DEVELOPMENT AND APPLICATION
OF A CFD MODEL OF LASER METAL DEPOSITION

A thesis submitted to the University of Manchester for the degree of

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JUANSETHI RAMSÉS IBARRA MEDINA

School of Mechanical, Aerospace and Civil Engineering
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Abstract

Name of university: The University of Manchester
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Laser metal deposition is one of the most versatile methods in the expanding field of additive manufacturing. Its outstanding advantage is its capability to process a variety of metallic materials for the freeform fabrication of objects having sound mechanical properties. The process is used in applications of rapid manufacturing, components repair and surface coating. During recent years, modelling has been increasingly used to study and improve the laser metal deposition process. However, most models have focused on analysing individual stages of the deposition process and thus have not thoroughly dealt with the occurrence of mutually-influencing phenomena. This work presents a new numerical model that, starting from the simulation of powder particles in the deposition head, integrates the important phenomena and interactions that govern the dynamics of a powder stream and a deposition melt pool, within a single model for the first time.

The resulting model is comprehensive enough to allow the prediction of the morphology of deposited tracks and structures and the heat flows during their creation; as well as the flexibility to simulate, in principle, any deposition shape. The model has been demonstrated using the settings of an actual laser metal deposition system, and has been applied to study clad formation in the deposition of single tracks, layers, walls and simple three-dimensional structures.

Moreover, the model has been used to study the formation of irregularities and excessive mass deposition. A new sensor-less deposition control technique based on the simulation and testing of different deposition strategies prior to actual deposition, is proposed. As a demonstration of this control technique, the model has also been used to study the case where excessive deposition develops at intersecting or cornered tracks. Improved deposition strategies have been tested using the model and applied to real deposits. A two fold improvement in layer height control has been achieved in the case of cornered layers.

The outcome of the work presented in this thesis can be applied in further studies and prediction of laser deposited shapes for real applications. Furthermore, it can be potentially used for improvement of the laser metal deposition technology through the simulation of deposition strategies prior to actual processing.
Declaration

I hereby declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Juansethi Ramsés Ibarra Medina

2012
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Perhaps my words will not be enough to express my gratitude to all those who have helped me in reaching this momentous occasion. To all of you: know that my appreciation is more profound than what my words can express. These humble words are dedicated to you.

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Nomenclature

\( A_c \)  area of laser irradiated computational cell (m\(^2\))
\( A_p \)  cross section area of particle (m\(^2\))
\( \text{Bi} \)  Biot number
\( C_D \)  drag coefficient
\( c_p \)  specific heat of particle (J kg\(^{-1}\) K\(^{-1}\))
\( d_p \)  particle diameter (m)
\( E_m, E_n \)  energy levels \( m \) and \( n \)
\( f_{mn} \)  frequency of transition \( mn \) (s\(^{-1}\))
\( F \)  fractional volume of fluid content
\( g \)  gravitational acceleration (m s\(^{-2}\))
\( h \)  convective heat transfer coefficient (W m\(^{-2}\)K\(^{-1}\))
\( h_e \)  enthalpy (J kg\(^{-1}\))
\( h^* \)  Planck’s constant (6.626196 x 10\(^{-34}\) J s)
\( I_p \)  energy intensity (W m\(^2\))
\( I_p \)  energy incident on powder particles (W m\(^2\))
\( l_p \)  characteristic length of particle (m)
\( k_s \)  thermal conductivity of substrate (W m\(^{-1}\) K\(^{-1}\))
\( k_p \)  thermal conductivity of particle (W m\(^{-1}\) K\(^{-1}\))
\( k^* \)  Boltzmann constant (1.380622 x 10\(^{-23}\) J K\(^{-1}\))
\( m_p \)  mass of a particle (kg)
\( N_m, N_n \)  relative populations at energy levels \( m \) and \( n \)
\( N_p \)  number of in-flight particles above irradiated cell
\( \mathbf{n} \)  
normal vector of free surface

\( P \)  
laser power (W)

\( p_g \)  
pressure of gas (Pa)

\( p_s \)  
pressure in liquid substrate (Pa)

\( \text{Re} \)  
Reynolds number

\( S_h \)  
enthalpy source (J kg\(^{-1}\))

\( S_{h,powder} \)  
enthalpy source from powder (J kg\(^{-1}\))

\( S_{L_f} \)  
latent heat of fusion (J kg\(^{-1}\) K\(^{-1}\))

\( S_{m(c)} \)  
mass source due to powder addition (kg)

\( t \)  
time (s)

\( \mathbf{t} \)  
tangential vector of free surface

\( T_g \)  
temperature of fluid (K)

\( T_p \)  
temperature of the particle (K)

\( T_{\infty} \)  
ambient temperature (K)

\( u, v, w \)  
velocity components (m s\(^{-1}\))

\( V_{p,(i)} \)  
particle volume (m\(^3\))

**Greek characters**

\( \alpha_p \)  
laser beam attenuation ratio

\( \gamma \)  
surface tension (N m\(^{-1}\))

\( \delta \)  
distance from focal plane (m)

\( \varepsilon \)  
emissivity coefficient

\( \eta_p \)  
absorption coefficient of particle

\( \eta_s \)  
absorption coefficient of substrate
**Nomenclature**

\( \theta \)  
- Laser beam divergence angle (°)

\( \Theta \)  
- Laser beam divergence for experimental beam quality calculation (rad)

\( \kappa \)  
- Surface curvature (m⁻¹)

\( \lambda \)  
- Wavelength of electromagnetic radiation (m)

\( \mu_g \)  
- Dynamic viscosity of gas (kg m⁻¹ s⁻¹)

\( \mu_l \)  
- Reference dynamic viscosity at liquid temperature (kg m⁻¹ s⁻²)

\( \mu_s \)  
- Reference dynamic viscosity at solidification temperature (kg m⁻¹ s⁻²)

\( \mu_{su} \)  
- Dynamic viscosity of substrate (kg m⁻¹ s⁻²)

\( \omega \)  
- Laser beam waist (m)

\( \rho_g \)  
- Density of gas (kg m⁻³)

\( \rho_s \)  
- Density of substrate (kg m⁻³)

\( \sigma \)  
- Stefan-Boltzmann constant (5.6704 x 10⁻⁸ W m⁻² K⁻⁴)

\( \sigma_n \)  
- Normal force of surface tension (N)

\( \sigma_t \)  
- Tangential force of surface tension (N)
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<th>Acronym</th>
<th>Definition</th>
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<td>AM</td>
<td>Additive manufacturing</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>CNC</td>
<td>Computerised Numeric Control</td>
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<td>DLF</td>
<td>Directed Light Fabrication</td>
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<td>FDM</td>
<td>Fused Deposition Modelling</td>
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<td>HPDL</td>
<td>High Power Diode Laser</td>
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<td>LASER</td>
<td>Light Amplification by Stimulated Emission of Radiation</td>
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<td>PLIC</td>
<td>Piecewise Linear Interface Construction</td>
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<td>RPM</td>
<td>Rapid Prototyping and Manufacturing</td>
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<td>SIMPLEC</td>
<td>Semi Implicit Pressure-Linked Equations Consistent</td>
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<td>SLA</td>
<td>Stereo-Lithography Apparatus</td>
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<td>STL</td>
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<td>TEM</td>
<td>Transverse Electromagnetic Mode</td>
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<td>Volume Of Fluid</td>
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Chapter 1

Introduction

1.1 Research motivation

Since the development of the first working ruby laser by Maiman in 1960 [1], lasers have evolved from being artefacts of scientific curiosity into tools of almost daily use. In present times, lasers are used in a variety of applications ranging from the manufacturing to the medical, communications, military and research fields. The demand for lasers has grown steadily year-on-year over the last three decades, barring a few years of exception [2]. In 2011, the worldwide sales of laser equipments amounted to 7.46 billion dollars (4.62 billion pounds) and from this, twenty six percent was for lasers dedicated to manufacturing applications [3]. Since the introduction of the first laser processing unit in a industrial environment around 1965, lasers have been widely used in processes such as welding, surface treatment, drilling and cutting [4].

During many years, by far the most common industrial applications of lasers were material removal and joining processes such as cutting and welding. However, during the last few decades a different approach consisting of the precise and controlled build-up of material has led to the development of an emerging family of technologies which are known generically as Additive Manufacturing (AM) processes. These are also referred to as Rapid Prototyping and Manufacturing (RPM). Most RPM processes make use of a laser beam to process a variety of materials using layer-by-layer fabrication techniques [5]. The early RPM systems were limited to processing materials such as resins and polymers, which resulted in
the production of weak components not suitable for functional use [5, 6]. However, the current tendency is towards the fabrication of fully-functional metallic components, which are designed in Computer Aided Design (CAD) software and manufactured using RPM [7].

One of the most versatile techniques, suitable for fulfilling this need is the Laser Metal Deposition (LMD) process. Its outstanding applications include the rapid production of tooling, the repair or salvage of damaged components, surface modification and rapid manufacture of high-value parts in small volumes [8]. LMD has been the focus of study of industrialists and researchers due to its extraordinary features, some of which include: improved wear resistance, low heat affected zone, reduced distortion, improved surface hardness, the ability to deposit material on a localised area and the added benefit of being suitable for automation [9].

Although substantial improvements have been achieved during the last decades, LMD is still affected by drawbacks such as low production rates, low material usage efficiency and particularly by high variability, which results in generally poor geometrical stability in the deposited tracks [7]. The selection of optimal processing parameters, aimed at reducing deposition variability, has been commonly achieved either by experimental trials or more recently by the use of closed-loop control systems [10]. Unfortunately, experimental trials can be costly and time-consuming; and control systems are expensive pieces of equipment.

Modelling can be a useful tool for predicting the process behaviour and hence be a cost-effective approach for an adequate selection of processing parameters. This requires a thorough understanding of the different mechanisms which rule the LMD process at its different phases: from phenomena occurring at the coaxial deposition head, up to the processes of layer formation over the work piece. The great majority of existing models have treated the different phases of the LMD process as detached blocks or stages, and as a consequence some mutually influencing phenomena occurring at the interfaces of such stages have not been captured. Overall, analytical models rely on approximations of energy balance or geometrical shape and are
inflexible to analyse a variety of processing scenarios. Thus, they can provide only a general guide of the process behaviour.

To date, no work has accounted for the various fundamental phenomena occurring at the different stages of the process in a unified approach. The analysis of phenomena such as flows of assistive gases in the coaxial nozzle, flow of powder particles through and after the coaxial nozzle, interactions between the laser beam and powder stream through powder heating and laser attenuation, melt pool formation/solidification and mass addition from powder to the melt pool; could represent a further contributor to the overall understanding and improvement of the LMD process.

1.2 Aim and objectives

The aim of this work is to develop a new numerical model which simulates the different stages of the LMD process: from the powder stream formation up to the clad solidification, within a unified domain for the first time. It is intended that this model will use a hitherto untried approach of process-stage integration within a unified domain which is adequate for a comprehensive simulation of a variety of deposition applications. With this new model, investigations of clad formation in single and multiple tracks will be performed.

Based on this, specific objectives are listed as follows:

- Develop a numerical model to study powder flow and heat transfer phenomena in the powder stream, through and after the coaxial nozzle.
- Develop a numerical model which couples the powder flow model with the track formation, giving rise to an integrated-flexible model of the LMD process.
• Simulate deposition applications in a variety of scenarios to investigate individual and interacting phenomena driving track formation.

• Study deposition strategies aimed at reducing geometrical variability of deposited tracks.

• Perform experimental investigations of powder stream and track formation for model validation.

The outcome of this project pursues the potential use of the developed model for improvement of the LMD technology, through simulation of deposition strategies. It also pursues the potential implementation of the developed model as an add-on tool in CFD software.

1.3 Thesis outline

Chapter 2 presents a literature review of additive manufacturing technologies. This information is relevant because it provides a background of the position that LMD stands among other competing technologies, as well as its capabilities, advantages and limitations. In addition, some of these technologies share some conceptual and technical similarities which are helpful to discuss. This chapter shows the importance of LMD and its diverse areas of application.

Chapter 3 gives a review of the fundamental principles of LMD. The basics of the laser are first given, and particular discussion is provided for the diode laser. This is relevant since this work used a high-power diode laser for experimental work. The chapter also discusses the typical architecture of a LMD system and describes the different versions available. A discussion is given on the phenomena involved in deposition and a review of existing analytical and numerical models is provided.
Chapter 4 provides a description of the developed model of the laser metal deposition process, discussing aspects relevant to the powder stream, to the track formation and the approach of integration between them which was applied.

Chapter 5 presents a numerical and experimental study of the powder stream in coaxial laser metal deposition, as well as a description of the experimental equipment used in this work. The study focuses on phenomena through and after the coaxial nozzle which affect powder stream behaviour, as well as the interactions between the powder stream, the laser beam and the substrate.

Chapter 6 presents applications of the developed model of laser metal deposition, for a numerical study of the mechanisms of track formation in single-line deposits. Qualitative analysis of track irregularities is discussed and quantitative analysis of results is analysed.

Chapter 7 focuses on applications of the model for multiple-track deposition. Simulations of lateral track layering and vertical track stacking are presented. This further highlights the flexibility and capabilities of the model. Moreover, phenomena describing layer and wall formation are discussed and analysed.

Chapter 8 summarises the main conclusions derived from this work. In addition, a discussion of future work recommendations is given.
Chapter 2

Literature review of additive manufacturing technologies

2.1 Introduction

In order to provide an adequate background in which to discuss LMD, it is first useful to provide an overview of AM techniques. This description is relevant because, in general, these techniques share conceptual similarities with laser metal deposition as well as some technical parallelisms. This chapter helps to better appreciate the applications, advantages and limitations inherent to LMD. Emphasis is put on technologies capable of metal processing.

2.2 Additive manufacturing technologies

Figure 2.1 shows a possible classification of manufacturing processes, according to the method of material processing. The category of material addition comprises processes which are relatively new inventions as compared to processes in the first two categories. In particular, additive manufacturing processes are very recent creations which have been made possible only through the combination of other manufacturing and computing techniques, such as such as Computerised Numerical Control (CNC), CAD and high-power lasers.
It has been said that the development of AM techniques has been driven by market forces, in which the need to reduce the time-to-market production cycle requires reducing the steps between the design of a component and its manufacture. Additive manufacturing technologies are regarded as a direct link between a digital design of a component in CAD and a physical component, without the need to employ traditional manufacturing processes such as those from the first two categories in Figure 2.1 [5].

The working principle behind all AM techniques is the layer-by-layer fabrication approach. The initial step in this approach comprises the digital design of a component using CAD software. This digital design is then transformed into a transfer file known as Stereolithography file (STL), in which the surfaces of a solid body are tessellated into triangles. A database of triangle nodes is generated from the face tessellation. This database is mathematically cross-sectioned into small layers comprising a contour and a raster surface. Layer slicing separation is set according to the requirements of a given AM process. Actual part building is made on a layer-by-layer basis. The different contour and raster surfaces are used as patterns to fabricate physical layers which are stacked and bonded on top of each other until a full three-dimensional part is completed [6].
AM techniques vary with respect to the choice of material and the method of layer fabrication and stacking, as shown in Figure 2.2, where the emphasis is put on metal processing techniques. From these, a differentiation can be made between those which are melting-free and those which are based on melting. Process control is more complicated to achieve in the latter due to inherent difficulties of dealing with liquid metal.

Many techniques shown in Figure 2.2 share some conceptual similarities with the pioneering process stereolithography [6]. For this, and the metal-based techniques, a description is provided in the subsequent sections. Particular emphasis is given to those employing a laser beam for layer fabrication.

Figure 2.2. Classification of additive manufacturing techniques. Adapted from [11].
2.3 Stereolithography

Stereolithography (SLA) is the pioneer technology in the field of AM. It was first marketed in 1988 [5] and it is still the most widespread technology in the AM market [12], although its applications are limited to production of concept prototypes. SLA is based on the photo-polymerisation phenomenon, in which a photo-curable resin undergoes solidification when exposed to electromagnetic radiation of a specific wavelength, normally in the ultraviolet range. Figure 2.3 illustrates a typical SLA configuration [13]. A movable platform is submerged in a vat filled with photo-curable resin by a depth corresponding to a layers’ thickness. A laser beam guided by galvo scanning mirrors scans over the resin according to a pre-defined pattern, thus producing a layer. The platform is lowered a layer’s thickness deep into the vat and the layer fabrication process is repeated with the following layer pattern. The process continues until the component is finished layer-by-layer. Unfortunately, the surface of the component is typically described by a non-smooth stepped-curvature, which is dependant on the layer thickness. This is known as the staircase effect.

Figure 2.3. Schematic of stereolithography [13].
The process requires the use of support structures in order to account for any overhanging features. These are produced along with the main component and must be manually removed after the part is finished. Further post-processing curing is required to solidify any uncured resin, and further manual grinding is normally required to smoothen surfaces [6].

The main application of stereolithography is found in the production of prototypes for visual conceptualisation and verification. Some light functional testing, such as fit testing, is also possible.

Advantages of stereolithography are:

- Suitable for production of concept prototypes.
- Fast processing times.
- Good surface finish and geometrical accuracy.

Disadvantages of stereolithography are:

- Limited to process non-functional materials such as resins or plastics.
- Resins are cost-expensive and limited in availability.
- Unable to process functional materials such as metals.
- The need for a vat restricts the size of component that can be built.
- Requires support structures.
- Requires post-processing operations to enhance resin solidification and eliminate the staircase effect.

2.4 Selective laser sintering

Selective laser sintering (SLS) is conceptually similarly to SLA in two aspects: in the layer-wise fabrication approach and in the use of a laser beam for layer fabrication. However, SLS offers more versatility. Instead of photo-curable resins, plastics,
ceramics or metals in powder form can be processed. This allows the production of stronger and durable components. In the case of metals, the production of functional parts is possible. SLS does not rely on the photo-polymerisation phenomenon, instead it is based on the fusing of powder particles through a thermally induced sintering process [14].

Figure 2.4 illustrates the working principle of the SLS process. An even bed of powder is distributed over a movable platform inside a confined chamber. A CO$_2$ laser beam is scanned over the bed using a galvo-scanning mirror system. The laser beam is absorbed by the powder particles. Their temperature is raised to the sintering temperature, such that particles soften and are able to fuse to each other. Melting is not reached in order to avoid the difficulties of dealing with liquid flow. In order to facilitate the sintering process, powder temperature can be increased using an induction heater, which reduces the required power of the laser beam and layer shrinkage problems [15]. The chamber can be filled with an inert gas in order to prevent oxidation issues [5].

![Figure 2.4. Schematic of selective laser sintering [16].](image)

A layer of sintered powder particles is produced after the laser scans the whole layer shape according to the digital data of the STL file. After a layer has been finished, the platform is lowered a layer’s thickness by a piston and a dispensing roller sweeps over the bed depositing another layer of powder. The process continues layer by
layer until the component is finished. In SLS, no extra support structures are required.

In the case of metal powder processing, particle bonding can be achieved either by indirect or direct mechanisms. In the indirect approach, bonding is achieved with the use of mixed polymer particles or low melting point fine metallic powder which fuse during the laser scanning process and keep the higher melting point particles together. Thus, complex post-processing operations are required. These are carried out in furnaces firstly to induce actual metal sintering and then to fully densify the component through infiltration with another metal such as copper [17]. In the direct approach, powder bonding is achieved by direct sintering of particles induced by diffusion phenomena taking place during laser scanning. This avoids the need for chemical binders. However, the process is slow and still requires post-processing operations to increase particle density [15, 17].

Due to its capability to process a variety of materials, SLS can be applied in the fabrication of both concept prototypes and functional prototypes for limited functional testing, as well as in the production of tooling suitable for applications such as low-volume plastic injection [16].

Advantages of selective laser sintering are:

- Materials which can be processed include plastics, ceramics, sands and some metals.
- Parts produced are suitable for functional testing.
- No support structures are required during processing.

Disadvantages of selective laser sintering are:

- Availability of metallic materials is narrow. Specially designed powders are required containing binders or low melting-point metal particles.
- An enclosed chamber is required.
- Metal sintering leads to porous and mechanically weak components.
Complex post processing operations are required to densify and strengthen components.

Infiltration is achieved using a low melting temperature material, such as copper. Thus, the mechanical properties of the component are lower than those of the material in base form.

### 2.5 Selective Laser Melting

Selective laser melting (SLM) is similar to SLS. In both techniques, a laser beam is used to scan over a bed of powder material which is placed over a piston. After each layer has been processed, the piston is lowered by a layer’s thickness and a roller deposits a new layer of powder material. This process is repeated until the component is finished. Two main differences arise. The first is that SLM is designed for the processing of metals only. The second is that the consolidation of powder is achieved by laser induced melting of particles, rather than sintering. Melting of particles implies additional complexities such as higher laser power requirements and difficulties related with controlling the liquid metal. A significant advantage of SLM is its ability to produce near fully-dense metal components with good mechanical properties. Components produced using this technique are suited for functional use [18].

Solid state lasers (Nd:YAG) are the preferred choice in SLM systems in order to take advantage of the better absorption of their shorter wavelength, as well as their smaller spot sizes. These aspects are beneficial due to the requirement for higher energy input [11, 19]. In many ways, the technique can be considered analogous to the laser sintering.

A limitation which is inherent to SLM is the need to scan the laser beam normal to the horizontally-laid powder bed. Hence, it is not possible to build-up a part from a side direction or over a inclined surface. On the other hand, in SLM, the succesive
layers of horizontally-laid powder form a compact bed which creates a supporting structure for any overhangs which may be built, thus eliminating the need for support structures, similar to SLS. However, part warping can become an issue, as layers tend to curl as build-up progresses. Hence, the use of an anchor base-plate for the first layer becomes necessary to avoid part curling [15].

