [6]. The particle morphology depends on the process used to produce the powder. Particle shape and surface features are included in particle morphology [6]. The shape of a powder particle can be described with terms shown in table 1.

Table 1. Particle morphology types

Type	Description	Picture	Reference
Spherical	Globular-shape		Modified from Kondas et al. [11]
Acicular	Long thin needle like shape		Modified from Nouri et al. [12]
Angular/Irregular	Sharp-edged, polyhedral-shaped or lacking symmetry		Modified from Nouri et al. [12]
Crystalline	A geometric shape freely developed in liquid		Modified from Kondas et al. [11]
Dendritic	Branched crystalline-shaped		Modified from Nouri et al. [12]
Fibrous	Thread-like		Modified from Nouri et al. [12]
Lamellar or flakey	Plate-like		Modified from Nouri et al. [12]
Modular	Round but irregular		Modified from Nouri et al. [12]

Spherical particles are generally preferred over irregular and rough particles, as they allow steady flow and a constant distribution on the substrate as well as greater packing density [5,12]. They also promote a more efficient fusion between particles. Irregular or acicular, needle-like particles, can improve the density of the final part in some specific applications [5]. While these particle shapes might be favored in certain situations, they usually decrease powder flowability and affect the deposition process [5].

In an experiment conducted by da Cruz et al. the effects of feedstock recycling to the changes in microstructure caused by morphology were investigated [13]. In the experiment a significant change in particle morphology was not detected with a scanning electron microscopy but a notable decrease in particle flowability was reported. In a similar experiment conducted by Terrassa et al. [14] it was also found that the amount of smaller particles decreased with increased reuse. Increased reuse also made the particles more irregular in shape. Particle flowability was found to slightly increase after each reuse [14].

### 2.3.2 Particle size distribution

One of the most important characteristics of the powder used in metal additive manufacturing is particle size distribution [6]. The three main parameters used to describe particle size distribution are modal, mean and median diameter [3]. The modal diameter of the powder is the powder size that appears most often [3]. The median diameter is defined as the particle size that is equal to the 50 % cumulative frequency, or in other words the middle value of the powder size, and the mean diameter is defined as the weighted average of size of the particles [3]. Particle size and size distribution can be determined with various methods. These include sieving, gravitational sedimentation, microscopy-based techniques and laser light diffraction [3]. Because of its simplicity, low cost and ease of interpretation sieve analysis is the most common method in use [3].

A constant particle distribution promotes fusion between powder particles and creates a more consistent deposition during the manufacturing process [5]. A distribution combining different size particles, can improve powder flow and reduces the possibility of defects forming such as porosity or lack of fusion [5]. Therefore the

optimization of particle size distribution has a crucial role in creating parts with controlled density and exceptional quality [5].

### 2.3 Powder catchment efficiency estimation

Powder catchment efficiency  $\eta_m$  is a parameter used to depict the amount of deposited mass or in other words the ratio of powder that lands and incorporates into the melt pool to the total mass flow rate of the delivered powder as shown in Eq. (1) [15]. The total mass flow rate includes losses caused by inefficiencies in the powder catchment process, making the catchment efficiency to always less than one  $0 < \eta_m < 1$  [15].

$$\eta_m = \frac{\dot{m}_{dep}}{\dot{m}_{tot}} \quad (1)$$

where  $\eta_m =$  powder catchment efficiency,  $\dot{m}_{dep} =$  deposited mass flow rate and  $\dot{m}_{tot} =$  total mass flow rate

A lack of understanding over catchment efficiency contributes to poor feedstock usage, which increase process expenses since unused powder may not be reused and the powder is a significant portion of the parts cost [8]. Accurate prediction of catchment efficiency is also needed to correctly program the tool path since the dimensions of the deposited layer depend on catchment efficiency [8]. The catchment efficiency can be determined via experimental methods or estimated with analytical methods [8].