Compared to SLS, SLM is easier to control as the powder is kept in the solid state. Because in SLM the powder is melted, the process suffers from inherent issues such as the liquid metal flowing through the pores of the powder bed by capillary action or the balling effect, which consists of the formation of unconsolidated agglomerations of powder [18]. In order to reduce these effects, process parameters must be carefully controlled such that the melt pool is quickly solidified behind the laser beam [15]. Kruth et al. [18] proposed the use of high-intensity laser pulses to induce vaporisation in order to reduce the balling effect. This is due to the induced recoil pressure over the melt pool which flattens the melt. However, recoil pressure may also produce material to be blown away from the melt and being solidified elsewhere on the part, thus increasing surface roughness [18]. As a result, parts must be machined to improve surface finish.

Only some specially designed powders are adequately suited for the SLM process due to the issue of balling. These powders may comprise a blend of particles of various materials such as Fe, Cu, Ni and F3P. Each material provides beneficial features to the mixture such as reducing the melting point of Fe and Cu, reducing the surface tension of the melt pool, reducing oxidation or increasing mechanical strength [18].

Advantages of selective laser melting are:

- Suitable for the processing of metallic materials.
- Produced components are near fully-dense, suitable for functional use.
- No post-processing furnace operations are required.
- Good geometrical accuracy.
- No support structures are required.
Disadvantages of selective laser melting can be described as:

- Size of produced components is limited by the dimensions of the enclosing chamber.
- Special powder blends are required to reduce pore-capillary flow or balling defects.
- Availability of materials is limited.
- Slow build-up rate. Limited to build parts on a vertical bottom-down orientation.
- Machining may be required for accurate dimensioning and improving surface finish.
- Layers can delaminate or deform due to the induced high thermal gradients.

2.6 Laser metal deposition

Laser metal deposition (LMD) combines powder metallurgy, laser, nozzle and numeric control technologies. Similar to SLS and SLM, laser metal deposition uses a high-power laser beam for layer fabrication. However, instead of dispensing beds of powder over a movable platform inside a containing chamber, the powder is delivered remotely to a metallic substrate via a supply nozzle. This characteristic implies that the powder, same as the laser beam, can be freely delivered in any orientation, be it vertical, horizontal or inclined. A robotic arm can be used for these purposes [20]. Moreover, layer fabrication can be carried out over a flat or round substrate. As the powder does not need to be accommodated into a carefully-laid flat powder bed inside an enclosed chamber, the process can be well-fitted for the processing of large-size components [21, 22].

As LMD is carried out on a solid substrate, the issues of melt pool control, such as capillary flow through voids and balling effect that occur in SLM are not encountered. As a result, most commercially available metallic powders can be
processed. Moreover, blends of different powder materials can be supplied during layer fabrication in order to create graded materials or even to create in-situ alloys, which is an unparalleled capability of LMD [11].

![Figure 2.5. Representation of laser metal deposition. (a) Basic set-up. (b) Scheme of working principle. Coaxial nozzle configuration.](image1)

Figure 2.5. Representation of laser metal deposition. (a) Basic set-up. (b) Scheme of working principle. Coaxial nozzle configuration.

![Figure 2.6. Representation of layer forming by track intersection. Lateral nozzle configuration. Adapted from [23].](image2)

Figure 2.6. Representation of layer forming by track intersection. Lateral nozzle configuration. Adapted from [23].

Figure 2.5 illustrates the basic working principle of LMD. A high power laser beam is made to scan over a metal base. As the laser beam generates a small melt pool on the substrate, the powder delivered through a nozzle is melted and fused to the melt pool and bonded to the substrate as a line or track of newly added material. The process continues with the laser scanning according to pre-defined programming of
the CNC system or robotic arm without the need for intermediate operations of powder bed dispensing. Overlapping of tracks, as shown in Figure 2.6, are used to create a layer, and layer stacking is used to form a three-dimensional shape.

There is no definitively agreed name for LMD. It has been known by different names by different companies and research groups, some of which include Laser-Engineered Net Shaping (LENS), from Optomec [24, 25]; laser powder fusion, from Huffman Corporation [26]; Directed Light Fabrication, from Los Alamos National Laboratories, USA [27, 28]; Direct Metal Deposition, from the University of Michigan [29]; laser direct casting, from the University of Liverpool [30]; and by various other names which are described in the literature [7, 30].

In lack of a universally accepted name, the term Laser Metal Deposition will be used in this work. This name succinctly summarises the key aspects of the technique in a simple acronym, and provides consistency throughout the work.

Advantages of laser metal deposition are:

- Layer fabrication can be carried out in horizontal, vertical or inclined orientations.
- A variety of materials, in powder form, can be processed.
- Combination of different powders in-situ is possible.
- Layers can be created over flat or round surfaces, which is adequately suitable for repair and coating applications.
- Large components can be manufactured.
- Higher deposition rates are possible.

Disadvantages of laser metal deposition are:

- Geometrical accuracy is lower than most other AM processes.
- Common defects include inter-track, dilution and low bonding.
Chapter 2. Literature review. Additive manufacturing technologies

- Stair-stepping effect can limit geometric accuracy due to the higher layer heights.
- Post-processing operations may be required to improve surface finish and geometrical accuracy.

LMD has also found an important application niche in the coating or repair of high-value components as well as components which have broken or suffered significant wear. One of the best-known examples is the repair of turbine blades for the aerospace sector [31], for which various studies have been reported [7, 9]. Applications also include the refurbishment of drilling rods for the offshore industry, repair or modification of injection mould tooling and coating of valves for the automotive industry [32].

The interest in LMD for coating and repair applications arises from the fact that fully dense deposits can be created if inter-track porosity is controlled and, contrary to SLS or SLM, metal can be deposited directly over the substrate without requiring a supporting powder bed. Moreover, as compared to traditional coating technologies such as welding or thermal spraying, LMD has advantages such as lower heat affected zone, reduced distortion, adequate bonding between the deposit and the substrate and process automation [32, 33]. LMD is gradually gaining importance in the market for coating and repair of high-value components. Various companies nowadays provide specialised services in this area [34-36].

An in-depth review of laser metal deposition is given in Chapter 3.
2.7 Laminated Object Manufacturing

The working principle of the Laminated Object Manufacturing (LOM) process consists of stacking thin sheets of material which are cut according to a layer raster pattern. These layers are assembled and bonded to form a three dimensional component. In principle, any material in sheet form can be used in this process if accompanied by a suitable binding method; one of the simplest combinations is paper layers bonded by glue [5]. The working principle is illustrated in Figure 2.7.

![Laminated Object Manufacturing Diagram](image)

*Figure 2.7. Representation of laminated object manufacturing. (a) Process sequence [5]. (b) Equipment set-up [15].*

In the case of metals, layers are processed in a laser cutting machine using a CO\textsubscript{2} laser. Bonding can be made using different techniques such as laser welding, ultrasonic welding, adhesives, screws or a combination of them. Finishing operations
of machining are finally carried out in a machining centre to eliminate stair-stepping defects [11, 37].

LOM has been used for the fabrication of tooling for punching and stamping applications. However, the technique is complex and requires different machinery for the different steps of layer cutting, layer bonding and component post-processing. Transport issues between the different machines and the CNC programming as well as layer alignment further increase the complexity of the LOM technique [37].

Advantages of laminated object manufacturing are:

- Suitable for processing of medium and large sized components, such as dies or metal forming tools.
- Wide choice of readily available materials in sheet form.

Disadvantages of laminated object manufacturing are:

- Layer bonding is critical. Poor layer bonding carries the risk of de-lamination.
- Strength of the produced components in the perpendicular direction to the layers is much less than in other directions.
- Various steps are required in the process, such as cutting, bonding and post-processing. This requires additional machinery, thus increasing the complexity of the technique.

2.8 Three-dimensional printing

Three dimensional printing (3DP) is, along with SLA, one of the early inventions in the additive manufacturing field [38]. The layer fabrication method is based on the use of beds of powder materials, but contrary to SLS, no laser beam is used. Instead, a printer head dispenses droplets of silica-based binder according to a pre-defined raster pattern in order to consolidate a layer of powder. Different powder materials can be consolidated using 3DP. The most widespread is a starch-cellulose mixture
which is used in the main application in recent years for 3DP: concept modellers [5, 15]. Some specially designed stainless steel powders can also be processed. In this case the binder is a low viscosity acrylic. However, furnace post-processing is required to densify the produced component [11].

The working principle of 3DP for metal processing is represented in Figure 2.8. A bed of powder is dispensed by a roller over a movable platform. A printing head prints the binder over the powder bed to form a layer. The platform is lowered by a layer’s thickness and the process is repeated for subsequent layers until the part is completed.

![Figure 2.8. Illustration of three dimensional printing process [13].](image)

The produced component is then heated in a furnace to remove the binder and to induce thermal sintering on the steel particles. After this, the part is infiltrated in a furnace using with a low-viscosity and low melting point material, such as copper.

These post-processing operations are not only complex and time-consuming, but also lead to issues such as component shrinkage or distortion. Moreover, due to the porous structure of the printed components or the infiltration process, produced parts have significantly lower mechanical properties than the build material in base form [11].
Advantages of three dimensional printing for metal processing are:

- High productivity is achieved due to use of efficient jet printers for binder dispensing.
- Good geometrical accuracy.
- No support structures are required.
- Parts are suitable for functional testing, after post-processing.

Disadvantages of three dimensional printing for metal processing are:

- As layers are formed using chemical binders, time-consuming post-processing operations are required.
- Furnace heating is required to eliminate the binder and induce particle sintering.
- Sintered part is porous, thus infiltration is carried out to increase density.
- Mechanical strength of produced components is lower than the material in base form.
- Limited choice of materials, which is dictated by the need for furnace sintering and infiltration steps.

2.9 Summary

This chapter has provided a background of additive manufacturing technologies. The review has emphasised those technologies which are suited for the processing of metallic materials. For each of them, a discussion on the working principle, applications, advantages and disadvantages has been provided.

From the perspective of building dense and fully-functional metal parts, laser metal deposition stands out as a valuable process due to various capabilities such as the ability to process a wide variety of metals without experiencing defects such as balling, the ability to mix different powder materials in-situ and the versatility to
deposit in different orientations and over flat or round surfaces. Applications are found in the repair or coating of high-value components such as damaged turbine blades or worn drilling tools.

The importance of laser metal deposition in the context of additive manufacturing and metal deposition has been made clear from this chapter. The following chapter will provide a review of technical aspects and governing phenomena of the process, along with a review of previous models.
Chapter 3

Literature review of laser metal deposition

3.1 Introduction

This chapter presents a review of the fundamentals of laser metal deposition. It begins with a discussion of the lasing principles and the types of lasers, with a particular emphasis given to diode lasers due to their importance in this work. After this, the fundamentals of laser metal deposition are covered. These include the working principles of the process and the different methods and phenomena of heat and mass transfer involved in the process. A revision and discussion of existing models is also provided.

3.2 Basics of lasers

A laser is a device which emits a beam of light with special properties. This beam is highly directional, coherent, and is emitted in a very narrow spectrum. The acronym *laser*, which stands for Light Amplification by Stimulated Emission of Radiation, is in itself a description of the basic working principle of these devices: the stimulated emission phenomenon, which was demonstrated by Einstein nearly one hundred years ago [39].
The direct predecessors of lasers were devices known as masers, which use the same basic working principle but operate in the microwave range of the electromagnetic spectrum, hence the letter \( m \) in the acronym. Masers were first developed by Gordon, Zeiger and Townes [40], and independently by Basov and Prokhorov [41, 42] in 1954. The principles of ‘optical masers’ were later described by Schawlow and Townes in 1958 [43] and the demonstration of the first working laser was achieved by Maiman in 1960, using a rod of synthetic ruby crystal pumped by a flash lamp [1]. This was closely followed by demonstrations of working lasers based on uranium doped calcium-fluoride and helium-neon [44].

### 3.2.1 Lasing phenomenon

Atoms show internal characteristic resonances at frequencies which range from the radio to beyond the optical range across the electromagnetic spectrum. These resonances are intrinsic properties of an atom; the same as, for instance, atomic weight and electronic configuration, and are defined by its energy levels. Atoms, molecules or ions have different sets of energy levels and associated discrete total energy values. The frequency of the transition between two energy values \( E_m \) and \( E_n \) \((E_m > E_n)\) is given by [45]:

\[
\nu_{mn} = \frac{E_m - E_n}{h^*}
\]

where \( \nu_{mn} \) is the frequency of the transition between the energy levels \( m \) and \( n \), and \( h^* \) is Planck’s constant \((6.626196 \times 10^{-34} \text{ J s})\). By convention, the lower energy level is known as the ground state.

When an atom, ion or molecule interacts with an appropriate electromagnetic signal which is close to one of its characteristic frequencies, an excitation occurs which is proportional to the difference in the number of atoms between the upper and lower...
energy levels for a given transition, which is known as the population difference. The relative population found in two energy levels is probabilistically described by the Boltzmann ratio [45]:

\[
\frac{N_m}{N_n} = e^{-\frac{h^* f_{mn}}{k^* T}} 
\]

(3.2)

where \(N_m\) and \(N_n\) are the populations at the excited level \(E_m\) and the ground level \(E_n\), \(T\) is the temperature in Kelvin and \(k^*\) is the Boltzmann constant (1.380622 \(\times\) \(10^{-23}\) J/K). Figure 3.1 provides a representation of the population difference of two energy levels, where the concept of energy gap, \(\Delta E\), is shown.

![Figure 3.1. Relative populations for two energy levels in thermal equilibrium according to the Boltzmann ratio [45].](image)

However, as there are no negative temperatures in Kelvin, the ratio \(N_m / N_n\) from equation 3.2 is always less than the unity, i.e. \(N_m < N_n\), and thus at thermal equilibrium there are always fewer atoms at the higher energy level. In this state, the
resonant nature of the transition $mn$ is always absorptive. In order to change the nature of the transition from absorption to emission, a situation must be achieved in which there are more atoms in the higher energy level than in the ground level, such that [45]:

\begin{equation}
N_m > N_n \quad E_n < E_m \quad \Delta N_{nm} < 0
\end{equation} (3.3)

This situation, which is schematically represented in Figure 3.2, is called population inversion, due to the negative sign of the difference in populations for the transition.

Figure 3.2. Representation of absorptive population difference and inverted population difference [45].

In a laser medium, atoms are made to interact with photons pumped by an external source. Atoms are thus excited to higher energy levels. A natural decay takes place to restore thermal equilibrium and in the process an atom releases a photon having frequency $f_{mn}$. This phenomenon of random nature is known as spontaneous emission. However, if a photon collides with another atom which is in excited state, a further photon is released which travels in the same direction and phase as the incoming photon. This is the process of stimulated emission, and is represented in Figure 3.3.
Stimulated emission is repeated as photons travel back and forth within the axial direction of a resonant cavity, and in the process elicit additional collisions and photon emissions having the same frequency, direction and phase as the triggering photons. Thus, the resonant cavity provides a closed-loop for light amplification [47].

A typical resonant cavity is shown in Figure 3.4. It consists of a chamber filled or made up of a suitable material, known as the lasing medium. The cross-section of the chamber is usually circular, although rectangular shapes are used in some cases.

On both ends of the chamber two mirrors are placed. These mirrors may be parallel or have another set-up such as be confocal or concentric. Mirrors provide the means to make photons travel back and forth. Any photons which travel off the oscillation
axis are lost either through diffraction from the lasing medium or through absorption by the chamber walls. One of the mirrors is highly reflective and one is partially transparent in order to allow some of the emitted light out of the chamber, or in some cases an aperture is provided in one of the mirrors [47].

Along with the resonant cavity, a pumping mechanism is also required. Different sources can be used for this purpose [46]:

- Optical source
- Electrical discharge
- Electron or ion beam excitation
- Radio-frequency or microwave signal
- Chemical reaction
- Gas-dynamic excitation
- Nuclear reaction

### 3.2.2 Laser beam characteristics

**Monochromaticity:**

The electromagnetic radiation emitted from a laser is confined to a very narrow bandwidth. It is considered as one of the most spectrally pure forms of electromagnetic radiation. As previously explained, the wavelength of a laser beam is determined by the frequency of the transitions taking place during the stimulated emission process. Figure 3.5 shows the characteristic wavelength at which various important lasers operate.
Broadening of the beam bandwidth can be induced by a number of factors, such as: spontaneous emission, possible transitions from upper energy states in the atoms or molecules of the lasing medium or by mechanical disturbances in the resonant cavity such as vibrations, possible thermal expansion or poor cavity design or construction. The broadening of the beam can reach $\Delta \lambda = 10^{-6}$ nm for a gas laser or $\Delta \lambda = 10^{-1}$ nm for a solid state laser, which is significantly smaller than for most other light sources [45, 47].

Coherence and collimation:

The radiation of a laser beam is emitted as a continuous wave having sinusoidal form and constant amplitude. This continuous wave form may be kept for several meters long. Moreover, the beam is highly collimated, which means the light is kept essentially parallel for a certain distance, the Rayleigh range, before it slowly begins to spread due to diffraction effects at the aperture of the resonant cavity. Collimation is important in laser material processing as it allows the electromagnetic radiation to be concentrated and focused into a small area [45].
Polarisation:

As previously discussed, due to the stimulated emission phenomenon, photons are emitted in phase and travelling in the same direction as triggering photons. As a result, in most cases a laser beam consists of wave trains which have their electric fields aligned in a same plane. This is called linear polarisation, or plane polarisation. The electric field of the beam is perpendicular to the travel direction of the beam. In contrast, in unpolarised light the electric fields of the waves are in random orientation to each other and perpendicular to the beam travel direction. Most practical laser devices comprise polarisers in order to deliver a linearly polarised beam [47]. For a polarised beam arriving at a surface, if the plane of the electric field is parallel to the plane formed between the direction of the beam and the normal of the surface, it is known as a p-ray. If the polarisation is perpendicular to the said plane, it is known as an s-ray [19].

Beam mode:

Within the resonant cavity, standing electromagnetic waves oscillate back and forth in the axial direction. However due to the design of the cavity geometry and alignment of the mirrors, these standing waves may interfere with each other. This causes the formation of a wave which emerges from the resonant cavity having a distinct intensity profile. This profile, which dictates the structure of the beam, is known as the transverse electromagnetic mode (TEM_{plq}) and is classified using the following indices [47]:

- \( p \): number of radial zero fields
- \( l \): number of angular zero fields
- \( q \): number of longitudinal zero fields

Commonly only the indices \( p \) and \( l \) are used. The index \( q \) is omitted as the longitudinal field has little influence in the characteristics of the beam for laser material processing applications. Figure 3.6 illustrates some higher order transverse
modes. In practice, the appearance of rectangular modes can be caused by mirror misalignment/tilting or the presence of Brewster windows [45].

Figure 3.6. TEM modes patterns. (a) Circular. (b) Rectangular. [19].

Beam quality:

A laser beam will experience unavoidable divergence due to diffraction at the laser aperture. Higher order beams experience higher divergence than a pure Gaussian beam (TEM$_{00}$). A quantitative measure of the quality of a laser beam is the $M^2$ value, which compares the divergence of a given beam against the theoretical divergence of a corresponding Gaussian beam of equal waist located at an equal position, such that [47]:

$$M^2 = \frac{\Theta_{act}}{\Theta_r}$$  \hfill (3.4)

where $\Theta_{act}$ is the actual divergence of a beam, and $\Theta_r$ is the divergence of a corresponding Gaussian beam. $M^2$ is essentially a ratio of actual against theoretical divergence. A pure Gaussian beam has an $M^2$ value of 1, whereas for near-Gaussian beams the value is slightly higher than unity. Poor quality beams can have values of several times the unity. $M^2$ limits the extent to which a beam can be focused [4].
A simplified approach for determining the value of $M^2$ uses the following equation [47]:

\[
M^2 = \frac{D_0 \theta \pi}{4\lambda}
\]  

(3.5)

where $D_0$ is the beam diameter at the waist plane and $\lambda$ is the wavelength. The beam diameter and divergence being experimentally measured [47].

### 3.3 Types of lasers

Lasers can be categorised according to different criteria such as the pumping method or operation mode, but the most common classification is based on the type of active medium used to achieve the lasing action. Under this criterion, lasers are classified as [46]:

- Gas
- Solid-state
- Semiconductor or diode
- Liquid
- Free-electron x-ray

From these; gas, solid-state and semiconductor lasers are relevant for material processing applications. A brief discussion is provided for these three categories.

**Gas lasers:**

These lasers use a gas as the gain medium and typically an electrical discharge as the excitation pumping source. Due to the important aspect of gas containment, a tightly
sealed container or tube is required. For this reason, some of the optics are fixed inside the container. Gas lasers provide various practical advantages. Gases are relatively inexpensive and there is no practical limit in the volume of the gas that is required. Gases are homogeneous media. There is no risk of damaging the gain medium due to thermally induced deformations, as it may occur in other lasers. Heat can be quickly dissipated by circulating the gas [4].

Some of the well-known gas lasers include helium-neon ($\lambda = 632.8$ nm); Argon ($\lambda = 334$ to 514 nm); CO$_2$ ($\lambda = 10.6$ $\mu$m) or excimer (KrF at $\lambda = 249$ nm; ArF at $\lambda = 191$ nm) [4].

**Solid-state lasers:**

In solid-state lasers, the active medium consists of a nonconductive solid of crystal or glass composition doped in a small percentage with ions. These are commonly rare earth ions which favour the lasing action. These crystal-like solids are normally manufactured in the form of rods or disks. The ends of the rod, or disk, are flattened and polished. Solid-state lasers are optically pumped. Traditionally, a high intensity lamp placed besides the laser rod was used. However, since a considerable amount of the supplied radiation is converted into heat within the rod, the issue of thermally induced distortion or cracking arises. This limits the practical power at which solid-state lasers may operate or in some cases dictates the need for pulsed mode operation. The use of diode lasers for optical pumping helps to reduce some of these issues [4].