Powder catchment can be determined by depositing single beads using different process parameters and measuring the dimensions of each bead. By measuring the cross sectional area of the bead or in other words the mass per unit time and comparing that with the measured mass flow rate of the system, catchment efficiency figures for different process parameters can be produced [16]. The ratio of the formed beads weight to the total mass of delivered powder can also be used when determining the catchment efficiency of a process [17]. A high speed imaging camera can be used to determine the mass of the powder that enters the melt pool as a percentage of the total feed rate which can be displayed as powder catchment

efficiency [16]. Donadello et al. [15] developed a system for real-time deposition mass measurement. They used two load cells on strain gauges to determine the mass of deposited powder and the mass of lost powder [15]. One of the two load cells was attached to the substrate and another one to a hopper under the substrate which caught the powder not incorporated in the melt pool.

Ancalmo et al. [8] measured the catchment efficiency for different laser spot diameters, powder size distributions and carrier gas flow rates by depositing 45 single beads using different printing parameters [8]. They used a digital scale to measure the steady-state powder mass flow rate and an optical profilometry system to measure the average cross-sectional area of added material. Catchment efficiency was then calculated with Eq (2). The powder feedstock they used was nitrogen-gas atomized 316L stainless steel. It was found that the catchment efficiency increased as the laser spot diameter increased. With powder diameter of 21-35  $\mu\text{m}$  and a carrier gas flow rate of 2 l/min (smallest particle size and lowest flow rate used in this experiment) increasing laser spot diameter from 1.5 mm to 2.5 mm the catchment efficiency increased from  $61.2 \pm 3.0 \%$  to  $84.6 \pm 4.2 \%$ . Further increasing the laser spot diameter to 3.5 mm catchment efficiency increased to  $95.8 \pm 4.8 \%$ . With small diameter powder particles, carrier gas flow rate had the highest effect on catchment, with lower carrier gas flow rates improving catchment efficiency. Larger particles had lower overall catchment and gas flow rates had a reduced effect [8]. In an experiment conducted by Takemura et al. [18] it was also determined that powder catchment efficiency increased as the carrier gas flow rate decreased with the exception of the lowest setting of 2 L/min. Koti et al. [16] found that the percentage area overlap between the melt pool and the powder stream has strong correlation to catchment efficiency suggesting that the powder stream shape and size should be similar to that of the melt pool.

$$\eta_m = \frac{A_{add} \cdot \rho_p \cdot u}{\dot{m}_p} \quad (2)$$

where  $A_{add}$  = Area of added material,  $\rho_p$  = powder density,  $u$  = laser scan speed and  $\dot{m}_p$  = powder mass flow rate

Geometric models have been used to estimate powder catchment efficiency by comparing the melt pool diameter with the particle stream diameter. In these models the volume of a 2D gaussian distribution by inscribed circle as shown in figure 5 is calculated with eq (3) [8]. The width of the melt pool and the laser spot diameter are assumed to be equal and not dependent of powder particle size and carrier gas flow rate [8]. All powder particles landing in the melt pool are also assumed to incorporate in it. The particle stream diameter is determined with calibrated constants or experiments. These assumptions may cause inaccuracies in certain conditions but they enable rapid catchment efficiency prediction [8].

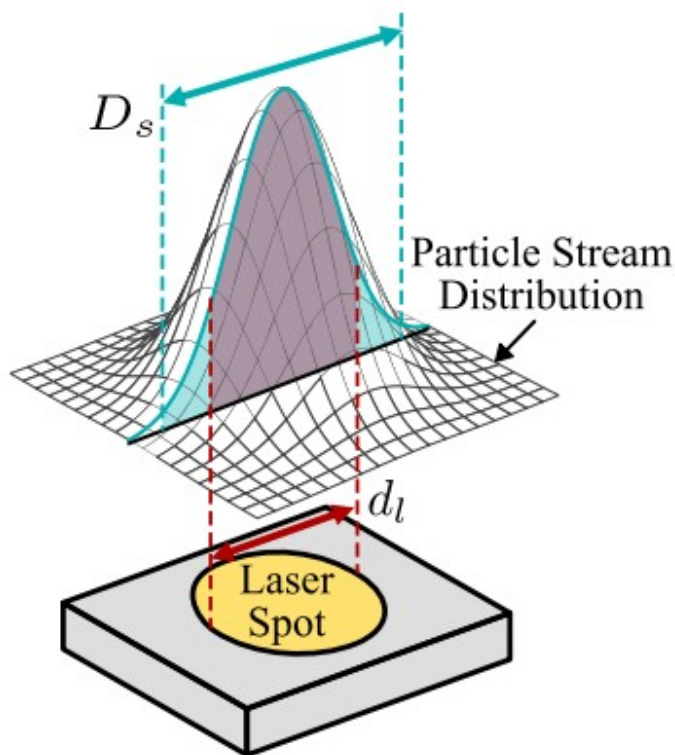


Figure 5. A schematic of geometry-based model (Modified from Ancalmo et al. [8])

$$\eta_p = 1 - \exp\left(\frac{-(\sigma_s \frac{d_l}{D_s})^2}{2}\right) \quad (3)$$

where  $\sigma_s$  = standard deviation of the defined particle stream diameter,  $d_l$  = melt pool width and  $D_s$  = particle stream width

Unocic et al. [10] calculated catchment efficiency as a logarithmic function of the parameter shown in Eq (4) as a ratio of the volumetric powder feed rate to the used

heat input. This parameter was used because it includes the main parameters that vary the catchment efficiency [10]. Melt pool diameter is determined by the heat input. Therefore this method is similar to the previously mentioned geometric based method.

$$\Gamma = \frac{\dot{V}_{fm}}{\eta_a \eta_m \frac{P}{S}} \quad (4)$$

where  $\dot{V}_{fm}$  = volumetric powder feed rate,  $\eta_a$  = energy transfer efficiency,  $\eta_m$  = melting efficiency,  $P$  = laser power and  $S$  = travel speed

Another method to estimate catchment efficiency is to calculate the Stokes number for the particle carrier gas flow [8]. The Stokes number can be used to estimate the particle stream diameter. The geometry-based model can then be used to predict the catchment efficiency. The Stokes number was calculated by Ancalmo et al. [8] as the ratio of characteristic time of particle motion to the characteristic time of fluid motion as shown in Eq (5). The characteristic time of particle motion was defined with Eq (6) and the characteristic time of fluid motion with Eq (7). The particle stream diameter was then predicted from Stokes numbers logarithm through linear regression as shown in Eq (8). Finally the geometry-based cathment efficiency model was used to calculate the predicted catchment efficiency [8].

$$Stk = \frac{\tau_p}{\tau_f} \quad (5)$$

where  $\tau_p$  = characteristic time of particle motion and  $\tau_f$  = characteristic time of fluid

$$\tau_p = \frac{\rho_p \cdot d_p^2}{18 \mu_f} \quad (6)$$

where  $\rho_p$  = particle density,  $d_p$  = particle diameter and  $\mu_f$  = carrier gas dynamic viscosity

$$\tau_f = \frac{d_n}{U_f} \quad (7)$$

where  $d_n$  = nozzle diameter and  $U_f$  = fluid velocity

$$D_s = \log(Stk) \cdot 0.252 + 2.65 \quad (8)$$

where  $D_s$  = particle stream diameter

Ancalmo et al. [8] determined that powder particle size and carrier gas flow rates changed the diameter of the particle stream by roughly 0.65 mm. It was found that flows that had lower Stokes numbers had particle streams with smaller diameters when compared to those with higher Stokes number. Also particle flows with lower Stokes numbers were found to have a higher predicted catchment efficiency [8]. The laser spot diameter was found to have the largest effect on predicted catchment efficiency while powder size, and carrier gas flow had a secondary effect, altering the predicted catchment by up to 9 % [8].

The geometry-based method had a root mean squared error of 11.5 [8]. Using the Stokes number root mean squared error was slightly higher at 11.8. The Stokes number method removes the need of in-situ monitoring while staying almost as accurate as the geometry-based method with particle stream imaging. Using the melt track width these numbers were notably lower at 4.59 for geometry-based and 4.33 for Stokes number method [8]. This suggests that the most effective method is the Stokes number with melt track width method and that melt track width monitoring is more important than particle stream monitoring since the Stokes number method estimates the particle stream diameter with good accuracy.

### 3 Results and discussion

Common methods used to calculate and predict the powder catchment efficiency are shown in table 2. The first two methods are experimental and the rest are numerical. The table is based on the information found during the literature review.