The first developed solid-state laser was the ruby laser, which consists of a chromium-doped aluminium oxide crystal (sapphire). However, nowadays one of the most widely used materials is a synthetic crystal of yttrium-aluminium-garnet doped with neodymium ions (Nd:YAG, $\lambda = 1.06$ $\mu$m). Some of its benefits are its favourable energy transition levels which require less intense pumping than ruby, high thermal conductivity and isotropic properties. Other known solid-state lasers include Ti:sapphire ($\lambda = 0.7$ – 1.1 $\mu$m), Yb:YAG ($\lambda = 1.03$ – 1.05 $\mu$m), Er:YAG ($\lambda=$
2.94 μm), as well as variations using silicate glasses as host material for fibre lasers [4, 46].

**Semiconductor or diode lasers:**

These lasers operate differently from gas or solid-state lasers. The process of stimulated emission also shows some differences. Rather than using a process of atomic energy decay between defined energy levels, photons are emitted through the change of energy between electrons in a semiconductor material. The active medium is a chip of a semiconductor material of a few microns in size which behaves as a diode. Hence these lasers are widely known as diode lasers. No pump source is required for initiating atomic excitation as in the case of gas or solid-state lasers. Diode lasers are important in applications such as communications, electronics, printing and various others. Their use in materials processing is increasingly important due to the relative ease of laser combination for delivering suitable high-power outputs. Moreover, their importance also arises from their compact size and crucially their high energy efficiency [47]. An extended description of diode lasers is given in the following section.

### 3.3.1 Principles of diode lasers

The principle on which the diode laser operates is based on the stimulated emission phenomena in semiconductor junctions of the p-n type (commonly AlGaAs or InGaAs) [48]. At equilibrium, a region is generated at the junction which separates the electrons of the negatively charged n-region from the holes (ions) of the positively charged p-region. Upon the application of an electric field, electrons and holes at the junction recombine. When electrons pass from the conductance to the valence energy bands they release energy in the form of photons. These photons can then induce further electron-hole recombinations which release additional photons travelling in the same direction as the inducing photons, thus creating a process of
stimulated emission [48]. As with any other laser system, a resonant cavity is required. This is achieved by coating or cleaving the end-faces of the diode, one of which is partially reflective. The photons can travel several times within the cavity before being emitted.

The majority of the supplied energy into an emitting diode is transformed into heat. Thus, there is a limit on the amount of energy that a diode can withstand without suffering damage, which depends on the thermal stress tolerance of the diode material. Additionally, heat can produce internal distortions in the diode which can reduce its efficiency [47]. To overcome this, the diode emitters are directly mounted on heat dissipators. Deionised water is circulated through micro-channels present in the dissipators. The operating temperature must be kept below 25°C for optimum performance [49]. A single emitting diode is typically about, or close to, \(0.5 \times 3 \, \mu m\) in size and is capable of producing a few watts in power [49]. Single emitting diodes can be assembled in a linear array to form a diode bar, which depending on the number of single emitters can deliver around 120 W in output powers or more if an efficient cooling system is used [50, 51]. A typical diode bar is shown in Figure 3.7.

Figure 3.7. Representation of a diode laser bar. Adapted from [52].
Diode bars can be assembled, commonly in the vertical direction, to form a diode stack, which generates several hundred watts of output power. Vertical stacking also helps to match the dimensions of the beam in the fast axis to that in the slow axis [50]. Moreover, it is also possible to combine beams emitted by separate diode stacks into a single beam using beam polarisers [53], as shown in Figure 3.8. This allows scaling the total output power to levels of several kilowatts, which is suitable for materials processing applications where the quality of the beam is not a critical aspect, such as in brazing, welding, hardening, forming and deposition.

Contrary to the classical cylindrical shape of the resonant cavity of solid-state and gas lasers, the non-circular shape of the active region in a diode laser has a high width to height ratio. As a result, the generated beam shows a different divergence in the perpendicular and parallel directions, relative to the plane of the p-n junction. In the parallel direction, known as the slow axis, the divergence can be about 5 – 10°; whereas in the perpendicular direction, known as the fast axis, the divergence can be as much as 100° [52]. These high divergences require the use of collimators to avoid
the beam quickly dissipating. The beam is first collimated in the fast axis by placing circular lenses near the emitting face of the diode bar. Then, the beam is collimated in the slow axis using a spherical lens [52].

Compared to other laser sources, high-power diode lasers (HPDL) offer advantages such as high wall-plug efficiency, compactness that allows simple integration into a manufacturing line, low-cost and ease of beam transmission through optical fibre [54, 55].

3.4 Basics of laser metal deposition

In its simplest form, laser metal deposition can be defined as a process in which a metal is overlaid on another using a laser beam. A high-power laser beam is focused over the surface of a substrate, where the intense energy is absorbed and a melt pool is generated. An external material, commonly in the form of powder or wire, is then fed to the melt pool, where it melts and adds to the volume of the pool. The laser beam is displaced relative to the substrate with the aid of a motion system such as a CNC table or a robotic arm. At the rear of the laser beam, the material quickly solidifies giving raise to a seam of newly added material fully bonded to the substrate [56, 57].

Figure 3.9 illustrates the general configuration of a laser deposition system. The laser beam provides the required heat input for melt pool generation. As a standard practice, the beam is aligned normal to the substrate’s surface, although work has been reported where it is aligned at an inclination angle [58]. A variety of lasers have been used in laser metal deposition, including CO$_2$, Nd:YAG and diode [54, 59, 60]. However, as a tight spot size or high beam quality are not critical aspects in LMD, diode lasers have become increasingly well established [61]. This is in part because of the other advantages of diode lasers such as their higher energy efficiency and better absorption [54].
The motion of the laser beam relative to the substrate is provided either by a CNC table or a robotic arm, and in rare cases galvo-scanning mirrors have been used [20, 62]. However, CNC tables or robotic arms are preferred since galvo-scanning mirrors are delicate, expensive and may be severely damaged by spatter. In applications where round-shape components are processed, CNC turning stages are also used [20].

Four different methods can be used for material delivery in LMD, which can be categorised as follows [56, 63]:

- Pre-placed powder
- Paste
- Wire feeding
- Blown powder
In the **pre-placed powder** method, shown in Figure 3.10(a), a bed of powder is distributed over the substrate prior to laser scanning. The laser beam is obstructed by the powder bed before reaching the substrate. The powder bed absorbs the laser energy and the melt pool is initiated on the bed. It is then propagated to the substrate, which results in poor bonding. Binders must be used in order to prevent powder blowing from the processing area before melting takes place [47].

In the **paste** method, shown in Figure 3.10(b), a powder-binder mixture paste is fed ahead of the melt pool via a special delivery system. Paste delivery can be a complex aspect of this method. The binder should dry quickly after being delivered but at the same time it must keep the particles together to prevent blowing. It should also allow a constant flow of powder through the delivery system and should also be evaporated by the laser beam. Paste flow rate is important. Too high flow results in an oversized paste which cannot be fully melted, thus leaving unmelted powder agglomerations to the side of the clad. Porosity can be a problem due to the evaporation of the binder [64].

Figure 3.10. Material delivery methods in LMD [63].
In the **wire feeding** method, shown in Figure 3.10(c), the material in wire form is fed to the melt pool. This holds some similarities with the welding process [65]. The wire feeding method offers various advantages. The material is cheaper in wire form than as powder, and at the same time handling a compact coil of wire is easier than handling powder or paste [63]. Wire can be fed with ease in difficult scenarios such as from the bottom to fill undercuts [60]. Moreover, wire for metal deposition can be fed using readily available equipment from welding systems [66, 67] and rollers can be adapted to straighten the wire and reduce plastic deformations [68]. However, the wire feed process is highly sensitive to the wire orientation with respect to the deposition direction. Kim and Peng [69] found that a wire oriented opposite to the deposited track, i.e. fed from the front, favours the formation of a continuous track. If the wire is oriented in the same direction, i.e. rear feeding, or in an orthogonal direction, a discontinuous and undulating track is formed as the wire obstructs the beam from irradiating the substrate. The angle of the wire with respect to the horizontal substrate plane has also been shown to influence deposition. An inclination angle in the range $20^\circ$ to $60^\circ$ has been observed to favour the formation of continuous tracks. A further drawback of the wire feed method is that material combination for in-situ alloy deposition, as discussed in Chapter 2, is not possible [66, 68, 69].

In the **blown powder** method, shown in Figure 3.10(d), the material in powder form is delivered to the melt pool using either a side nozzle, a set of radially aligned nozzles or a coaxial nozzle. The powder flow is controlled by a powder feeder unit and a flow of argon gas is commonly used for blowing the powder flow. Blown powder is the most widespread method in use due to its various advantages. Obstruction of the laser beam is not a critical aspect as in the pre-placed or paste methods, which results in good bonding formation, and at the same time no binders are required. Melting powder particles requires lower laser intensities than melting a solid wire. Moreover, with the use of coaxial or radially aligned nozzles, the deposition is not orientation-dependent, which makes the process omnidirectional and results in stable track formation [63, 66]. In addition to this, combination of
material in powder form is relatively easy, which is suitable for in-situ alloy deposition [9, 70].

The early blown-powder laser metal deposition systems used lateral nozzles for powder delivery. However, nowadays most systems employ coaxial nozzles, as shown in Figure 2.5(b). At their most basic, these nozzles are essentially a pair of open ended cones arranged concentrically to the laser beam and forming a narrow annular passage through which the powder is blown. This ensures that a continuous coaxial stream of powder arrives at the melt pool [71, 72]. Figure 3.11 shows one of the early developments of a coaxial nozzle for laser metal deposition. Different variations and embodiments have been proposed since then [58, 73-87]. However, the basic coaxial design remains unchanged.

![Figure 3.11. Embodiment of a coaxial deposition nozzle, according to [71].](image)

Key elements are the central passage, the powder and the external gas passages. The central passage houses the laser beam path, whereas the powder passage focuses the powder particles. The secondary passage supplies an external flow of gas aimed at providing a wider protective atmosphere and at enhancing consolidation of the powder stream [88]. This secondary passage is not encountered in all LMD systems.
Lin [89] suggested that the elements of the nozzle most exposed to reflected energy form the melt pool should be fabricated using copper due to its high reflectivity. This reduces the risk of nozzle obstruction through particle clogging [90].

3.5 Mass and heat transfer in laser metal deposition

3.5.1 Mass transfer in the powder stream

In LMD, deposition is achieved by supplying a controlled mass flow of powder particles to the melt pool. Powder particles converge and form a consolidated stream at a distance below the nozzle tip. Stream consolidation is influenced by the coaxial nozzle geometry and the assistive gases. It has been shown that increasing the flow of assistive gases increases the velocity of powder particles [91]. However, the consolidation of the powder stream under the nozzle is affected in different ways by the carrier and inner gases. It was suggested that the inner gas induces an outwards-spreading effect on the powder stream, whereas the carrier gas, which flows towards the axis of the nozzle, impinges a drag force on particles converging towards the nozzle axis [89, 92].

The inner geometry of the coaxial nozzle has also been shown to influence the motion of powder particles and the behaviour of the powder stream. Lin [88] investigated the effect of two different nozzle tip geometries. He investigated an inwards and an outwards tip configurations, as shown in Figure 3.12, and found that an outwards tip configuration promotes the formation of a tighter stream consolidating further from the nozzle tip, as compared to the inwards design. This occurred because the width of the powder passage was effectively smaller, thus accelerating the carrier gas, impinging additional momentum on powder particles and improving stream consolidation as a result [88].
Chapter 3. Literature review. Laser metal deposition

It has been shown that when the powder passage width is kept constant for both the outwards and inwards nozzles, as shown in Figure 3.13, then better powder stream consolidation is achieved in the inwards configuration due to the smaller outer diameter of the powder passage [93].

Figure 3.12. Nozzle tip configuration and half-plane particle concentration below nozzle. (a) inwards. (b) outwards. [88].
Further studies of different nozzle configurations, where the nozzle tips are aligned at a same level, have shown that a narrowing of the powder passage leads to an increase in particle concentration at stream consolidation, whereas a reduction of the inner diameter of the powder passage moves the consolidation region closer to the nozzle tip [93]. In addition to this, an acute inclination angle in the nozzle walls increases peak powder particle concentration and brings the consolidation region closer to the nozzle tip [94].

3.5.2 Mass transfer for track formation

Further to powder stream consolidation aspects, mass addition into the melt pool is influenced by various factors such as laser power, powder flow rate, scanning speed, laser spot size and standoff distance. If other parameters are kept constant, the shape of a deposited track is directly related to the laser power, i.e. track width and height increase in positive linear relations with the laser power [95, 96]. A similar trend is observed for the dilution ratio, which increases near-linearly with the laser power [69]. Dilution ratio is defined as the percentage of the track volume which is due to
melting of the substrate. Alternatively from a geometrical viewpoint, it is understood as the ratio of the thickness of melted substrate to the overall layer thickness inclusive of the melted substrate [63].

It has been identified that the scanning speed also plays a significant role. Yellup [97] observed a decreasing trend in the dilution ratio with increasing scanning speeds in a near linear relation. Wu et al. [96] showed that increasing the scanning speed reduces the height of deposited tracks in a near linear relation. Hu et al. [98] observed that the height of the track decreases with increasing speed in a near reciprocal relation, and Yellup [97] also observed a decreasing trend after a threshold velocity. Fathi et al. [99] showed that the relation is near linear at lower speeds and changes to near reciprocal at higher speeds. The width of the track reduces linearly with increasing scanning speeds, as observed by Hu et al. [98]. Other authors have also confirmed the negative relation between clad width and scanning speed [100, 101]. However, a relation between track width and specific energy has also been observed [97, 98]. This shows the influence of the laser spot size, which is modified by the beam divergence and the standoff distance. Pinkerton and Li [102] showed that the powder mass addition can be reduced by decreasing the standoff distance, which also affects the position of the substrate relative to the powder stream consolidation region.

The influence of powder mass flow rate is important in LMD. The powder flow rate is directly related to the size of deposited tracks. Various authors have reported a positive linear relation between track height and powder flow rate [98, 101, 103, 104]. However, it has also been observed that while this relation holds true at low powder flow rates, at higher powder flow rates the increase in track height subdues [105]. This is related to the higher powder clouding occurring at higher powder flow rates, as shown by Liu et al. [106].

As can be seen, in LMD factors such as laser power, scanning speed and powder flow rate exert a combined influence. Keicher and Smugeresky [107] observed that track height is influenced by a relation between power density and scanning speed, rather by a single parameter. Wu et al. [96] showed the influence of the combined
parameters of specific energy and powder density on track dimensions. They proposed a process map for feasible deposition based on these combined parameters. Steen [47] mapped the influence of various combined parameters that determine areas of feasible deposition, as shown in Figure 3.14, where $P$ (W) stands for absorbed power, $m$ (g/s) is the powder flow rate, $D$ (mm) is the spot size, $U$ (mm/s) represents the scanning speed.

![Figure 3.14. Processing window showing relation between powder feed rate, power per spot diameter and combined parameters [47, 63].](image)

This map is based on deposition of the cobalt-chromium alloy Stellite 6 and shows the relation between the powder flow rate, power per spot diameter and other combined parameters. Line A indicates the minimum amount of energy required for producing a continuous track avoiding discontinuities. Line B indicates a limit beyond which dilution occurs. This is 2500 (J /g mm) for the case of the cobalt-chromium alloy. Line C represents a limit for the aspect ratio beyond which inter-track porosity is likely to occur. The aspect ratio is defined as the track width to height ratio. An aspect ratio of 5 was found as the threshold value for the case of Stellite 6 [47].
3.5.3 Heat transfer for track formation

The dimension of a typical melt pool in LMD is in the order of a few millimetres [9]. Its temperature can reach magnitudes of several hundreds of Kelvin in short times [9, 108]. Melt pool temperature increases with the laser power in a linear relation [109]. The size of the melt pool is affected by different factors. Kim and Peng [69] showed that the melt pool depth and width decrease with scanning speed but increase with the laser power. Moreover, Pinkerton and Li [109] reported an increase in melt pool length with increasing laser power, but observed a stabilisation occurring at higher powers. In addition to this, dilution was observed as a transient, showing an initial growth with respect to the processing time followed by a stabilisation trend [69]. The size of the laser spot can also impact the melt pool. A reduction of the laser spot size can increase the length of the melt pool in wall fabrication, as shown by Pinkerton and Li [110]. Moreover, Vasinonta et al. [111] showed that an increase in the wall height leads to melt pool enlargement, which occurs as heat flowing through the wall becomes two-dimensional, which was confirmed by Peyre et al. [112].

Figure 3.15 shows a thermal image of a moving melt pool on a 316 stainless steel substrate produced using the LENS system, whereas Figure 3.16 shows a temperature profile of the melt pool and substrate, taken from the pool centre to its rear. This shows the noticeable thermal gradients which develop at the melt pool surface.

The laser generated melt pool experiences internal flows. These are due to surface tension and buoyancy phenomena. The latter is driven by the temperature dependent density of the molten metal. The former is known as Marangoni flows, and is driven by surface tension gradients [113]. It has been shown that Marangoni flows are dominant over buoyancy flows in laser processing [114]. The flows occur due to the temperature-dependency of the surface tension.
Figure 3.15. Thermal image of a melt pool generated on 316 stainless steel substrate [108].

Figure 3.16. Temperature profile from centre to rear of melt pool. Measurements taken from a side-view thermal image [115].

Under laser heating, temperature gradients develop on the melt pool and this induces surface tension gradients on the surface of the melt pool. The relationship between the two is given by a surface temperature tension coefficient, such that:

\[
\frac{\partial y}{\partial s} = \frac{\partial y}{\partial T} \frac{\partial T}{\partial s}
\]  

(3.6)
where $\gamma$ is the surface tension and $s$ is the distance along the surface of the melt pool. As higher temperatures are nominally located at the centre of the pool than at its edges, the higher surface tension at the edges pulls the liquid from zones having lower surface tension at the centre. Thus, the centre of the melt pool collapses forming a depression [116], as shown in Figure 3.17 for the case of a negative surface tension coefficient. A flow is naturally initiated to compensate for this collapse and this is the force behind the Marangoni flow. The Marangoni force acts in the tangential direction to the curvature of the pool [117].

![Figure 3.17. Visualisation of a melt pool on a steel substrate, created using a CO$_2$ laser and illuminated with both diffused and focused argon-ion laser light [116].](image)

Zhao et al. [113] showed that for a negative surface tension gradient, the direction of the melt pool flow is from the centre to the periphery. This is known as outwards flow and leads to the formation of a wide and shallow melt pool. By contrast, for a positive surface tension gradient, the direction of the melt pool flow is from the rims to the centre, which is known as inwards flow. This kind of flow promotes the formation of a narrow but deeper melt pool. Surface active elements can also induce gradients in the surface tension, such as oxygen and sulphur [118, 119]. Zhao et al.
[113] showed that under increasing oxygen content in the melt pool, the surface tension gradient changes from positive to negative, and as a consequence the Marangoni flow can change from outwards to inwards.

Figure 3.18 shows an experimental observation of Marangoni flows in a laser generated pool in a vat of NaNO₃, whereas the modelled flows inside a molten pool of 304 stainless steel are shown in Figure 3.19.

![Figure 3.18. Experimental visualisation of flows in a pool of NaNO₃, induced by a CO₂ laser beam of 2.5 W [120].](image)

![Figure 3.19. Streamline plot of outwards-flow in a modelled melt pool in 304 stainless steel [121].](image)
3.6 Modelling of laser metal deposition

A review of models presented by previous researchers shows that it has been a widespread practice to segment the different phases of the laser metal deposition process and analyse them as individual blocks which are detached from each other.

3.6.1 Powder stream modelling

Most previous works on powder stream modelling have not dealt with the interaction of powder particles with the substrate or the melt pool. Lin [88] used the FLUENT code to develop one of the early models of the free-flowing powder stream, which treated the gas as a diluted phase within the gas flow and did not account for particle collisions with the nozzle or the substrate. Pinkerton and Li [122] presented an analytical model of the powder stream using the geometry of the nozzle as the basis for predicting powder focus and powder distribution. They assumed a Gaussian distribution for the powder under the nozzle and developed the theoretical powder distribution at different planes under the nozzle, as shown in Figure 3.20. Yang [123] later used a similar approach but the velocities of the powder particles were calculated taking the properties of the surrounding assistive gas into account.

Pan et al. [94, 124] numerically modelled the effects of particle wall collision and irregularities in powder shape using an Euler-Lagrange approach to realistically represent the powder. However, the gas-particle coupling was made only inside the nozzle cavities, and the presence of the substrate was neglected. On the other hand, Toyserkani et al. [63] modelled the trajectory of a single particle being deflected by the substrate, but the assistive gas and the powder particle were assumed to have equal velocities, and collisions inside the nozzle walls were neglected.

Subsequent models also included the in-flight heating of the powder stream before reaching the melt pool.
Liu and Lin [125] modelled the heating of a spherical particle irradiated by a defocused laser beam, as represented in Figure 3.21. This was useful to study heating processes for the powder stream. However, their work dealt with only a single particle in free-fall trajectory, which is far from a typical coaxial-nozzle-formed powder stream, where many particles are present, and can have tilted trajectories.
The interactions of a laser beam and a powder stream produced by a lateral nozzle were studied numerically by Diniz Neto [126] and analytically by Huang et al. [127, 128]. In the latter case, the powder particles were assumed to have constant velocities during their in-flight trajectory and beam divergence was not considered, which affects the interaction times of the laser and powder and hence the overall heating of powder particles. For both the former and the latter, the effects of gas acceleration inside the nozzle as well as particle collision were neglected. Pinkerton [129] analytically modelled the powder-laser interactions with a special focus on the phenomena of laser beam attenuation. By deducing the number of powder particles present in the powder stream, using the stream shape and the powder flow rate, he calculated the increasing attenuation of the laser beam with increasing offset distances from the nozzle. He produced attenuation maps showing the attenuation has annular distribution before the stream consolidation, which changes to a distribution showing maximum attenuation levels at the stream axis. Lalas et al. [130] analytically looked at the role of surface tension in the melt pool but assumed that the substrate was solid and the powder arrived totally in liquid form. Wen et al. [131] used the FLUENT code to model the powder stream heating, but similar to the majority of previous works, the presence of a substrate was neglected. He et al. [132] looked at particle impingement patterns using a numerical-analytical decoupled model, in which the effects of substrate melting and real particle deposition were not considered. Tabernero et al. [133] used a decoupled numerical-analytical model for estimating laser attenuation. Their approach was based on a semi-empirical approach requiring prior experimental characterisation of the laser and powder interactions.

3.6.2 Clad formation modelling

Focussing on a different aspect of the process, various models have been developed to study the process of clad formation. Some models have used analytical expressions which idealise the distribution of powder particles and mass entering the melt pool. Picasso and Hoadley presented some of the early analytical [134] and
Finite Element [135] models in this field, which were developed for a simple two-dimensional problem. Hoadley and Rappaz [136] developed a further two-dimensional model which considered surface tension forces, but the powder stream was neglected. Pinkerton and Li [110] developed a two-part analytical model for temperature distribution in wall deposition to study the effect of standoff distance. Partes [137] analytically studied powder catchment assuming an elliptical melt pool shape and powder Gaussian distribution. El Cheikh et al. [138] analytically described the transverse geometry of a single track relying on a number of assumptions such as a spherical melt pool shape, no melt pool flows, the absence of the powder stream and no heat transfer. Toyserkani et al. [139] used the FEMLAB code to model the clad growth by mesh deformation, using an additional decoupled MATLAB code for powder calculations. A similar approach was used by Zhao et al. [140]. Wang et al. [141] used the technique of element activation-deactivation in the SYSWELD code to study the melt pool stability in thin wall cladding applications. As shown in figure 3.22, their approach was far from reality as the shapes of the clads were simplified into stacked slabs with manually adjusted heights. Aspects such as powder and melt pool dynamics were not considered. At the same time that the heat input in the model was adjusted after each track, to match the simulated and experimental temperature distributions, rather than the model being used for predicting them.

![Figure 3.22. FEM model of melt pool. (a) Temperature distribution on thin wall. (b) Melt pool stability at increasing layer number. [141].](image)

Fallah et al. [142] analysed the formation of the melt pool using a similar approach of element activation, as shown in Figure 3.23, but the powder stream was calculated
externally using analytical formulations, and the effects of fluid flow inside the melt pool could not be considered due to the use of FE techniques. Similarly, Lei et al. [143] modelled temperature distribution for the pre-placed powder method using FE techniques. No account was taken of the fluid flow for actual track shape.

Han et al. [144] modelled the flows in the melt pool, and used the level-set method to determine the shape of the clad in a two dimensional domain. However, it has been shown that the motion of the free surface shows imbalances which cannot be captured in a two dimensional domain. He and Mazumder [145] and Qi et al. [146] developed a three dimensional model of the clad growth using the level-set method. They accounted for flows inside the melt pool and Marangoni effects, but assumed a simplified powder stream with an idealised Gaussian distribution, which miscalculates the amount of extra heat added to the melt pool and the location of mass sources for the clad’s free surface.

Wen and Shin [147] have used a similar approach for simulating a LENS system. They developed numerical models of the powder stream and of the clad formation but unfortunately they kept them separate. They ignored the ricocheting of powder particles, laser attenuation effects and used constant properties for the deposited
material. Additionally, and similar to Mazumder et al. and Qi et al., the length of the modelled track was very short, roughly 1.5 mm in length, which is arguably an insufficient distance to objectively compare it with an actual experimental quasi-stationary track. More recently Wen and Shin [148] presented an upgrade of such a model, in which they simulated a case of three overlapped tracks. They kept the same simplifications and produced tracks of less than 0.5 mm in length. A typical experimental deposition requires a few millimetres to exhibit a stable behaviour, so their modelled tracks represent only the initial deposition zone of a clad. In real applications, where tracks of several millimetres are commonly deposited, it is arguable that these modelled tracks would be of little use. In addition to this, full integration with the powder stream was not achieved and aspects such as attenuation were simplified.

It can be seen that most works to date have treated different elements of the LMD process as detached blocks. As a consequence some mutually influencing phenomena such as the effect of the substrate position and melt pool evolution on powder stream dynamics, or the influence of powder particles mass and heat transfer on the evolution of the molten clad, have not been captured. This can be better achieved when calculations are made within a single fully-coupled domain.

### 3.7 Summary

This chapter has provided a review of the basics of laser metal deposition, including laser fundamentals, deposition fundamentals and process modelling. The literature has highlighted the role of models in the continuing development of LMD. Models have helped to understand fundamental phenomena of the process which otherwise could be difficult to elucidate by experimental means alone. Their use in process optimisation is also valuable. The review has also highlighted the segmentation that has prevailed in the study of LMD and the need for a comprehensive approach for process modelling.
Chapter 4

Formulation of a flexible CFD model of laser metal deposition

4.1 Introduction

The importance and use of numerical models for the study and improvement of the laser metal deposition process was described in Chapter 3. Models are valuable tools to carry out studies which could be difficult to undertake solely by experimental means. Previous models have either relied on numerous simplifications, or been designed to study fixed cases, or have segmented the process into different stages. This chapter describes the formulation of a new numerical model of laser metal deposition using CFD software. The chapter is divided in three sections. The first section briefly discusses general aspects of modelling the LMD process and the approach for integrating the stages of LMD. The second section describes the development of a model aimed specifically at powder flow simulation through a coaxial nozzle. The third section deals with the model developed for the study of the whole LMD process.

4.2 General aspects of a LMD model

A schematic representation of the modelled LMD process is shown in Figure 4.1. The key constituents, or stages, of the process are the powder stream flow through
and after the coaxial nozzle and the melt pool formation and mass addition at substrate level. A numerical modelling approach which accounted for these stages, and at the same time provided modelling flexibility, was devised.

Figure 4.1. Representation of the LMD model constituents.

Figure 4.2 illustrates approaches which were considered for the integration of LMD stages in a numerical model. The first two approaches represent examples of modelling variants consisting of various meshes for the coaxial nozzle, the substrate and the region between them. These approaches required a moving mesh either for the nozzle or for the substrate. In both cases, regardless of if the nozzle mesh was moving and the substrate mesh was fixed, or vice versa, modelling the geometry of the nozzle required the use of additional cells which increased the computation requirements and simulation times. Moreover, it is known that the use of moving meshes incurs in additional procedures for cell and node displacement throughout the simulation which further increased the computation requirements.
The approach represented in Figure 4.2(c) is an efficient choice which was adopted in this work. This approach avoided the use of a mesh representing the nozzle, which eliminated the need for extra computing resources which would otherwise had been dedicated to calculating powder flow through the nozzle. The powder stream and laser beam were modelled from the tip of the nozzle. They were assigned displacement paths, whereas the mesh remained static. This consequently eliminated the need for extra computing operations for mesh displacement, which would had been required in the other approaches.

Figure 4.2. Examples of modelling integration approaches.

The applied approach requires the prior modelling of the powder flow through the nozzle in a different domain, in order to supply the powder data at the nozzle tip which was used in the LMD model for a simultaneous simulation of the powder stream and track formation. Thus, the integration of the process stages in LMD was achieved in a computing-resource-saving approach, using a model for the powder stream through the nozzle and a model for integrating the powder power stream to the track formation. The intersperse between these two was achieved at the region below the nozzle tip, where the in-flight powder stream is formed.
Chapter 4. Formulation of a flexible CFD model of laser metal deposition

The following sections describe the structure of the model of LMD, describing first the model of the powder stream alone, and then the integrated LMD model.

4.3 A CFD model of the powder stream in laser metal deposition

4.3.1 Scope

As shown in Chapter 3, the powder stream is an important element in the laser metal deposition process. It provides the mass that is deposited over the substrate, and as a consequence the behaviour of the powder stream can affect the behaviour of the deposition process as a whole. Powder stream formation is characterised by an intricate combination of physical phenomena including: motion of the powder stream caused by the influence of surrounding gas, trajectory deflections caused by collision with the coaxial nozzle walls, powder heating caused by interaction between the in-flight particles and the laser beam, heat transfer from powder particles to the surrounding environment, and influence of the substrate on powder concentration within the stream.

Studying these phenomena by experimental techniques can be a difficult task to achieve due to the very high energy intensities associated with the laser beam incident on a small processing area, as well as by the high velocities at which powder particles are travelling. Moreover, particles can not be measured while travelling inside the coaxial nozzle. Hence, simulation can represent a tool well suited to study these phenomena. Previous models have simplified the study of the powder stream by neglecting the influence of different phenomena, and the great majority have overlooked the influence of the substrate, as discussed in Chapter 3.

This section presents a numerical model of the powder stream for the coaxial laser metal deposition process. The model takes into account phenomena of powder
stream formation, power stream heating and powder addition into the melt pool, while considering the three-way interactions between the laser beam, the powder stream, and the substrate. These capabilities allow for better analysis of the powder stream as well as an improved description of powder impingement patterns.

4.3.2 Model description

A schematic representation of the modelled process is shown in Figure 4.3. A flow of powder particles is fed into the nozzle via four radially aligned inlets. At the same time, a flow of carrier argon gas is fed into these inlets and a secondary flow of argon gas is fed into a central hollow passage. Motion of powder particles is described by drag forces from the carrier gas and collisions with the nozzle walls which modify their final trajectory.

A laser beam having uniform energy intensity distribution irradiates the powder particles emerging from the powder stream. Particles lose heat to the surrounding shroud gas. Depending on their trajectory, particles may fall inside or outside the limits of the molten region.

The following assumptions were applied in the model:

- The laser has a uniform intensity distribution. This is reasonable as the beam is generated by a diode laser which is transmitted by a fibre optic cable delivering a beam having a top-hat shape.

- Powder particles are assumed to be spherical in shape, which is reasonable for gas-atomised powders, as shown by prior imaging of the powder material [149, 150]. For the case of water-atomised powders showing irregular shape, a correction factor will be required in the model in order to determine an equivalent spherical diameter [129, 150].

- The stream can be assumed to be formed by particles of equal radius, which is a valid approximation for gas-atomised particles [150].
• Oxidation effects in powder particles are neglected. This is reasonable as the use of an inert gas shields the powder from oxidation.

• The dispersion of powder particles within the carrier gas and the low powder volume fraction is such that interparticle clouding and collisions can be regarded as negligible [106, 134, 151].

Fluid flow is described using the well-known Navier-Stokes equations. The first principle of these equations is that mass is conserved, which is stated as the balance between the time rate of change of mass within a certain control volume, and the

Figure 4.3. Representation of the model of the powder stream, scheme and phenomena map.
Chapter 4. Formulation of a flexible CFD model of laser metal deposition

flow of mass through the surface of the said control volume. This is expressed as [152]:

\[
\frac{\partial \rho_g}{\partial t} + \frac{\partial (\rho_g u)}{\partial x} + \frac{\partial (\rho_g v)}{\partial y} + \frac{\partial (\rho_g w)}{\partial z} = 0
\]  

(4.1)

where the first term in the left side describes the time rate of change of mass and the following terms in the left side describe the flow of mass in the Cartesian directions. The density of the gas is defined as \( \rho_g \), \( u \), \( v \) and \( w \) are the velocity components and \( t \) is the time.

The second principle in the governing Navier-Stokes equations is the application of Newton’s second law, namely that the net force of the fluid equals its mass times the acceleration. This is expressed in the momentum conservation equation, for a Newtonian fluid, as [152]:

\[
\frac{\partial \rho_g u}{\partial t} + \nabla \cdot \left( \rho_g \mathbf{u} \right) = - \frac{\partial p_g}{\partial x} + \nabla \cdot \left( \mu_g \nabla u \right) + g \\
\frac{\partial \rho_g v}{\partial t} + \nabla \cdot \left( \rho_g \mathbf{v} \right) = - \frac{\partial p_g}{\partial y} + \nabla \cdot \left( \mu_g \nabla v \right) + g \\
\frac{\partial \rho_g w}{\partial t} + \nabla \cdot \left( \rho_g \mathbf{w} \right) = - \frac{\partial p_g}{\partial z} + \nabla \cdot \left( \mu_g \nabla w \right) + g
\]  

(4.2)  

(4.3)  

(4.4)

where \( \mathbf{v} \) is the velocity vector, \( p_g \) is the pressure, \( \mu_g \) is the dynamic viscosity of the gas, and \( g \) is the gravitational acceleration force. In broad terms, these equations, expressed in the three Cartesian components, relate body forces, surface forces, and the mass and acceleration of the fluid within a control volume.

Motion of powder particles is treated using a Lagrangian approach. In this, particles are treated as discrete entities travelling within the continuum of the surrounding gas media. This approach offers the advantage that the discrete-phase location of
particles can be calculated at any point within the domain, regardless of the size of the cell in which the particle resides. Particle motion is described by the expression [153]:

\[ m_p \frac{dv_p}{dt} = \frac{A_p \rho_p g}{2} (u_g - u_p) |u_g - u_p| + m_p g \]  

(4.5)

in which the term in the left side is the product of particle mass times its acceleration, the first term in the right side represents the net force on the particle caused by the surrounding fluid, and the second term represents the force caused by body forces such as gravity. In this expression, \( m_p \) is the mass of the particle, \( v_p \) is the particle velocity vector; \( u_p, v_p \) and \( w_p \) are the Cartesian velocity components of the particle, \( A_p \) is the area of the particle defined as \( A_p = \pi d_p^2 / 4 \), \( d_p \) is the particle diameter, \( \rho_p \) is the density of the particle, \( g \) is the gravitational force and \( C_D \) is the drag coefficient, which is calculated according to the local Reynolds number (Re) as follows [153]:

\[ C_D = \frac{24}{Re} \quad \text{for} \ Re \leq 1 \]  

(4.6)

\[ C_D = \frac{24}{Re} \left(1 + 0.15 Re^{0.687}\right) \quad \text{for} \ 1 \leq Re \leq 1000 \]  

(4.7)

\[ C_D = 0.44 \quad \text{for} \ Re > 1000 \]  

(4.8)

where the local Reynolds number is defined as:

\[ Re = \frac{\rho_g |u_g - u_p| d_p}{\mu_g} \]  

(4.9)

The heating of powder particles is considered in the following manner. Powder particles emerge from the nozzle having converging trajectories towards a certain zone under the nozzle. As they travel downwards, a number of particles will intersect the path of the laser beam and will be subjected to high energy irradiance that will
cause rapid temperature increase. On these conditions, heat transfer in powder particles comprises phenomena of energy absorption, internal conduction and external convection and radiation. In previous studies of thermal plasma heating of particles, the role of internal conduction within a particle has been studied. In general, it has been shown that the temperature of a single spherical particle rises faster when its thermal conductivity is high, but rises more slowly for higher specific heat and larger particle diameters [154]. The Biot number (Bi), the ratio of convective to conductive heat transfer, can be used as a criterion for determining the relative importance of internal conduction. The Biot number is defined as:

\[
\text{Bi} = \frac{h l}{k_p}
\]  

(4.10)

where \( h \) is the convection coefficient, \( k_p \) is the particle thermal conductivity and \( l \) is the characteristic length, which for a spherical particle is defined as: \( l = d_p \). It has been shown that if values of Bi are small, temperature gradients within the particle can be treated as negligible [154-156]. In this work, where stainless steel powder and argon gas are considered, \( \text{Bi} = 0.004 \). Thus, the assumption of infinite conduction within the particle can be made [157]. The energy balance can be described by the following relation:

\[
m_p c_p \frac{dT}{dt} = I_p \eta_p \pi r_p^2 - h (T - T_g) 4\pi r_p^2 - \varepsilon \sigma (T^4 - T_\infty^4) 4\pi r_p^2
\]  

(4.11)

in which the term in the left side represents the net energy stored in the particle, the first term in the right side represents the heat input by the laser beam, the second term is the heat loss by convection, the and third term is the heat loss by radiation to the surroundings. In this expression, \( m_p \) is the mass of the particle, \( c_p \) is the specific heat, \( T \) is the temperature of the particle in the time \( t \), \( \eta_p \) is the particle absorption coefficient, \( h \) is the heat convection coefficient, \( T_g \) is the temperature of the surrounding gas, \( \varepsilon \) is the particle emissivity, \( \sigma \) is the Stefan-Boltzmann constant, \( T_\infty \) is
the ambient temperature, \( r_p \) is the particle radius defined as \( r_p = d_p/2 \). The laser energy directly incident on powder particles, \( I_p \), follows a uniform distribution according to [125]:

\[
I_p = \frac{P}{\pi (\tan(\frac{\theta}{2}) \delta + \omega)^2} \tag{4.12}
\]

where \( P \) is the laser power, \( \theta \) is the divergence angle, \( \omega \) is the beam waist and \( \delta \) is the distance from the laser beam focal plane.

4.3.3 Solution procedure

The commercial code CFD-ACE+ (ESI Group, France) [158] was used in this work. This code is based on the Finite Volume method, in which the domain is divided into control volumes known as cells. Values for variables are stored at cell centres representing the average value of any quantity inside the cell. Figure 4.4 illustrates the concept of a computational cell, in which the cell centre \( P \) is shown along with the area of the face \( A_e \) and the normal vector \( n \).

![Figure 4.4. Illustration of a hexahedral computational cell of unequal faces. Adapted from [159].](image)
The general solution procedure of the model is shown schematically in Figure 4.5.

Blocks $a$, $b$, $c$ and $d$ from Figure 4.5 refer to the standard procedure applied by CFD-ACE+ for solving the governing equations of fluid flow. This is a segregated, iterative method in which the set of equations for each cell are solved sequentially. The standard solution procedure uses the discretised form of the mass and
momentum conservation equations. In the case of the momentum equations, the
generalised form of the transport equation for a quantity, namely $\phi$ (e.g. $u$, $v$, $w$ or
another), is used [159]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho \mathbf{v} \phi \right) = \nabla \cdot (\nabla \phi) + S_\phi$$  \hspace{1cm} (4.13)

After integrating the transient, convection, diffusion and source terms of equation
4.13 over the control volume, a discretised expression is obtained for each term as
follows [159]:

**Transient term:**

$$\frac{\rho \phi \partial - \rho^0 \phi^0 \partial^0}{\Delta t}$$  \hspace{1cm} (4.14)

where $\partial$ is the cell volume, the superscript $^0$ indicating a previous time and no
superscript indicating the current time.

**Convection term:**

$$\sum_e (\rho_e \Phi_e v^n_e) A_e$$  \hspace{1cm} (4.15)

where $e$ refers to the face of a cell, $v^n_e$ is the component of velocity in the direction
normal to the face. Figure 4.6 helps to illustrate these terms using a simplified 2D
cell representation.

![Figure 4.6. Illustration of terms for linking two cells P and E.](image)

An upwind advection scheme is used for evaluating fluxes at cell faces. In the
upwind scheme, the value of $\phi$ at $e$, i.e. $\phi_e$, is taken from the value of the upstream
cell centre according to the direction of the flow at the face $e$. This is expressed as [159]:

$$\phi^\text{upstream}_e = \begin{cases} \phi_P & \text{if } v^e_P \geq 0 \\ \phi_E & \text{if } v^e_P < 0 \end{cases}$$ (4.16)

**Diffusion term:**

$$\sum_{e'} \frac{\Gamma_e}{\nabla_e} \delta_{P \to E} A_e - \sum_{e'} \frac{\Gamma_e}{\nabla_e} \delta_{C2 \to C1} \frac{\phi_{C2} - \phi_{C1}}{\delta_{C2 \to C1}}$$ (4.17)

where $\Gamma_e$ is the diffusion, or viscosity term, $\delta_{P,E}$ is the distance between $P$ and $E$, and $\delta_{C2,C1}$ is the distance between $C2$ and $C1$.

**Source term:**

$$S^U \theta + S^P \theta \phi_P$$ (4.18)

where $S_U$ an $S_P$ are terms used to define explicitly or implicitly the source term.

Assembling the transient, convective, diffusion and source terms, and after manipulating the expression, it renders the following discretised form of the transport equation:

$$(a_p - S_p) \phi_p = \sum_{nb} a_{nb} \phi_{nb} + S_u$$ (4.19)

where the subscript $nb$ represents values at neighbouring cells. The equation takes the following form for the momentum equation in the $x$ direction:

$$(a_p - S_p) u_p = (\sum_{nb} a_{nb} \phi_{nb} + S_u) P - (\sum_{e} (P_e \cdot A_e \cdot n_e)) P$$ (4.20)

where the subscript $nb$ indicates values at the neighbour cell $P$, which are also referred to as link coefficients. For the directions $y$ and $z$, the momentum equation uses the $v_p$ and $w_p$ velocity components and the neighbour cell $P$ changes accordingly.

In the case of mass conservation, the discretised form of the equation takes the form [159]:

$$\frac{\rho\theta - \rho_0\theta_0}{\Delta t} + \sum_e \rho_e V_e^n A_e = \dot{m}\theta$$ (4.21)
where \( \dot{m} \) is the mass flux through the cell. CFD-ACE+ applies the SIMPLEC (Semi Implicit Pressure-Linked Equations Consistent) method is used to evaluate and correct the pressure field.

The solution for particle motion and heat transfer uses a sequential procedure, applying equations for particle flow and heat balance particle by particle. Block \( e \) in Figure 4.5 indicates the start of particle phenomena treatment by CFD-ACE+. A database file which describes particle location, motion, temperature and diameter is read. This database file can be either a file which describes initial particle conditions or a file which describes particle conditions in the previous time step. Figure 4.7 illustrates the structure of the initial database file for a simplified two-particle file. In the model, a file was provided for each inlet in the nozzle domain for the initial particle state. As the simulation progresses, CFD-ACE+ then produces output files for subsequent time steps.