Table 2. Powder catchment efficiency calculation methods

Method	Description	Advantages	Disadvantages	Ref.
Weight ratio	Ratio of deposited mass to total powder mass flow rate	Real time measurement, low cost	Powder can stick to the substrate outside the melt pool causing inaccuracies	[17]
Cross-sectional area	Ratio of cross-sectional area to powder mass flow rate	Accurate measurement	Requires a profilometer to measure the cross-sectional area of the melt track	[8]
Geometry-based	Ratio of laser spot diameter and particle stream diameter	Enables rapid prediction	Requires assumptions that may cause inaccuracies and high-speed imaging	[8]
Geometry-based with Stokes number	Particle stream diameter predicted with the calculated Stokes number	Do not require particle stream imaging	Requires more complex calculation and assumptions that can lead to inaccuracies	[8]
Geometry-based with melt track width	Ratio of track width and particle stream diameter	Accurate prediction	Requires a method for extracting the track width	[8]
Geometry-based with Stokes number and melt track width	Ratio of track width and particle stream diameter predicted with Stokes number	Accurate prediction, doesn't require particle stream imaging	Requires more complex calculation and assumptions, requires a method for extracting the melt track width	[8]
Logarithmic function of the parameter $\Gamma$	Ratio of the volumetric powder feed rate to the heat input used for melting	Incorporates the main processing variables affecting deposition	Requires complex calculations and empirical testing	[10]

Laser spot diameter has the largest effect on catchment efficiency. Larger laser spot creates a larger melt pool which increase powder catchment efficiency. Smaller particle size and lower gas flow rates also increased catchment. Ancalmo et al. [8] calculated the Stokes numbers for different carrier gas flow rates and particle diameters. Lower gas flow rates and smaller particle diameters caused a smaller particle stream diameter and increased catchment. This would suggest that the main factor in powder catchment efficiency is the ratio between particle stream diameter and melt pool diameter. The melt pool diameter cannot always be increased, therefore reducing particle stream diameter is an effective method for increasing catchment efficiency.

Lowering carrier gas flow rate increased efficiency for the most part. In an experiment conducted by Takemura et al. [18] decreasing carrier gas flow too much decreased the catchment efficiency. This was caused by the powder supply path being jammed because of the low carrying force. This jamming could be avoided by using powder feedstock with better flowability as Ancalmo et al. [8] didn't experience jamming while using the same carrier gas flow rate. Ancalmo et al. [8] achieved a greater efficiency by using smaller diameter particles, but even with similar particle sizes as Takemura et al. [18] supply path jamming wasn't reported. This could be caused by higher quality powder, different nozzle or powder feeding system for example. The powder used by Ancalmo et al. was 316L stainless steel while Takemura et al. used inconel 625 which could also be the cause of lower flowability [8,18].

Accurately predicting powder catchment efficiency is difficult because of the many different process parameters that affect it. For processes with little to no variation in parameters the catchment efficiency can be determined by empirical testing but for processes that require changing parameters this can be difficult. Geometric models can be used to calculate the predicted efficiency fairly accurately. The accuracy of these models can be improved by in-situ monitoring of the laid track. The Stokes number can be used to predict the particle stream diameter removing the need for in-situ imaging of the particle stream. Creating a method for accurately predicting the

track width would increase the prediction accuracy without the need of in-situ monitoring.

## 4 Conclusions

This thesis analysed the effects of powder feedstock material on powder catchment efficiency for laser-powder Directed Energy Deposition. The main goal was to understand how particle size, size distribution and particle morphology affect the powder catchment efficiency. Outcomes of the study are listed below:

- One of the main factors in powder catchment efficiency is the ratio between particle stream diameter and melt pool diameter.
- Particle size affects deposition efficiency by altering the particle stream diameter and Stokes number of the flow.
- Particle size, size distribution and morphology affect flowability which can have an affect on the catchment efficiency.
- Catchment efficiency can generally be improved by choosing a smaller particle size, lowering carrier gas flow rate and increasing laser spot size.
- Catchment efficiency for different processing parameters can be determined by experimental methods and predicted with numerical methods to a fairly good accuracy.
- The Stokes number can be used to accurately predict the particle stream diameter.

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