Particle phenomena calculations are carried out for all particles, as shown in block \( f \) of Figure 4.5, and each particle undergoes the sequential procedure.

![Figure 4.7. Example of a two-particle database file as structured for use in CFD-ACE+.
Arbitrary values shown for illustration purposes.](image)

The procedure for particle heat transfer is applied in block \( g \), which was written as external subroutines, and is described in summarised form in Figure 4.8. Data describing the particle is obtained from the CFD-ACE+ solver, as well as data describing the flow of the cell in which the particle is residing. The Re number and drag coefficient are calculated as described in equations 4.6 - 4.9. Then, the drop volume is calculated from the particle diameter assuming a spherical shape as \( 4/3 (\pi r_p^3) \). From this, the particle mass is determined relating the volume and the density as \( \rho \cdot \text{volume} \). Particle cross section area \( \pi r_p^2 \), and surface area \( 4\pi r_p^2 \), are then
determined. Convection and radiation heat losses are calculated as shown in the second and third terms in the right side of equation 4.11.

The laser intensity irradiating a particle is determined first by reading the beam location and radius, which are specified as constant values in the subroutines. This is then compared against the location of the particle. If the particle is determined to be located inside the body of the laser beam, the laser intensity distribution is determined. This is done as shown in equation 4.12, where \( \delta \) is the distance between
the particle location and the beam waist in the y direction. It is worth nothing that any other laser intensity distribution could be applied in the model, but a uniform distribution is used in this work since the experimental laser used had a uniform intensity distribution. The energy absorbed by the particle is determined as shown in the first term in the right side of equation 4.11. Finally, terms in the heat balance equation 4.11 are combined to determine the temperature increase in the particle.

Particle motion is calculated then, as shown in Figure 4.5, starting from block h. Particle data and cell flow data were read in previous steps of the procedure. Thus, the information is applied as shown in equation 4.5, for each velocity component $u_p$, $v_p$, $w_p$. This determines the new particle velocity, which is also used as a momentum source for the particle, which is then added to the current particle location to determine the new particle location, as schematically marked as block k in Figure 4.5. Finally, CFD-ACE+ outputs an updated particle data file with the new particle location, velocity and properties, which is used in the next time step.

A typical mesh used in the model is shown in Figure 4.9. The geometry of this mesh was based on the design of a built-in-house coaxial deposition nozzle, which is illustrated in section 5.2. It is worth mentioning that this mesh represents one of a number of different geometries and designs that can be simulated. The present model allows for other nozzle designs to be considered. In order to achieve this, the mesh should be changed accordingly. The geometry shown in Figure 4.9 was used throughout this work, as it represents the design of the coaxial nozzle fitted in the experimental LMD equipment used in this work. A wide-diameter standoff-region below the nozzle was added in the mesh to ensure that the placement of the boundaries did not introduce any disturbances in the flow field below the nozzle. The standoff distance in Figure 4.9 was 10 mm, but this can was varied to represent deposition cases having different standoff distances.

The structured mesh in Figure 4.9 was created using the CFD-GEOM tool, which is the mesh generator of the CFD-ACE+ software. The geometry of the nozzle allowed the use of a symmetry condition. The mesh comprised 163000 cells, the minimum cell size at the powder passage was 275 $\mu$m and 65 $\mu$m at the region of the nozzle tip.
Boundary conditions were specified as follows. An inlet condition was defined for the faces of the inner and carrier gas inlets. A constant velocity can be determined from the knowledge of the experimental gas flow rates and inlet surface area. A no-slip wall boundary condition was defined for all other faces of the nozzle, except for those on the symmetry plane, where a symmetry condition was defined. On the substrate face, a no-slip boundary condition was defined. In addition, a geometry stick-condition was defined in this face for the powder particles. This condition enforced the catchment of powder particles hitting a circular area which was defined from experimental knowledge of melt pool size. Particle bouncing is enforced for particles hitting outside this area. Constant-pressure outlet boundary condition is applied on ambient boundaries below the nozzle tip.

Figure 4.9. Three dimensional domain of the coaxial nozzle.
Table 4.1 indicates the relevant properties for materials used in this work. Argon was used for the inner and carrier gases, whereas the powder material was AISI 316L stainless steel.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon [160]:</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1.67</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>0.0163</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>520</td>
</tr>
<tr>
<td>Dynamic viscosity (Pa s)</td>
<td>$2.09 \times 10^{-5}$</td>
</tr>
<tr>
<td>AISI 316 L [161]:</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>7950.0</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>13.4</td>
</tr>
<tr>
<td>Specific heat (J/kg K)</td>
<td>470</td>
</tr>
<tr>
<td>Melting temperature (K)</td>
<td>1723.0</td>
</tr>
<tr>
<td>Absorptivity coefficient [162]</td>
<td>0.4</td>
</tr>
</tbody>
</table>

4.4 A flexible CFD model of track formation in laser metal deposition

4.4.1 Scope

This section presents an improved multi-physics numerical model which simulates simultaneously the fundamental phenomena found in the various phases of the LMD process, from those occurring at the deposition head up to those taking place in the melt pool, in an integrated approach. This allows to study in a better manner the four-way interaction between the powder stream, the laser beam, the substrate and the melt pool; and thus a more realistic analysis of the process can be achieved. Developments described in section 4.3 regarding the powder stream, are incorporated
in this model. Thus, its integration with the track formation is achieved. Additionally, the model is well suited to produce tracks of reasonable lengths that can be compared against experimental samples.

4.4.2 Model description

The arrangement of a laser metal deposition system was shown in Figure 4.1. As discussed in section 4.3, the trajectories of powder particles are shaped into converging directions, within the coaxial nozzle. As the gas inputs and powder flow are parameters which are kept constant during typical deposition applications, and since the nozzle geometry remains fixed, the powder stream behaves in a quasistationary state. Based on this, the modelling approach illustrated in Figure 4.2(c) can be carried out. In this model, data of powder particles at the nozzle tip such as particle’s location, velocities, temperatures and properties; are extracted from the powder stream model described in section 4.3. This is used in the model of the LMD process, as an input for calculating the powder flow below the nozzle tip. The quasistationary state of the powder flow through the coaxial nozzle means that the input powder data remains a valid representation of the powder flow exiting the nozzle throughout the deposition process. This can be assumed provided that input gas and powder flow remain unaltered, which is typical in LMD applications. Figure 4.10 illustrates the adopted approach. Powder data transfer is carried by using powder data generated with the model of section 4.3, and processing it using spreadsheet software to generate an input database which is used in the LMD model.

The set-up of the model of laser metal deposition is shown in Figure 4.11. Powder particles travel towards the substrate having converging trajectories. During their in-flight stage, interactions arise between the laser beam, powder stream and substrate. Particles are heated while clouding the laser beam and attenuating the energy that irradiates the substrate. At the substrate, different phenomena occur such as: melt
pool formation, heat and mass transfer from the powder stream and solidification of the deposited material.

Figure 4.10. Illustration of powder stream integration approach.

The present model analyses the most important phenomena taking place during deposition in a unified approach. That is, the powder stream is analysed at the same time as the melt pool develops. The classical approach of detaching the powder stream from the melt pool formation is avoided in this work.

Figure 4.11. Representation of the model of laser metal deposition.
The following assumptions were applied in the model:

- Assumptions pertaining to the simulation of the powder stream, which were described in section 4.3.

- Below the nozzle tip outlet, the powder stream remains in a quasi-stationary state. This is reasonable provided that the inputs of the gas and powder flow at the nozzle inlets remain constant.

- The laser beam is defined to have a converging-diverging shape, and the half divergence angle is 2.3 degrees. This is supported by experimental observations of the spot size.

- The energy intensity of the laser beam is assumed to have a uniform distribution.

- Laser attenuation is related to the proportion of area of powder particles that is projected to the laser irradiated area [129, 134].

- The melt pool temperature does not reach the evaporation point. This is because evaporation is undesirable in deposition, as the aim is to obtain maximum mass addition into the melt pool. Thus, no evaporation or plasma effects are considered.

- The liquid flow is assumed as laminar and incompressible [121, 146, 163].

- The shroud gas pressure on the melt pool is small and can be ignored [147, 164].

- The interaction between powder particles and substrate can fall in one of the following situations [165]: (a) catchment occurs when liquid particles collide with liquid substrate, (b) catchment occurs when solid particles collide with liquid substrate, (c) ricocheting occurs when solid particles collide with solid substrate.

- Laser absorption is kept constant. This is reasonable, since the use of shroud gas providing an oxygen-protected atmosphere reduces possible oxidation effects in absorptivity. Additionally, stainless steels have been observed to minimise possible absorptivity increments due to temperature rise and oxidation. [162]. The assumption for constant laser absorption should remain valid provided that
Chapter 4. Formulation of a flexible CFD model of laser metal deposition

the irradiated surface is nominally homogeneous. However, if major differences exist across the surface, such as localised higher roughness or local higher opaqueness; then the absorptivity should be modified in order to reflect these conditions.

• Material properties such as thermal conductivity, specific heat capacity, viscosity and surface tension, are defined as linear functions of temperature.

As laser metal deposition comprises the presence of a liquid phase, the continuity and momentum equations are again applied for treating fluid flow. This is similar to equations 4.1 – 4.4. However, this model is aimed at phenomena taking place at the substrate. Thus, terms in the equations relate to the substrate, such that the equations for conservation of mass and momentum are expressed as [152]:

\[
\begin{align*}
\frac{\partial \rho_s}{\partial t} + \frac{\partial (\rho_su)}{\partial x} + \frac{\partial (\rho_sv)}{\partial y} + \frac{\partial (\rho_sw)}{\partial z} &= 0 \quad (4.22) \\
\frac{\partial \rho_su}{\partial t} + \nabla \cdot \left( \rho_s \rightarrow u \right) &= - \frac{\partial \rho_s}{\partial x} + \nabla \cdot \left( \mu_{su} \nabla u \right) + g \quad (4.23) \\
\frac{\partial \rho_sv}{\partial t} + \nabla \cdot \left( \rho_s \rightarrow v \right) &= - \frac{\partial \rho_s}{\partial y} + \nabla \cdot \left( \mu_{su} \nabla v \right) + g \quad (4.24) \\
\frac{\partial \rho_sw}{\partial t} + \nabla \cdot \left( \rho_s \rightarrow w \right) &= - \frac{\partial \rho_s}{\partial z} + \nabla \cdot \left( \mu_{su} \nabla w \right) + g \quad (4.25)
\end{align*}
\]

where \(\rho_s, \mu_{su}\) and \(\rho_s\) are the pressure, dynamic viscosity and density of the substrate respectively.

Solid and liquid phases are found in the substrate, where the liquid phase is the melt pool and the solid phase is the bulk base. The solid phase outside the melt pool is treated by applying an effective viscosity sufficiently large such that velocities are extinguished. As proposed by Ravindran and Lewis [166], the flow through the mushy zone at the interface between the solid and liquid regions can be treated by
modifying the effective viscosity using an exponential function that is related to the liquid fraction content, such that:

\[
\mu_{su} = \mu_l \left( \frac{\mu_s}{\mu_l} \right)^{(1 - \text{LiqFrac})} \tag{4.26}
\]

where \(\mu_l\) is the viscosity at the liquidus temperature. A large value for the viscosity at the solidus temperature, \(\mu_s\), is chosen as to achieve that flow velocities in the solid region become extinct. The governing energy equation is expressed as [159]:

\[
\frac{\partial \rho h_e}{\partial t} + \nabla \cdot \left( \rho v h_e \right) = \nabla \cdot (k_s \nabla T) + \frac{\partial p_s}{\partial t} + \frac{\partial (\tau_{xx})}{\partial x} + \frac{\partial (\tau_{yy})}{\partial y} + \frac{\partial (\tau_{zz})}{\partial z} + \frac{\partial (\tau_{xy})}{\partial y} + \frac{\partial (\tau_{yx})}{\partial x} + \frac{\partial (\tau_{xz})}{\partial z} + \frac{\partial (\tau_{yz})}{\partial y} + \frac{\partial (\tau_{zx})}{\partial x} + \frac{\partial (\tau_{yz})}{\partial y} + \frac{\partial (\tau_{xy})}{\partial x} + S_h \tag{4.27}
\]

where \(h_e\) is the enthalpy, \(k_s\) is the substrate thermal conductivity, \(\tau_{xx}, \tau_{yy}, \tau_{zz}\) are the normal stresses due to the pull by the bulk of the fluid moving ahead of the control volume, \(\tau_{xy}, \tau_{yx}, \tau_{xz}, \tau_{zx}, \tau_{yz}, \tau_{zy}\) are the shear stresses due to friction between layers of fluid, and \(S_h\) is an enthalpy source which takes the form:

\[
S_h = \eta_s (1 - \alpha_p) I_p + S_{h,\text{powder}} + S_{Lf} \tag{4.28}
\]

where \(\eta_s\) is the substrate absorption coefficient, \(\alpha_p\) is the attenuation by powder particles, \(S_{h,\text{powder}}\) is a heat source due to powder arriving at the melt pool, and \(S_{Lf}\) is a source for the latent heat of fusion.
The free surface of the deposition is tracked in this model using the volume of fluid (VOF) method [167]. This method uses a function $F$ to represent values of fractional volume content of the liquid material inside cells. This function describes the motion of the free surface as:

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0$$  \hspace{0.5cm} (4.29)$$

$F$ represents the volume of a cell that is occupied by a secondary fluid, i.e. the metallic material. A cell with an $F$ value of one, would represent a cell completely constituted of metallic material, whereas an $F$ value of zero would represent a cell filled only with argon gas. The function $F$ is initialized with values of unity for cells representing the geometry of the substrate, and with values of zero for cells representing the gas media, such as in Figure 4.12.

![Figure 4.12. Illustration of the initial and transient state of the $F$ function.](image)

The transient behaviour of the free surface is influenced by mass addition from powder particles arriving at the melt pool, as well as by forces acting on the free surface. The former contributor is incorporated as a mass source constituted from the powder particles arriving at the free surface of the melt pool, according to the previously outlined assumptions.
4.4.3 Solution procedure

The model was developed using the commercial code CFD-ACE+. The standard procedure for solving fluid flow phenomena is carried out as explained earlier in section 4.3.3, where blocks a-d from Figure 4.5 can also be observed in Figure 4.13.

Figure 4.13. General solution procedure for the model of laser metal deposition.
Subroutines were written for calculations which describe different phenomena in LMD. Such phenomena are represented by blocks in Figure 4.13 and the detail of the procedures that are carried out is represented in the form of flow diagrams in the following pages.

Block $e$ from Figure 4.13 refers to the calculation of the laser heat source on the substrate caused by the incident laser beam. This was written as a subroutine and represents the term $I_p$ in equation 4.28. It is illustrated in Figure 4.14.

![Flow diagram](image-url)
This routine first determines the displacement of the laser beam using the scanning velocity vector and a simple linear function of the form $position = position^0 + vel \cdot time$ for each direction. This is used for an updated laser position every time step. The position of the cell is provided by CFD-ACE+ and it is compared against the position of the laser beam. If the cell is found inside the laser beam body, then the laser intensity is calculated according to equation 4.12. The heat source is applied only on the cells which belong to the free surface. To achieve this, the volume of fluid content, $F$, of cells is compared against a threshold value which assured that a cell represents the metallic substrate and not the gas medium above it. A threshold value of 0.9 was shown to be the adequate threshold value. It is worth mentioning at this point, that due to the nature of the VOF method and the use of the surface tension forces, the free surface experiences a slight diffusion across various cells which produces difficulties in the correct identification of the free surface. Thus, considerable effort was put in enforcing conditions and checks in the subroutines for the correct identification of those cells which truly represent the free surface. The comparison against a threshold for $F$ at 0.9 in Figure 4.14 was carried out over neighbouring cells in the vertical direction. This resulted in the correct identification of the cell containing the free surface. Once the cell of the free surface is identified, the laser energy is determined for the cell by a multiplication of the cell area and the laser intensity. The determination of the laser heat source follows and adapts to the free surface shape, and thus follows the curvature of the deposited track.

The term $\alpha_p$ in equation 4.28 refers to the attenuation of the laser beam by in-flight powder particles above the substrate. The attenuation, $\alpha_p$, is determined from the clouding of in-flight powder above the irradiated area. The method presented by Pinkerton [129] was adapted for this model, using the following expression:

$$\alpha_p = \frac{\sum_{i=1}^{N_p} A_p}{A_c} \quad (4.30)$$

It represents the percentage of the area clouded by flying particles, with respect to the total irradiated area. $A_p$ is the in-flight particles’ cross sectional area, $A_c$ corresponds
to the cross section area of an irradiated cell within the mesh, and $N_p$ is the number of particles located above that control area $A_c$. The treatment of the attenuation was developed as a subroutine, which is illustrated in a summarised form in Figure 4.15, and represents block $l$ in Figure 4.13.

![Figure 4.15. Detail for procedure of laser attenuation.](image)

In this procedure, the position, size and velocity vector of each powder particle is read from the CFD-ACE+ solver. This is used to determine the time a particle is found in its containing cell. The cross section area for the particle is determined
using the particle size and the assumption of spherical shape. The particle cross section area is used to determine the shaded area over the cell receiving the heat source. This is compared against the area of the cell to determine the total shade area and the attenuation ratio $\alpha_p$. The procedure is carried out on a cell-by-cell basis for cells where the heat source is applied, hence all particles above an irradiated cell contribute to the overall attenuation, as represented in Figure 4.16.

![Figure 4.16. Illustration of laser attenuation procedure.](image)

Figure 4.17 illustrates the detail of block $g$ in Figure 4.13, which refers to the treatment of the latent heat of melting. This was written as a subroutine. In simple terms, this procedure takes the temperature of a cell and compares it against the melting point. If from a previous time step, a heating-cell which previous temperature below the melting point is predicted to increase beyond it, or a cooling-cell which previous temperature above the melting point is predicted to reduce below it; then the routine imposes a heat source/sink which prevents the cell from changing temperature during the phase change state until the latent heat energy has been consumed or released. If the energy consumed or released during a time step is less than the latent heat energy, then the value of the heat source/sink is accumulated in the following time steps, until the total accumulated energy equals the latent heat energy. A considerable number of lines of coding were required for the flagging of cells undergoing phase change and the accumulation of the consumed/released
energy across different time steps. Figure 4.17 provides a summarised illustration of this routine.

The solution of the energy equation is then carried out. This is represented as block $h$ of Figure 4.13. This is carried out by a standard procedure in the CFD-ACE+ solver.
The energy equation, 4.27, is solved following the discretised form of the general transport equation 4.19. Again, CFD-ACE+ solves the equation in sequential form for all cells in the domain. The terms for the energy equation are evaluated as explained above, from the laser heat source, laser attenuation and latent heat. Heat source from powder particles is evaluated by CFD-ACE+ in block $t$ of Figure 4.13, using a standard procedure on a cell-by-cell basis. Particle enthalpies within a cell are summed to obtain values which are added to the cell energy equation. The next set of procedures corresponds to the calculation of the free surface. Mass addition is first treated by determining mass sources from the powder particles. Figure 4.18 shows the procedure for the evaluation of these sources, represented as block $i$ in Figure 4.13. This procedure makes use of a database file of powder particles which identifies particles which being deposited on the melt pool, and which is written by a subroutine. This database file, known as file of deposited powder, is created every time step, as shown in block $r$ of Figure 4.13. Details of this are described later in this section. The procedure in Figure 4.18 reads the deposited powder particle data from the said file. If the particle is static, i.e. velocity magnitude negligible, its mass is placed as a source for the F function in the cell in which the particle resides. However, as discussed earlier, the free surface can suffer from diffusion to cells around the free surface, which impacts the location in which the static particle is located. In order to ensure that the mass source is correctly placed inside the melt pool, checking procedures compare the cell F content against a threshold value. If the cell in which the particle has an F content which is less than the threshold, the mass source is transferred to the lower neighbour cell, and if this cell does not satisfy the F content condition, the mass is transferred to the following lower cell, beyond which the mass source is not considered. The mass is summed for all falling particles, on a cell-by-cell basis. Thus, in the expression:

$$S_{m(c)} = \sum_{i=1}^{n} V_{p(i)} \rho_{p(i)}$$

(4.31)
$S_{m(c)}$ determines the added mass for a cell $c$. $V_{p(i)}$ and $\rho_{p(i)}$ are the volume and density of powder particles found in the cell $c$, respectively. The location of powder particles is determined accurately and directly due to the integrated simulation of the powder stream.

Figure 4.18. Detail for procedure of mass addition.
The mass source from falling particles is then used to update the $F$ function, as shown in equation 4.29, representing the volume of fluid. This is done for each cell after every time step. Increase of the $F$ function leads to the growth of the depositing track. The interface of the free surface is evaluated using a standard procedure in CFD-ACE+; blocks $j$, $k$ and $l$ in Figure 4.13; by using the Piecewise Linear Interface Construction (PLIC) method [168, 169]. This interface tracking method is illustrated in Figure 4.19 for the simplified case of the free surface moving to a new cell. The PLIC method first uses the direction of the gradient vector of $F$, which represents the direction of fluid growth, in order to determine the orientation of the interface. A positioning point for the free surface interface is then determined within the cell, such that the fractional volume value of the function $F$ is satisfied. The evaluation of the normal component of the surface tension force is then carried out by applying surface tension values in the normal direction and balancing pressure differences across the interface.

![Figure 4.19. Representation of free surface evaluation.](image)

Sources for the momentum equation are then evaluated on cells where the free surface interface is located. The forces acting on the free surface include surface
tension and thermocapillarity applied in the normal and tangential directions, as follows:

\[
\sigma_n = \gamma \kappa \cdot n \quad (4.32)
\]

\[
\sigma_t = \frac{\partial \gamma}{\partial T} \nabla T \cdot \vec{t} \quad (4.33)
\]

where \(\sigma_n\) and \(\sigma_t\) are the normal and tangential forces, \(\gamma\) is the surface tension, \(n\) is the normal vector of the free surface and \(\kappa\) is the surface curvature. These forces are incorporated as sources in the momentum equation.

The integrated calculation of the powder motion is then calculated. Blocks \(m, o\) and \(p\) in Figure 4.13 are carried out as described earlier in section 4.3.3, with reference to Figure 4.5, starting from block \(f\). However, the displacement of the laser beam and the nozzle is introduced in this integrated model, as shown in block \(n\) in Figure 4.13 and illustrated in Figure 4.20.

---

Figure 4.20. Detail for procedure of nozzle/laser displacement.
The displacement of the laser beam uses the scanning velocity vector and simple linear function as described earlier. This is used for an updated laser position every time step as well as for updating the position of the particles in the database file, integrated from the model of the powder stream as described in section 4.4.2.

Block $q$ in Figure 4.13 represents the handling of the interaction between the powder particles and the substrate. This subroutine determines the powder bouncing/catchment conditions, as described earlier in the model assumptions outlined in section 4.4.2. The solution procedure of block $q$ is shown in Figure 4.21.

![Diagram of powder bouncing/catchment](image-url)

**Figure 4.21.** Detail for procedure of powder bouncing/catchment.
In simple terms, this procedure identifies where the free surface is located and whether powder particles are colliding with it. Powder location and trajectory data are first used along with the cell flow data in order to determine the motion of the powder particle and predict its position in the next time step. From this position, the cell where the particle will move in the next time step is determined. The F content of this new cell is used to determine if a particle hits the free surface. A threshold value for the F content is used as a conditioning decision, along with the cell temperature of the cell, which must be above the melting point, and the particle direction, which must be moving in the negative y direction. If the particle does not satisfy all conditions, it is determined that it will hit the substrate in solid state, outside the melt pool boundaries. Then, momentum sources are added on the particle $v_p$ in order to reserve its trajectory and induce bouncing. The magnitude of the momentum source is twice the acceleration of the particle applied in the positive y direction.

![Diagram](image-url)

Figure 4.22. Detail for procedure of deposited powder evaluation.
If a falling particle does not bounce against the substrate and enters the melt pool region, it loses practically all its momentum due to it moving from a gas region to a molten metal region where the flow conditions are drastically different. Such a particle is identified using the procedure illustrated in Figure 4.22, which corresponds to block \( r \) in Figure 4.13. A \( F \) threshold value is used to identify where static particles are located. The low threshold value is necessary due to the diffusion of the free surface across cells around the free surface, which is an inherent limitation of the VOF method, already discussed. This subroutine in essence discriminates those particles which are added into the melt pool from those which are in-flight and eventually passes this information to a further subroutine, marked as block \( s \) in Figure 4.13, which is described in Figure 4.23.

![Flowchart](image)

Figure 4.23. Detail for procedure of particle database file update.

Particle data is written to two different output files, depending on whether they are previously identified, or flagged, as trapped in the melt pool. These output files are
used in the next time step for the determination of the mass sources in block $i$, as well as for particle motion in $m$ to $p$. In block $t$, the sources for energy equation from the powder particles are evaluated, as discussed earlier, by CFD-ACE+ using a standard procedure in which particle enthalpies for a cell are summed. These enthalpies are added to the cell enthalpy and the difference is added to the energy equation.

An example of a mesh used in the model of LMD is shown in Figure 4.24. This mesh was created using CFD-GEOM, the proprietary mesh generator tool of the CFD-ACE+ software. This structured mesh comprises hexahedral elements, which were required due to the nature of the PLIC method.

This mesh comprised 104742 cells and the smallest cell size was 285 um, located in the region at the top of the substrate level. A time step size of 0.001 seconds was used in the simulations. This chosen time step was adequately small to ensure that the maximum displacement of the free surface at any time step was kept less than the minimum grid spacing, thus maintaining numerical stability. Boundary conditions were specified as follows. A no-slip wall boundary condition was defined for the faces of the substrate. Outlet boundary conditions are defined for the faces of the argon gas zone. An adiabatic condition was applied for the faces of the substrate.
Properties of the materials used in this work are shown in Tables 4.2 and 4.3. Argon was used as the gas above the substrate. AISI 316L stainless steel was applied for the substrate and powder material.

### Table 4.2. Material properties for Argon [160].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1.67</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>0.0163</td>
</tr>
<tr>
<td>Specific heat at constant pressure (J/kg K)</td>
<td>520</td>
</tr>
<tr>
<td>Dynamic viscosity (Pa s)</td>
<td>2.09 x 10$^{-5}$</td>
</tr>
</tbody>
</table>

### Table 4.3. Material properties for AISI 316L stainless steel [161].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature (K)</td>
<td>1723.0</td>
</tr>
<tr>
<td>Solid density at 300 K (kg/m$^3$)</td>
<td>7950.0</td>
</tr>
<tr>
<td>Solid density coefficient (kg/m$^3$K)</td>
<td>-0.5129</td>
</tr>
<tr>
<td>Liquid density at 1723 K (kg/m$^3$)</td>
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</tr>
<tr>
<td>Liquid density coefficient (kg/m$^3$K)</td>
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</tr>
<tr>
<td>Solid thermal conductivity at 300 K (W/m K)</td>
<td>13.4</td>
</tr>
<tr>
<td>Solid thermal conductivity coefficient (W/m K$^2$)</td>
<td>0.0136</td>
</tr>
<tr>
<td>Liquid thermal conductivity at 1723 K (W/m K)</td>
<td>28.5</td>
</tr>
<tr>
<td>Liquid thermal conductivity coefficient (W/m K$^2$)</td>
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</tr>
<tr>
<td>Solid specific heat (J/kg K)</td>
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<tr>
<td>Solid specific heat coefficient (J/kg K$^2$)</td>
<td>0.184</td>
</tr>
<tr>
<td>Liquid specific heat (J/kg K)</td>
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</tr>
<tr>
<td>Latent heat of fusion (J/kg)</td>
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</tr>
<tr>
<td>Dynamic viscosity at $T_s$ ($\mu_0$) (Pa s)</td>
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</tr>
<tr>
<td>Viscosity coefficient (Pa s /K)</td>
<td>-3.72 x 10$^{-6}$</td>
</tr>
<tr>
<td>Surface tension coefficient (N /m K)</td>
<td>-3.9 x 10$^{-5}$</td>
</tr>
<tr>
<td>Absorptivity coefficient [162]</td>
<td>0.4</td>
</tr>
</tbody>
</table>
4.5 Conclusions

This chapter has described the development of a flexible model of laser metal deposition which integrates the different stages of the process into a unified domain, thus being able to consider the interactions taking place between the powder stream, laser beam, substrate and melt pool. Due to the different procedures applied, the model has been developed with the sufficient flexibility to simulate a variety of deposition situations, and it is adequately comprehensive to consider a number of process phenomena at the different stages of the process. A description of typical meshes was provided with the example of meshes that will be used for simulations in the following chapter. The developed model will be used in the following chapter to study various aspects of powder stream and track formation.
Chapter 5

Analysis of the powder stream in laser metal deposition

5.1 Introduction

As shown in Chapters 3 and 4, the powder stream is an important element in the laser metal deposition process. It provides the mass that is deposited over the substrate, and as a consequence the behaviour of the powder stream can affect the deposition process as a whole. Powder stream formation is characterised by an intricate combination of physical phenomena including: motion of the powder stream caused by the influence of surrounding gas, trajectory deflections caused by collision with the coaxial nozzle walls, powder heating caused by interaction between the in-flight particles and the laser beam, heat transfer from powder particles to the surrounding environment, and influence of the substrate on powder concentration within the stream. This chapter uses the powder stream model discussed in Chapter 4 for a numerical analysis of the powder stream for the coaxial laser metal deposition process.

The chapter is divided in two parts. In the first part, a brief description of the experimental equipment and materials which were used for different validating observations, is given. This description is also relevant to subsequent chapters. The apparatus used in this work included a high power diode laser system coupled with a fibre delivery head, a dual-hopper powder feeder unit, a coaxial deposition head and digital imaging and microscopy equipment. The material used in this work was 316L stainless steel for both the powder and the substrate. The second part of this chapter
Chapter 5. Analysis of the powder stream in laser metal deposition

presents the numerical analysis of a coaxial powder stream. Phenomena analysed include powder stream formation, powder heating and interactions between the laser beam, the powder stream, and the substrate.

5.2 Experimental equipment

5.2.1 Diode laser: Laserline LDL 160-1500

The laser system employed in this work was a LDL160-1500 high power diode laser manufactured by Laserline GmbH. This compact modular system comprises a control and supply unit, the laser head and a delivery system. The control and supply unit accommodates the electronic and control systems, the user-interface display, the power supply, and the cooling unit. The laser head houses an array of diode stacks, which are the core of the laser system. The system uses two wavelengths for power scalability, thus operating the wavelengths 800 - 980 nm. The diode head was coupled to a fibre delivery system. The final delivered beam had a circular shape with a top-hat distribution.

The laser beam diameter was measured experimentally by placing a white cardboard shim covered with a dark-coating at different distances from the focusing lens. Low power laser pulses were aimed at the shim until the dark coating had been removed. This was made visible by the appearance of a white spot from the original material colour. The beam spot diameter was obtained by measuring the heat affected zone using a digital calliper. Figure 5.1 shows the measured spot diameter at different distances from the nozzle tip. The measured range of distances was chosen because past experience has shown it comprises the processing window which improves the efficiency of the process in the used LMD system. The measured spot diameter values were used in later experimental and modelling activities. The power of the laser beam after the laser head was measured using a Gentec UP55N-300F-H9 power
The power was set on the control unit of the Laserline system in incremental levels of 50 W. Output power was measured up to the operational limit of the power meter, as shown in Figure 5.2. The data was extrapolated to determine the output power after the fibre beyond the limits of the power meter.

Figure 5.1. Measured spot diameter below the coaxial nozzle.

Figure 5.2. Nominal and measured power output.
5.2.2 Deposition nozzle

The nozzle used in this work is shown in Figure 5.3. It is a built-in-house nozzle of the coaxial kind. It was designed at the University of Manchester and manufactured externally by DeBe Lasers Ltd. It comprises an upper housing for assembling to the fibre-optics-coupling, a pair of oblique nozzles and a cooling channel for water circulation. Nozzle components are made of aluminium in order to reduce the overall weight with the exception of the tips, which are made of copper in order to reduce the absorption of reflected energy from the working area.

![Figure 5.3. The coaxial nozzle used in this work: (a) Assembled. (b) Components.](image)

The design of the deposition nozzle is schematically represented in Figure 5.4. A protective transparent mask positioned at the top of the nozzle provides protection to the focusing optics. Gas is blown through two inlets situated at the top of the nozzle in order to create a protective flow which further shields the optics from spatter bouncing from the melt pool [63, 71]. This gas flow also provides a covering
atmosphere to the working area. Argon is employed as both a central protective gas and conveyance gas in order to create the oxygen-free atmosphere [91].

Figure 5.4. Inner design of the coaxial nozzle used in this work.

A further flow of argon gas and powder particles is supplied through four inlets positioned at a lower level than the inner-gas inlets. These four inlets are aligned at right angles with the nozzle axis. The flow of gas and powder travels through a 1 mm wide conical passage with a taper angle of $20^\circ$. Within this passage, the trajectory of powder particles is modified through collisions with the nozzle walls. The first of these collisions is significant and takes place right after particles leave the four inlets and hit the passage walls. Some commercial nozzles attenuate this collision by providing an inclination angle to the inlets. This can contribute to achieve a better shaping of the powder particles trajectories within the powder passage [90]. The final element in the nozzle is an outer grooved-sleeve providing a channel through which water is circulated in order to dissipate heat from the nozzle. The nozzle used in this work does not include an outer conical passage for a secondary shielding gas flow.
5.2.3 Powder feeder: FST-PF

The flow of powder material was supplied by a FST-PF disk powder feeder manufactured by Flame Spray Technologies. This dual-hopper powder feeder uses a flow of argon gas to blow the powder particles to the coaxial nozzle. Each of the hoppers has a capacity of 1.5 litres and a mixing system, which helps to dispense the powder evenly to a feeding wheel. The control of the powder delivery is based on the rotational rate of a grooved feeding wheel, which provides a constant volumetric delivery of powder. The rotational rate is set in revolutions per minute (rpm), and the mass delivery rate must be established depending on the properties of the powder material used. The rotation of the feeding wheel is set using a Siemens OP-3 controller and the flow rate of the assistive gas can be adjusted individually for each hopper using a flow meter gauge.

The mass flow rate for the AISI 316L powder was measured at different rotational rates. The measuring procedure consisted of collecting the powder delivered by the powder feeder at constant rpm rates for a known period of time in a container. The container was weighted before and after the powder was collected using a digital scale. The difference between the weight of the empty container and the container after the powder blowing determined the amount of delivered powder. The relation between rotational rates and powder mass flow rate was established as shown in Figure 5.5.

![Figure 5.5. Mass flow rate for AISI 316L powder. Powder size 53 – 150 µm.](image-url)
5.2.4 Optical imaging equipment

The microscope used in this work was a Keyence VHX-500. This is a compact and versatile microscope. It includes a portable control unit with a foldable LCD display for visualisation, control and measurement. The operating software provided capabilities for image composition, handling, labelling and measuring. The measuring functions comprised tools for calculating distances, areas, angles and circumferences. The camera had a resolution of 2.1 megapixels. The illumination source was a 100 W halogen lamp. The microscope had two quick-interchangeable system of lenses which provide magnifications ranges from 20x to 200x and from 100x to 1000x respectively. For samples whose dimensions extended beyond the depth-of-field, a depth composition function allowed the topography to be visualised and measured by constructing a three dimensional image from a series of images taken at different depths within the sample.

5.2.5 Auxiliary equipment

A Guyson Sandblaster was used to sandblast the substrate samples. A Struers Accutom precision cut-off machine was used to cut samples that required cross-section dimensioning. A Presi Mecatech grinding machine was used to grind samples. A Thermovision Flir A40 thermal camera was used for visualisation of powder stream heating.

5.2.6 Materials

The material used in this work for both the substrate and the powder was the austenitic stainless steel 1.4404 (X2CrNiMo17-12-2) as classified by the European norm EN 10088-1:2005 [170] and as AISI 316L according to the norms A240 / A240M of the American Society for Testing and Materials. The name 316L will be used in this document hereafter.
These kinds of steels have low carbon content of less than 0.03 percent, chromium content between 16.5 to 18.5 percent and nickel content between 10 to 13 percent. Some of the advantages of these steels are that their austenitic phase is maintained at very high temperatures and the formation of intergranular carbides is reduced due to the low carbon content [171]. Also, they exhibit good corrosion resistance, high ductility, exceptional weldability and good biocompatibility [172, 173]. The applications of 316L stainless steel are wide and can range from fabrication of structural components for the construction industry to the manufacture of specialised surgical instruments.

The steel powder used in this work was provided by Sandvik Osprey Ltd. It was produced using the gas atomisation method, and particles had a spherical or near-spherical shape, as supported by prior imaging of the powder material [149]. The particle size was in the range from 53 to 150 µm. To ensure the powder was free from any spurious particles which may be trapped during handling, the powder was sieved using a 150 µm mesh before being poured into the powder feeder.

The steel substrates used in this work were blocks of nominal size 50 mm x 50 mm x 10 mm. Prior to experimental work, a standard face milling operation was carried out on the steel blocks to eliminate any obvious surface unevenness. Subsequently, they were sandblasted to enhance laser absorptivity and finally they were degreased using ethanol.

5.2.7 Procedure for experimental measurement of powder stream shaping

The experimental setup used for powder stream visualisation and measurement of powder stream formation is shown in Figure 5.6. A high intensity lamp was placed next to the discharge area of the coaxial nozzle, and a slit mask was positioned between the lamp and the powder stream. A narrow groove of about 1 mm in width in the mask allowed a thin sheet of light to pass and illuminate the formed powder stream.
Chapter 5. Analysis of the powder stream in laser metal deposition

The mask was positioned such that the groove was aligned with the axis of the coaxial nozzle. The narrow light sheet illuminated the centre of the powder stream and the light scattered by powder particles was captured by a high resolution digital camera aligned at right angles with the place of the light sheet. The camera was set to high definition, and a black background was placed behind the illuminated stream to enhance the contrast in the pictures captured with the camera. Ambient illumination was kept approximately constant throughout.

![Experimental set-up for powder stream measurement](image)

Figure 5.6. Experimental set-up for powder stream measurement.

Pictures were processed using imaging software to enhance the illumination contrast of the stream against the dark background and to produce gray-scale pictures, as shown in Figure 5.7. These pictures were used to determine the distribution of powder concentration within the stream. Areas of higher concentration are represented by brighter pixels in the pictures [91]. A typical luminance distribution measured along the centre of the stream and starting from the tip of the nozzle is shown in Figure 5.8. The powder stream shows an initially low powder concentration which gradually increases until the point where the annular stream reaches its maximum convergence. After this point, the powder concentration gradually decreases due to the divergence of the stream. The location of highest powder
concentration can be measured from this graph, as a distance from the tip of the coaxial nozzle. This is the distance of powder stream consolidation. It is worth noting that the stream consolidation distance is different from the standoff distance, which in LMD is the distance from the nozzle tip to the top surface of a substrate. The consolidation distance is relevant as it can be used as an indication of the optimum substrate position which helps to increase the powder that can be concentrated into the deposition zone.

Figure 5.7. A typical gray-scale image of the coaxial powder stream.

Figure 5.8. A typical luminance distribution graph in the axial direction.
5.3 Results and discussion

5.3.1 Powder stream formation

The modelled flow of powder particles is shown in Figure 5.9(a). The following parameters were used in the simulation. Powder material was AISI 316L. Powder flow rate was set at a rate of 0.58 g/s. The flow of inner and carrier gases were set at $6.67 \times 10^{-5}$ m$^3$/s and $8.33 \times 10^{-5}$ m$^3$/s respectively. Corresponding parameters were used in the experimental comparisons. In these, the laser was kept off and no substrate was positioned under the nozzle.

Two aspects can be observed in Figure 5.9(a). The first is that particles enter through the top inlets and experience a sudden collision with the inner nozzle wall, making them decelerate and at the same time to deflect in different directions. They continue to be propelled by the argon gas and gradually gain momentum. During their passage through the nozzle cavity, particles collide several times with the walls, causing them to repeatedly change directions. These collisions play an important role in determining the final trajectory that particles have when emerging from the nozzle, and could provide an idea of why the powder stream is found to merge at a position that is different than that predicted by methods based only on the geometry of the nozzle. Figure 5.9(b) illustrates the path-shaping collisions occurring within the nozzle.

For ease of visualisation, only powder emerging from one inlet is shown. Under the tested parameters, the average stream velocity is $2.3$ ms$^{-1}$, and is predicted to converge at a zone between 7.9 and 10 mm under the nozzle tip.

The second aspect is related to the shape of the stream. At nozzle tip level, the stream is shown to have an annular shape. However, in contrast to what is typically assumed, the distribution of particles within the annulus is not even. As shown in Figure 5.9(c), a higher concentration of particles can be observed at four zones within the annulus, which correspond to the location of the four nozzle inlets. On
moving away from the nozzle, the stream gradually merges into a fully converged spot at the distance mentioned earlier. After converging, the stream diverges again, showing a cross-like cross-section.

Figure 5.9. Modelled powder stream. (a) Front view, cross section. (b) Perspective view, showing powder from a single inlet. (c) Transverse particle distribution at different in-flight positions: $P1$ 5 mm above focus; $P2$ at focus point; $P3$ 3 mm below focus. Carrier gas flow: \(8.33 \times 10^{-5} \text{ m}^3/\text{s}\). Inner gas flow: \(6.67 \times 10^{-5} \text{ m}^3/\text{s}\). Powder flow: 0.58 g/s.

Figure 5.10 shows the concentration of mass in the powder stream directly below the nozzle, on the stream axis. The powder stream shows an initially low powder concentration. As distance from the nozzle increases, the mass concentration steadily
increases until reaching a maximum level after approximately 8.5 mm. After this point, the mass found on the axis of the stream reduces according to its divergence.

Figure 5.10. Mass concentration along axial direction. Powder flow rate 0.58 g/s, carrier gas flow: $8.33 \times 10^{-5}$ m$^3$/s, inner gas flow: $6.67 \times 10^{-5}$ m$^3$/s.

Procedure described in section 5.2.7 was used for obtaining the experimental results. Good agreement can be observed between the modelled and experimental results up to the merging zone. After this, the modelled mass concentration falls sharply, while the experimental one observed a more gradual decrement. Differences between the experimental and modelled curves, after the stream merges, are thought to be due to the experimental technique as well as to the increasing diameter, and hence volume, of the annulus of the numerical stream after the merging point. In the experimental technique, it is possible that divergence of the light sheet could be illuminating a slightly wider zone at the centre of the stream and this in turn increases the luminance values, thus overestimating the mass concentration. Furthermore, the sharp drop in the modelled curve is due to the increase in the diameter of the powder stream due to divergence. As the mass remains unchanged as an annulus, but the stream diameter increases with the standoff distance, the same mass is weighed over
an increasing stream volume, thus decreasing the mass volumetric concentration sharply.

5.3.2 Influence of substrate position on mass concentration

It has been a common practice in previous works to simulate the powder stream as a free-flowing flux of particles, while neglecting the presence of the substrate. It may be that it has been thought that the powder stream can be fully studied as a stand-alone element or that the substrate has been considered as not to have an influence on powder stream formation. However, placing a substrate in the simulation shows a clear influence, as Figure 5.11 illustrates.

![Figure 5.11. Representation of substrate influence on particle bouncing](image)

As previously discussed, the powder stream has a converging/diverging shape, where the region in which the stream achieves its minimum spot size can be roughly regarded as a powder focal plane. If the substrate is positioned below this plane, particles having diverging trajectories will bounce away from the powder stream. By
contrast, if the substrate is positioned above the plane, particles will have mainly converging trajectories. Thus, on bouncing from the substrate, particles will travel towards the bulk of the stream.

The influence of the substrate can be observed in Figure 5.12. There is a marked increase in powder mass concentration as the standoff distance is reduced. It can be noticed that when the substrate is placed further from the nozzle tip, at 60 mm, the smallest mass concentration is found, whereas at a distance of 10 mm, a sharp increase is observed. This is explained by the fact that at such distance, a number of particles hit the substrate outside the boundaries of the melt pool and bounce back into the main stream, thus increasing its overall mass.

![Figure 5.12. Influence of substrate position on average mass concentration, along axial direction. Powder flow rate: 0.42 g/s. Carrier gas flow: 8.33 x 10^{-5} m^3/s. Inner gas flow: 6.67 x 10^{-5} m^3/s.](image)

### 5.3.3 Influence of assistive gases

The role of assistive gases on the powder stream was also studied. Figure 5.13 shows changes in the consolidation distance due to the assistive gases and powder flow rate.
For these studies, two levels of flows, $1 \times 10^{-4}$ and $1.33 \times 10^{-4}$ m$^3$/s, were chosen for the inner and carrier gases. These levels were applied in order to create situations in which the inner gas flow rate was higher than carrier gas flow rate, in which the carrier gas flow was higher than the inner gas flow rate, and in which they were equal. In addition powder flow rates of 0.15, 0.42 and 0.65 g/s, which are in the range commonly used for deposition applications, were also used.

![Figure 5.13. Influence of powder flow rate. (a) Carrier gas flow: $1 \times 10^{-4}$ m$^3$/s; inner gas flow: $1.33 \times 10^{-4}$ m$^3$/s. (b) Carrier gas flow: $1.33 \times 10^{-4}$ m$^3$/s; inner gas flow: $1 \times 10^{-4}$ m$^3$/s. (c) Carrier gas flow: $1.33 \times 10^{-4}$ m$^3$/s; inner gas flow: $1.33 \times 10^{-4}$ m$^3$/s.](image)

Figure 5.13 shows the effect of changing the setting of inner and carrier gases at the coaxial nozzle. It is possible to observe that as the inner gas flow was increased, the powder consolidation distance was displaced about 0.2 mm further from the nozzle tip, which suggests a pushing effect of the inner gas which prevents the annular
powder stream from consolidating at an earlier distance. Conversely, when the
carrier gas was set at higher flow rates than the inner gas, the consolidation distance
was slightly reduced, thus improving the focusing quality of the powder stream.
Figure 5.13 also illustrates the effect of powder flow rate. An increase in the powder
flow rate from 0.15 g/s to 0.65 g/s caused the consolidation distance to be further
displaced from the nozzle tip by approximately 0.4 mm. This occurred both in the
case where the carrier gas flow was lower than the inner gas flow, and in the case
where it was higher. This can be understood if it is considered that increasing the
powder flow rate causes an increase in the volume fraction of powder within the
argon gas. A higher amount of powder particles could slightly attenuate the drag
force of the gas. Hence, the carrier gas propelling force of the gas could be reduced
and thus, the stream could focus closer to the nozzle tip. Experimental observations
were obtained with the procedure described in section 5.2.7. Good agreement was
achieved between the predicted and observed consolidation distances. Trends are
similar, and the differences remain within seven percent between the predicted and
observed values.

5.3.4 Powder stream heating

After emerging from the nozzle, powder particles intersect the laser beam. Depending on the geometry of the beam, and their trajectory and velocity, particles
can experience significant temperature increases. A thermal image of the irradiated
powder stream was obtained using a Thermovision Flir A40 thermal camera. The
camera was positioned at right angles to the beam axis and aligned with the nozzle
tip. The powder flow was set at a rate of 0.58 g/s, the inner gas was at 6.67 x 10^{-5}
m^3/s, the carrier gas at 8.33 x 10^{-5} m^3/s and the laser power was set at 1000 W.
A thermal image is shown in Figure 5.14. The obtained readings were found useful
to analyse heating trends, albeit not the actual temperature in the stream, as the
maximum recorded value in the stream, 373 K, was arguably too low. This was
deemed to be caused by the fact that the powder stream consists of small particles travelling at high speeds. The powder stream can be regarded as a semi-transparent material, in which the thermographically measured temperature is affected by the density in the stream as well as the temperature of the particles. As the powder stream, taken as a whole body, has a very low density, the scale in the temperatures recorded was too low to be used for quantitative comparison. Nonetheless, the obtained images show useful information regarding heating behaviour within the stream.

A distance exists after the nozzle tip where no powder heating takes place. This indicates the region before interaction between the powder and the laser beam starts to occur. It can be observed that the highest powder temperature is achieved below the laser focal plane.

Figure 5.15 shows the modelled heating of the powder stream for the case where the laser power is 300 W and the standoff distance is 60 mm. Initial powder heating occurs at around 3.5 mm under the nozzle. At this point, the laser beam is still
defocused and the temperature rise is moderate. The highest rate of temperature increment occurs when particles cross the laser focal plane at 7.5 mm.

Only a few particles which travel within the path of the laser beam for a longer time continue to be heated below the laser focal plane. However, the majority of particles in the stream, more than 98 %, are below 1800 K. Modelled temperatures for these processing parameters are in good agreement with reported values for comparable materials and laser beam parameters. Wen et al. [131, 147] reported temperatures on the heated powder stream in the range 1300 - 1800 K for 316L powder for a free-flowing converging stream irradiated by a 300 W laser beam, and 1700 - 2500 K for Stellite 6 powder, which has similar specific heat and thermal conductivity as 316L.

Figure 5.15. Modelled heating of the powder stream. Cross section view. Power: 300 W. Standoff distance: 60 mm. Powder flow: 0.58 g/s. Carrier gas flow: $8.33 \times 10^5$ m$^3$/s. Inner gas flow: $6.67 \times 10^5$ m$^3$/s.
Figure 5.16. Modelled average powder stream heating along axial direction. Free flowing powder stream. Laser focal plane: 7.5 mm under nozzle. Powder flow rate: 0.58 g/s.

Figure 5.16 shows average stream temperatures along the axial direction for different laser powers. It can be observed that powder heating begins at about 3.5 mm below the nozzle tip. Temperature increase is initially moderate. However, a higher gradient is found at around the position of the beam focal plane. This is followed by a zone where a more gradual temperature increase is observed until a maximum is reached. Subsequently, gradual cooling is observed as the powder moves further from the beam waist. Standoff distance also has a noticeable effect on powder stream heating. Figure 5.17 shows two contrasting cases where the standoff distance is 60 and 10 mm. Higher temperatures can be seen in Figure 5.17(b), with the 10 mm standoff, which can be explained by the effect of particles bouncing back into the bulk of the stream, and being further heated by the laser beam.
5.4 Conclusions

This chapter presented application of the developed CFD model of the powder stream in laser metal deposition. Phenomena of gas and powder particles motion were used for simulating the coaxial powder stream. Particular emphasis was put on analysing particle heating, interactions between the laser beam, powder stream and substrate. The inclusion of the substrate in the model, in contrast to previous works, allowed a simulation closer to real processing conditions.

It was found that the trajectory of powder particles is mainly determined by wall collisions inside the nozzle cavity and drag forces from the assistive gases. Gas flows have a slight effect of powder consolidation. Whereas the carrier gas tends to favour better stream consolidation, the inner gas tends to distance the consolidation further
from the nozzle. Accurate trajectory predictions cannot be achieved solely by the use of trigonometry and geometrical methods. The role of the substrate is reflected on its effect on powder impingement and powder bouncing at different standoff distances from the nozzle. The standoff distance influences aspects such as mass concentration within the powder stream, overall powder stream temperature and powder delivered to the melt pool. At large standoff distances, powder particles bounce away from the stream and its mass concentration remains unaltered. By contrast, mass concentration increases as the substrate is positioned closer to the nozzle, since more particles bounce from the substrate back into the bulk of the stream. This in turn impacts the powder stream heating. Average powder stream temperatures can be modified by particles bouncing back into the bulk of the powder stream when the standoff is at the level of, or above, the stream consolidation. The amount of powder that falls inside the boundaries of the melt pool is affected mainly by: dimensions of the powder stream, powder flow rate, properties of the powder and the substrate, laser power, substrate absorptivity, scanning speed, and standoff distance.

The standoff distance at which mass deposition rate can be maximised depends on the location of the powder stream focus region, which does not necessarily coincide with the laser focal plane. The ideal standoff distance for each LMD equipment depends mainly on nozzle geometry and flow of assistive gases, which dictate the focusing of the powder stream. The model can be used to study this.

Better understanding of the process can be achieved when the important elements presented in this chapter such as accurate prediction of particle motion, presence of the substrate and interactions between laser beam, powder stream and substrate, are considered at the same time.
Chapter 6

Study and prediction of track formation in laser metal deposition

6.1 Introduction

This chapter presents an application of the flexible numerical model of laser metal deposition described in Chapter 4, for the analysis of track formation. Phenomena which are simulated occur at the different phases of the LMD process, from those occurring at the deposition head up to those taking place in the melt pool, in an integrated approach. This allows to study in a better manner the four-way interaction between the powder stream, the laser beam, the substrate and the melt pool; and thus a more realistic analysis of the process can be achieved. Developments described in Chapter 4 regarding the powder simulation and track simulation, are incorporated in this work. Additionally, the model is well suited to produce tracks of reasonable lengths that can be compared against experimental samples.

6.2 Simulation of a melt pool with no powder addition

Prior to presenting results on the simulation of a deposited track, it is relevant to discuss the modelling of a melt pool created on a 316L substrate using a high-power diode laser, in the absence of powder flow. This is useful to show the role of melt pool flows as well as to validate the model against existing results.
It is well known that flows within the melt pool are important to understand its behaviour [113, 120, 174, 175]. Figure 6.1 presents the simulation of a laser generated melt pool in the absence and presence of melt pool flows. As shown in Figure 6.1(a), neglecting flows clearly leads to an unrealistic flat melt pool shape. In contrast, Figure 6.1(b) shows that inclusion of flows leads to the formation of the characteristic crater-shape melt pool, which has been reported in the past [116].

For validation purposes, a simulation of a stationary melt pool generated on a 316L substrate using a 730W Gaussian beam was carried out. This was compared against results obtained by Yang. et al. [121], for a melt pool produced on a AISI 304 substrate. Properties for this material are closely similar to those of AISI 316L, including similar surface tension and viscosities [161]. This creates a valid comparison reference. The laser power and interaction time chosen for the simulation were such that the melt pool surface temperature fell within 5 percent of that obtained by Yang. et al., i.e. 2679 K for their work compared to 2718 K for the present free surface model. These similar temperatures ensured that closely similar surface tension gradients were compared, which according to Mills [161], are equivalent for 304 and 316L steel. Figure 6.2 shows the calculated melt pool from
Chapter 6. Study and prediction of track formation

the present model and the result reported by Yang, et al. Good agreement in melt flow patterns can be observed. Vortices form at both sides of the melt pool and reduced flow is observed at the centre.

![Melt pool transverse cross section showing velocity vectors](image)

Figure 6.2. Melt pool transverse cross section showing velocity vectors. (a) Present free surface model, (b) Yang et al. [121]

A clear difference is the concave melt pool surface in Figure 6.2(a). This is caused by lower surface tension forces at the centre of the melt pool centre and a redistribution of material to the edges, where higher surface tension forces are found. The difference with respect to the flat shape in Figure 6.2(b) is explained by the different methods applied in both works. Whereas the upper boundary for the melt pool in Figure 6.2(b) was fixed, thus restricting the motion of the melt pool, a free surface approach was applied in Figure 6.2(a). This meant that the surface of the melt pool was not restricted by any fixed boundary and the concave surface was naturally formed by the lower surface tension at the melt pool centre. Furthermore, the surface of the melt pool developed sloshing due to the use of a free surface. This is reflected in variations of the velocity distributions at the melt pool surface at different instants, as shown in Figure 6.3, in which a distribution curve shows the maximum velocity located at the left side, another curve shows its location at the right side, and a further distribution curve shows a balance in maximum velocity at both sides of the melt pool. This continuous behaviour underlines the transient behaviour of the melt pool and the phenomena caused by the Marangoni effect.
Velocities at the surface of the melt pool are shown in Figure 6.4 for the cases shown in Figure 6.2. Good agreement is also achieved for the velocity magnitude and distribution. Differences in the distribution are thought to occur due to the use of the free-surface approach in this model as well as by small differences between the spot sizes of both models. Bearing in mind these considerations, it can be said that velocity magnitudes at the melt pool surface, as well as velocity distribution, are shown to agree well, which provides additional validation.

After this verification, a simulation of a stationary melt pool generated using a beam with top-hat intensity distribution, was carried out. This is because a uniform beam is
used in future simulations of laser metal deposition. Figure 6.5 shows the comparison between a Gaussian and a uniform laser beam.

![Figure 6.5. Velocity vectors in transverse cross section for stationary melt pool using two beam intensity distributions. Power: 730 W; spot size: 1.7 mm. (a) Gaussian beam. (b) Uniform beam.](image)

Due to the different energy distributions, different temperature distributions are created across the melt pool surface, and as a consequence, reduced surface tension gradients arise. This results in different flow patterns. The melt pool generated using a uniform beam is clearly less concave than the one formed with a Gaussian beam. As the surface tension distribution across the melt pool is more homogeneous, the generated flows become less strong and only a small recirculation zone can be observed. The stacking of material at the rims is also less pronounced. Velocity magnitudes at the melt pool surface are shown in Figure 6.6, reflecting the effect of changes on surface tension distribution. For the case of a uniform laser beam, there is a reduction of about 50 percent of the mean velocity developed using a Gaussian beam. However, the velocity distribution across the surface of the melt pool smoothens for the case of a uniform beam. This can be observed in the difference in velocity from the centre to the edges of the melt pool: 0.1 m/s for the case of a uniform beam and 0.26 m/s for the case of a Gaussian beam.
The behaviour of the melt pool is modified when it changes from stationary to moving state, as shown in Figure 6.7. In this case, the redistribution of material, discussed in Figure 6.2, concentrates towards the rear of the melt pool. This gives rise to a small seam of solidified material, which on average measures 41.4 μm in height, in this case.
6.3 Experimental procedure for single track deposition

For verification purposes, experimental runs were carried out in a laser metal deposition system. This system comprises a Laserline LDL 160-1500 high power diode laser which is coupled to a fibre delivery unit and delivers an output beam having a uniform energy distribution. The motion system was provided by a 2-axes Isel C116-4 CNC stage. Motion in the vertical direction is provided via a manually operated lift mounted on the stage. The powder material was fed into the system using a FST disk powder feeder. A built-in-house coaxial nozzle was used to deliver a shaped stream of powder particles to the substrate. This coaxial nozzle uses a carrier gas flow to propel the powder particles and an inner gas flow to protect the optics from splatter, but it does not comprise an outer shrouding gas. The material for both the powder and the substrate was AISI 316L stainless steel. The powder size was in the range 53 - 150 \( \mu \text{m} \). Substrate blocks of nominal size 50 x 50 x 10 mm were used. The standoff distance was at 10 mm below the nozzle tip, as this was shown to produce better results in terms of powder usage, with the equipment used [176].

Three sets of experiments were carried out to evaluate the responses to three changing processing parameters: laser power, scanning speed and powder flow rate. The combination of processing parameters was defined as follows. In one set of experimental runs the laser power was set at three levels: 1000 W, 730 W and 510 W. The mass flow rate and scanning speed were kept constant at levels of 0.28 g/s and 10 mm/s, respectively. In a second set of experiments, the scanning speed was increased from 5 mm/s to 15 mm/s, in increments of 2.5 mm/s. In these runs, the laser power was kept fixed at 730 W, whereas the power flow was set at constant rate of 0.28 g/s. In a third set of experiments, the powder flow rate was increased from 0.14 g/s to 0.58 g/s, in four incremental levels. In these experiments, laser power was kept constant at 730 W, whereas the scanning speed was set at 10 mm/s.
In modelling runs, the laser beam waist was positioned at the coordinates \( x = 0 \) mm, \( y = -7.5 \) mm, \( z = 0 \) mm; where a spot size of 1.76 mm was defined. The displacement of the beam was defined in the negative ‘\( x \)’ direction at equal magnitudes for the different experimental runs. Parameter settings for the different simulations were matched with those of the experimental runs against which they are compared.

6.4 Results and discussion for single track deposition

6.4.1 Simulation of track formation

Figure 6.8 illustrates the integrated calculation of the powder stream and a single track deposited using the parameters defined in section 6.3. Powder particles forming an annulus leave the coaxial nozzle travelling with converging trajectories towards the substrate. They form a fully consolidated stream at a distance between 8 and 10 mm below the nozzle tip. Material wastage can occur in the form of particles hitting the substrate outside the melt pool and bouncing to the outer environment. Those powder particles falling into the laser generated melt pool are instantaneously absorbed and their mass is assimilated into the pool.
The melt pool is created on the substrate due to the high energy intensities of the laser beam. Flows develop inside the pool due to forces of buoyancy and temperature-dependant surface tension changes. The addition of powder mass into the pool slightly modifies the flows as the newly added material has to be redistributed across the melted area of the clad. However, as the powder stream is focused coaxially to the laser beam, the leading edge of the pool receives a higher amount of powder as compared to the trailing edge. Thus, at different moments during cladding, a slight accumulation of mass can be observed at the front edge of the pool. This accumulation is redistributed to the trailing edge as the melt pool moves forward. Zones of irregularities such as lateral undulations or top waves can develop along the longitudinal surface of the clad, which can be partially captured by the present model as shown in Figure 6.9.
These irregularities are caused by slight fluctuations in melt pool size and temperature. Such behaviour may comprise stages where the melt pool temperature is increased by a combination of enhanced heat transfer by convection, a temporarily reduced laser attenuation or an increased intake of powder mass. Having a higher temperature allows the melt pool to absorb additional powder particle mass which is redistributed to the rear of the pool, and subsequently accumulated at the top of the clad leading to the formation of a wave. This however, can be maintained only for a short time, as the additional amount of added powder takes additional heat from the pool and decreases its temperature. The fluctuating behaviour may also comprise stages where the melt pool size is slightly decreased, leading to a section in the clad which shows a reduced width, or undulated zone. Thus, zones of both top waves and lateral undulations can be found in a laser deposited clad.

Figure 6.10 shows the predicted deposited tracks using three different power levels at 1000 W, 730 W and 510 W. The reduced energy input in the third case leads to a reduction in the melt pool size, which limits the amount of powder particles that are trapped. The shape of the experimental track deposited with a 1000 W beam is closely matched by the predicted track. For the case of a 730 W beam, some differences can be observed, as the modelled width is overestimated by 13 %, and the
predicted height by 8%. The simulation of the 510 W beam shows a good prediction of the overall track area and a small overestimation of the track width.

Figure 6.10. Predicted and actual track shapes at varying laser power: (a) 1000 W. (b) 730 W. (c) 510W.

Differences in the track widths could be due to discrepancies between the material properties of the actual work piece and those used in the simulation, which are taken from the literature. However, it is also possible that small percentage differences in the track size are simply due to the effect of top waves and lateral undulations. These effects introduce variations which can slightly modify both the experimental and simulated transverse track profiles at different points along their lengths. Overall,
good agreement is observed between the profiles of the experimental and modelled tracks.

Figure 6.11 shows the modelled dilution percentage corresponding to the cases shown in Figure 6.10. An increase in the dilution ratio from 14 to 46 percent can be seen as the laser power increases from 510 W to 1000 W. This tendency is in line with behaviour reported previously in the literature [69, 99, 145, 147]. Moreover, the observed high dilution ratio is in agreement with reported results of deposition of equal powder-and-substrate material combinations, such as that of He and Mazumder [145], who reported a 38 percent dilution for deposition of H13 tool steel, using comparable processing parameters.

![Figure 6.11. Predicted dilution and cladding dimensions respect to laser power. Powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, standoff distance: 10 mm.](image)

Figure 6.12 shows the influence of magnitude changes in selected processing parameters on the final track dimensions. Figure 6.12(a) shows a decrease in the cladding height as the scanning speed increases, which is mainly caused by a contraction in the melt pool length at higher speeds. The opposite effect is observed when the powder flow rate is increased and additional mass is trapped in the melt pool, thus giving rise to track height as shown in Figure 6.12(b). Both figures also show the good match that has been achieved between the experimental and predicted track height values.
From Figure 6.8 and 6.9, it was possible to observe track irregularities which cause the track to depart from a smooth surface finish. These irregularities are indicative of the transient behaviour of the laser metal deposition process. This can also be observed in Figure 6.13, where the in-process rate of added mass into the melt pool is shown. It is clear that mass addition does not remain constant throughout deposition. After the melt pool forms, an initially gradual rise in the rate of mass addition can be observed, which is followed by the appearance of fluctuating spikes. These occur because not all of the powder arrives at the melt pool at the same time as particles are travelling in different directions and at different velocities. This causes irregular powder impingement patterns which differ from those assumed in previous models, where distribution equations idealised the powder arriving on the melt pool as a homogenised stream impinging evenly across the area of the melt pool. A closer look at the spiking line in Figure 6.13 reveals increase/decrease cycles in the levels of mass addition. A smoothing averaging curve imposed on the data helps to illustrate this phenomenon. As previously discussed, these cycles can be a contributing factor in the formation of track irregularities. The overall average rate of mass addition in Figure 6.13 is 0.057 g/s, which corresponds to 20 percent of the powder flow rate.
Figure 6.13. In-process mass addition rate. Laser power: 730 W, powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, standoff distance: 10 mm.

The net input energy from the laser beam which is effectively absorbed into the substrate is shown in Figure 6.14, along with the averaged laser attenuation. The behaviour of these in-process parameters is relatively stable.

Figure 6.14. In-process laser energy input and attenuation. Laser power: 730 W, powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, standoff distance: 10 mm.

When the cladding process begins, slightly higher attenuation levels are caused. This is because at initial stages, the powder stream is constituted by falling and bouncing
particles. Attenuation levels tend to stabilise to levels of around 83 percent after the melt pool develops fully. The energy input from the laser beam shows a moderately uneven behaviour after about 0.075 s, which roughly coincides with the beginning of the spiking of the powder addition rates after the melt pool is fully developed.

6.4.2 Cooling and solidification

The model was used to analyse cooling rates within a track. The analysis was performed at two positions: at the end of the track and at the middle of the track. Figure 6.15 shows the cooling rates which develop at the end of the track immediately after the laser beam is switched off. Cooling rate is measured at the top and bottom of the track.

Figure 6.15. Cooling rate at the end of track after laser beam is switched off. Laser power: 730 W, powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, standoff distance: 10 mm.
Three zones can be observed in Figure 6.15. The first zone corresponds to the liquid phase, where very high cooling rates are observed as the melt pool quickly disappears. Cooling rates at the bottom of the melt pool are lower in comparison. This is reasonable, as the highest temperatures are found at the top of the pool. The magnitude of the cooling rate is higher than reported values by Wang et al. at a maximum of about 9000 K/s, using material properties for 316 steel [141]. The difference could be partly due to the measuring point being placed at the middle of the track in those models, rather than at the top, as is done in this model. The difference could also reflect the impact of taking into account flows in the melt pool. Cooling rates are reduced at the bottom of the melt pool. This is due to heat flowing from upper areas of the melt pool to the bulk of the substrate. The second zone in Figure 6.15 corresponds to cooling during the transition from liquid to solid phase, in which the latent heat is released and cooling rates are stabilised. A small rise in both curves is also observed. This is caused by; as seen in Table 4.3; an increase in thermal conductivity during the transition from liquid to solid. The increase in thermal conductivity enhances heat flow to the substrate, which is reflected in an increase in the cooling rate. The third zone in Figure 6.15 corresponds to cooling during the solid state, where only heat conduction drives heating. This is characterised by a steady falling trend.

Figure 6.16 shows the cooling rates at the middle of the track. Measurements are made at the top and bottom zones immediately after the melt pool has moved forward and left the measuring points behind. Thus, curves in Figure 6.16 represent cooling rates during the solidified state. Cooling rates are smaller at the middle of the track than at the end because the laser beam moving ahead of the middle of the track continues to provide heat into the track. Some slight spiking can be observed, which is thought to occur due to fluctuations in the melt pool, as discussed earlier. However, as the melt pool continues to move forward and distances from the measuring area, the influence of any fluctuations becomes less significant. In broad terms, the mid-point of a track can be regarded as representative area of other areas, apart from the start and end points.. Thus, the cooling behaviour shown in Figure
6.16 could be regarded as representative of other areas within the bulk of the deposited track.

Figure 6.16. Cooling rate at the middle of the track, immediately after melt pool has moved forward from middle of track. Laser power: 730 W, powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, standoff distance: 10 mm.

6.5 Conclusions

This chapter has presented applications of the developed model of LMD, as well as an analysis of track formation. A distinctive feature of the model was the integration of the different stages of the process in a unified framework, starting from the motion of particles of the powder stream, to the mechanisms of track formation involving the four-way interaction between the powder stream, laser beam, substrate and melt pool. Due to this, fewer assumptions were made in the model. Capabilities of the model included the prediction of melt pool and track formation in three dimensions,
heat transfer in the powder stream and the track; and simulation of irregularities. The model was able to produce tracks of realistic shape in terms of transverse profile and track length. Good agreement was achieved with the experimental observations. It was seen that melt pool fluctuations produce irregularities in the final track shape, such as lateral undulations or top waves. These were caused by combined phenomena of fluctuations in the melt pool temperature, uneven mass addition rates and redistribution of powder mass from the leading to the trailing edge of the pool. Qualitative simulation of these irregularities was also achieved. High cooling rates were observed at the end point of a track immediately after the laser beam was switched off. Reduced cooling rates were seen in the bulk of the track, where heat was flowing from the moving melt pool to the rear of the track, which reduced temperature gradients.

The following chapter will discuss various applications and studies of multiple track deposition. These will focus on practical uses of the model in actual deposition situations.
Chapter 7

Multiple track deposition: analysis and prediction

7.1 Introduction

Applications of coating, repair or rapid manufacture using laser metal deposition require single tracks to interact through overlap, overlap or intersection. The study of these situations through modelling techniques requires the simulation of multiple tracks in a fully three dimensional environment. However, the majority of analytical and numerical studies of laser metal deposition to date have focused on single track applications.

This chapter uses the flexible model of LMD developed in this work to simulate multiple track deposition applications in a variety of configurations including: lateral track overlapping, vertical layer stacking and track intersection. Chapters 5 and 6 presented analyses of the mechanisms of track formation. These included, among others, aspects of powder motion, heat transfer and track morphology. This chapter now takes the model and uses it in applications oriented to the formation of laser deposited structures. In section 7.4, arrays of quadruple tracks deposited at different lateral offset distances, predict the deposition of coating layers, including the effect of the offset distance on layer morphology. Then, section 7.5 shows the deposition of a vertical thin wall structure comprised of four single-track layers stacked in a vertical direction. Finally, section 7.6 analyses the deposition of two orthogonal intersecting tracks and predicts the morphology at the intersection. The model is used
to improve the shape of the layer at this junction. In all cases, the modelled results are compared against experimental observations and agreement is obtained. Results not only show the capabilities and adaptability of the model to study a variety of deposition situations, but also to facilitate the study of LMD behaviour in multiple-track applications. In the section where intersecting tracks are simulated, a proposal is made to use the model as a tool for process improvement through the planning of deposition strategies which reduce layer variability. This is proposed either as a complement or as an alternative to the closed-loop control systems [177-180].

7.2 Modelling procedure

Different meshes were created for the different simulations presented in this chapter. These meshes were designed and set as shown in Chapter 4 (see Figure 4.12). However, different domain sizes were used in the different simulations, as was required by the deposition operations shown in Figure 7.1.

Figure 7.1. Typical operations of multiple-track formation in laser metal deposition.

The above schematic representation illustrates the nature of the different simulated deposition applications. In the case of lateral track overlapping, individual tracks
were deposited adjacent to each other with a constant offset for the laser beam and coaxial nozzle after each new track. Following the convention of Figure 7.1 the first track was the one located at the left hand side. Offset was given to the right hand side. The deposition of every new track was carried with the substrate being initially at room temperature. For the case of vertical layer stacking, an offset in the vertical direction was given for the laser beam and coaxial nozzle after each new layer. The offset corresponded to the mean height increase achieved in the previous layer. For the case of intersecting tracks, the scanning direction for both tracks was aligned at right angles. The intersection point was located at the middle point of both tracks.

### 7.3 Experimental procedure

In order to verify modelled results, three different sets of experiments were carried out using a laser metal deposition system, which comprises the elements previously described in Chapter 6.

In the first set of experiments, i.e. lateral track overlapping, processing parameters were defined as follows: laser power was set at 730 W, powder flow rate at 0.28 g/s, scanning speed at 10 mm/s and standoff distance at 10 mm under the nozzle tip. At this position, the defocused laser beam produced a spot size of 1.76 mm. Four different quadruple-track layers were produced using four different inter-track offset distances. These distances were defined in terms of the overlap percentage. Further details are provided in section 7.4. Each new track was deposited after the substrate had cooled down to approximately room temperature.

In the second set of experiments, i.e. vertical layer stacking, processing parameters for laser power, powder flow rate and scanning speed were defined as in the first set. Four tracks were stacked in a vertical direction to form a thin-wall structure. A vertical offset distance of 0.7 mm was provided after each track using a manually operated lift, mounted on the CNC table. Similarly, each track was deposited after the sample had cooled down to approximately room temperature.
In the third set of experiments, i.e. track intersection, processing parameters were defined as in the first experimental set. Two tracks were deposited at right angles such that the intersection point and mid-points for both tracks were coincident, forming a cross. Three of these crosses were produced using different scanning strategies. Further details are provided in section 7.6. Similarly, each track was deposited after the sample had cooled down to approximately ambient temperature.

In the corresponding simulations, the beam waist was used as the reference point. It was positioned at the initial coordinates $x = 0$ mm, $y = -7.5$ mm, $z = 0$ mm. At this location, a spot size of 1.76 mm in diameter was matched to the experimental spot size. The scanning speed was defined in the negative $x$ direction. In all cases, procedures, parameters and settings for the simulations were defined so as to match the experimental deposits to which they are compared.

### 7.4 Lateral track overlapping

Typical applications of laser metal deposition are not limited to the overlay of a single track. Applications such as surface coating require two or more tracks to be deposited adjacent to each other with a certain degree of overlap. Figure 7.2 shows the sequence of a quadruple track deposited using a 730 W laser beam being displaced 1.6 mm in the positive Z direction between each track.

In surface coating, shape and dimensions of typical overlapped tracks are not homogeneous. The overlap ratio introduces variations between contiguous tracks which can produce an uneven or irregular layer of variable thickness.

Figure 7.3 shows a cross section of an experimental layer consisting of four tracks produced with an overlap ratio of 0.2. A small difference can be seen across heights of the four tracks. Second to fourth tracks observe a small but gradual increase in height.
Figure 7.2. Deposition sequence of overlapped tracks: numbers one to four. Laser power: 730 W, powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, standoff distance: 10 mm, beam offset: 1.6 mm.
Thus, a gradient is formed in the transverse direction. This gradient is related to the overlapping ratio. If the overlap ratio is such that a portion of the laser beam irradiates a previously deposited track, then this portion of the beam is effectively irradiating an elevated surface. The melt pool generated on this surface is above the substrate level and thus as powder mass is added, the deposited material may rise above the level of the adjacent track. This process is repeated for subsequent tracks and a stepped increase in track height is produced. Thus, differences in height can initially be expected between adjacent rows at higher overlap ratios.

Figure 7.4 shows the measured and simulated cross sections of four layers comprised of four tracks deposited at different overlap ratios, according to the parameters shown in Table 7.1. The order in which tracks were deposited is from left to right. Reasonably good agreement is observed between the experimental and predicted layer transverse profiles in all cases. For the case of the lower overlap ratios, the predicted layer profile shows good agreement although some discrepancies can be observed at the zones where two tracks meet.

Table 7.1. Processing parameters for deposition of overlapped tracks.

<table>
<thead>
<tr>
<th>Case</th>
<th>Overlap ratio</th>
<th>Beam offset (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.0</td>
<td>1.612</td>
</tr>
<tr>
<td>b</td>
<td>0.2</td>
<td>1.289</td>
</tr>
<tr>
<td>c</td>
<td>0.4</td>
<td>0.967</td>
</tr>
<tr>
<td>d</td>
<td>0.6</td>
<td>0.646</td>
</tr>
</tbody>
</table>
It is interesting to observe that even at a theoretical zero overlap condition, Figure 7.4(a), a slight overlapping is actually produced. The valley between tracks is raised above the substrate level by approximately one third of the first track’s height. This
is particularly clear at the intersection between tracks two and three, and between three and four. This effect may be explained by irregularities and fluctuations occurring in the melt pool, as explained in section 6.4. The formation of lateral undulations causes the melt pool to displace to its sides at different points. If deposition is made adjacent to a previous track, these displacements may produce a slight contact between the melt pool and the neighbouring track, thus creating a small elevated region between tracks even at the zero overlap condition. At higher overlap ratios, Figure 7.4(b-d), there is direct re-melting of adjacent tracks by the laser beam. In this condition, the liquid material flows to distribute itself across an area which occupies zones of the substrate and of the adjacent track at the same time. The high overlap ratio of case four, Figure 7.4(d), almost caused the divisions between tracks to disappear. At this high overlap ratio, tracks two to four were effectively deposited over the inclined surface of their preceding track, thus leading to the steep slope to the left hand side of the layer.

Overall, it can be observed that an increase in the overlap ratio leads to a reduction in the layer width which is accompanied by a corresponding increase in the layer thickness. Nonetheless, the transverse layer profile is not smooth. Whereas at low overlap ratios the profile is characterised by the bumped shapes of individual tracks, at high overlap ratios a gradient to the left of the layer is developed and more tracks are required before an even layer thickness is produced. It could be argued that a more regular profile is obtained at a 0.4 overlap ratio, as bumps from individual tracks are reduced and the gradient effect is not as steep as in the case of a 0.6 overlap ratio. The model has been able to capture track and layer shape with reasonable accuracy, accounting for the heat flow and ‘lifting’ effect of interacting tracks. Thus, it could be used as a tool for predicting and reducing the gradient effect in layering applications. A strategy for such a purpose would be to modify the beam offset from track to track, rather than keeping it constant.
7.5 Vertical layer stacking

Laser metal deposition comprises not only the lateral overlap of tracks to form layers, but also the overlay of multiple layers in the vertical direction. The combination of the two can be employed for coating or repair applications requiring thicker layers, or even for the fabrication of three dimensional structures. The so-called ‘thin-wall’ structure has been widely used as a model for studying the behaviour of tracks as they are stacked over previously deposited ones. Studying the formation of this structure has been used, for instance, to test closed-loop feedback control systems [177] and to study thermal cycles and microstructure [181]. Very few attempts have previously been made to model this important structure. Wang et al. [141], modelled a thin-wall structure which was made using conduction heat transfer alone and assuming an idealised and simplified slab shape for the stacking of tracks. Peyre et al. [112] modelled heat transfer in a thin-wall structure using a hybrid analytical-numerical method. Only heat conduction was considered to calculate melt pool temperatures which were based on the use of an enhanced thermal conductivity value and the use of different laser absorptivity coefficients for the analytical and the numerical calculations. No work has previously used a comprehensive fully-coupled model to simulate full three dimensional thin-wall structures.

Using the methodology explained in sections 7.2 and 7.3, a quadruple track deposition, with the tracks vertically aligned to produce a thin-wall structure, was simulated. Figure 7.5 shows the deposition sequence achieved using a 730 W laser beam source. Figure 7.6 shows an alternative cross-section-view of the wall deposition, showing track formation at different times for each layer.

The formation of the thin-wall is characterised by elongation in the melt pool from track two, compared to that developed in track one. This is caused by a reduction in the heat dissipation to the substrate, which leads to an accumulation of heat in the region trailing the laser spot, thus allowing the melt pool to expand.
An increased re-melting of the previous layer occurs as a consequence of the melt pool growth. A slight increase in the melt pool temperature is also observed as the layer number increases, although fluctuations in the pool lead to more noticeable irregularities, such as waves and undulations. A clear irregularity is the gradual fall-off in height at the end of the wall, which is a classic and undesirable defect of any multi-layer deposition application. This irregularity is caused by a phenomenon in which the melt pool quickly contracts after the laser beam is switched off, leading to end-of-track collapses. These are compounded as subsequent layers are overlaid, which intensifies the overall fall-off in height for the thin-wall structure.
Figure 7.7 shows cross sections of the evolving thin-wall structure from layers two to four. Reasonably good agreement is observed between the experimental and modelled shapes. In layer two, Figure 7.7(a), a slight oversized layer is predicted, whereas at layer three, Figure 7.7(b), a closer match can be seen. At layer four, Figure 7.7(c), wall height is slightly underestimated and some lateral wall widening is also observed.

Differences in wall height are thought to occur due to local absorptivity variations on the surface of previous layers which may be caused by local roughness variations induced by the presence of stuck particles. Local absorptivity variations are not considered in the model. In addition to this, irregularities in previous layers such as top waves can lead to local variations in the standoff distance which can modify melt pool size or the mass addition.
7.5.1 Thin-wall deposition for cylindrical structures

Figure 7.8 shows the deposition sequence of a cylindrical thin-wall structure formed by three stacked circled-shape layers of 2.5 mm in radius deposited using a 730 W beam source at a scanning speed of 10 mm/s and powder flow rate of 0.28 g/s.

No vertical offset was applied after each layer. Furthermore, deposition was continuous and no cooling time was allowed between each layer. As a result of this,
heat accumulation in the structure led to excessive mass deposition which caused undulations along the structure, such as would occur in actual deposition. This application of a cylindrical thin-wall structure further illustrates the flexibility and capabilities of the model.

Figure 7.8. Deposition sequence of a thin-wall forming a cylindrical structure. Laser power: 730 W, powder flow rate: 0.28 g/s, scanning speed: 10 mm/s, layer radius: 2.5 mm.
7.6 Track intersection

One of the most well-known problems in laser metal deposition is the variability in surface morphology. This is particularly recurrent in applications involving the intersection of tracks, where a significant excess of deposited mass can develop at the intersection. One of the well-known examples of this was described by Mazumder et al. [182] in their experiment of deposition of two cylinders in tangential contact. In their work, a considerable protrusion was formed at the intersection between the two cylinders due to the laser scanning twice over the contact point.

In order to address the problem of layer height variability, different control techniques have been applied. Characteristic examples of the different techniques which have been used are those of Tang et al.[178] who used a closed-loop control system to regulate the powder flow rate, Mazumder et al.[182] who used a closed-loop system to control the firing of the laser beam, and Fearon and Watkins [183] who used a sensor-less approach which relied on the accurate standoff positioning of a four-port nozzle.

In the first of these approaches, the powder flow rate was controlled at the powder feeder and not at the outlet of the nozzle thus introducing a natural delay between any adjustments made in the powder feeder and changes occurring in the powder stream.

In the second approach, the laser beam was the element being controlled with the use of a sensor-based monitoring system. The laser beam was halted where an excess of mass build-up in the layer was detected according to pre-defined threshold criteria. This approach is arguably more suitable for responding rapidly to any changes in cladding conditions.

In the third approach, the standoff distance was carefully determined so as to achieve that the location where the powder stream begins to consolidate coincided with the maximum desirable track height and thus the powder flow became non-existing.
above this height, hence restricting layer height to grow no larger than what the powder stream allowed. Unfortunately, because restricting the amount of supplied powder results in increasing the melt pool temperature and as a consequence the volume of the melt pool, this incurs in deeper remelting which increases dilution and coarsens the microstructure of deposited tracks, thus reducing their mechanical properties.

The work presented in this section proposes a further approach for reducing layer height variability, which could be either an alternative or complement to the previous two. The objective of this approach is to use the capabilities of the developed model in order to predict and ultimately prevent the formation of excessive mass deposition at critical zones in a layer, such as at intersections or corners. The idea is to first simulate the three dimensional morphology of a given layer. If any major surface irregularities or defects are predicted, then changes can made to processing parameters, e.g. laser power or scanning speed, and the layer simulated again. The process parameters to optimise the layer morphology can thus be predicted and set prior to actual deposition. This approach can be applied to activate/deactivate/regulate the laser beam, the motion system or the powder flow, in order to reduce deposition excess.

Figure 7.9 shows the intersection of two perpendicular tracks. An excess of mass can be observed at the intersection, which results in the appearance of a significant bump in the second track. The maximum height of the layer at this zone is as much as two times the average height along the rest of the layer.

Figure 7.10 shows the deposition sequence of the two tracks as predicted by the model. A good match was achieved between the predicted results and the experimental results in Figure 7.9, both qualitatively and geometrically. The model predicts reasonably well the formation of the bump at the intersection zone. Minor differences can be attributed to localised variations in absorptivity when the laser beam scans over the surface of the first track in the experimental layer.
Chapter 7. Multiple track deposition: analysis and prediction

Figure 7.9. Cross-shape deposition. (a) Experimental single track. (b) Experimental second track.

Figure 7.10. Modelled cross-shape. (a) Single track. (b) Second track.

The model was used to determine an alternative and improved deposition strategy, namely adjusting the laser beam power over a specific period such that deposition was arrested and the height of the layer at the intersection was kept nominally equal to the rest of the layer, as shown in Figure 7.11.
Figure 7.11. Modelled cross-shape. (a) Constant power: 730 W. (b) Power at 365 W during interval 420 – 580 ms. (c) Power at 50 W during interval 420 – 580 ms.

Figure 7.12 shows the longitudinal profile along the second track for the modelled cases in Figure 7.11. At constant laser power, the bump shape was predicted reasonably well as compared to the experimental result. This is shown in the first plot of Figure 7.12. The second plot, in which the laser power was reduced when scanning over the intersection, shows a reduced bump. An adjustment was made to the deposition strategy and the laser power was further reduced such that the bump was practically eliminated, as shown in the third plot. It was found that a strategy consisting of reducing the laser power to 50 W from 420 ms to 580 ms, led to a significant improvement in layer stability.
The three strategies corresponding to the modelled profiles in Figure 7.12 were then applied in practice and longitudinal profiles corresponding to the experimental depositions are shown in Figure 7.13. The experimental outcome for the case where the laser power was set at 50 W during the interval time 420 - 580 ms is shown in Figure 7.13(c). As predicted, the bump at the intersection was considerably reduced and the layer height across the intersection remained within 0.13 mm of the nominal layer height. Slight differences between the modelled and observed results are thought to occur due to local absorptivity variations in the actual sample due to localised roughness or oxidation variations, which are not accounted for in the model.
Figure 7.13. Measured longitudinal profile of different cross-shape depositions. (a) Using constant laser power. (b) Using initial deposition strategy. (c) Using final deposition strategy.

Cooling along the second track is dramatically altered when the laser beam is suddenly reduced to the negligible level of 50 W, as a result of the strategy. This is shown in Figure 7.14, which corresponds to the cases portrayed in Figures 7.12(a) and 7.12(c). Cooling rate was measured during a time of 50 ms, and is shown for different locations on the top surface of the second track. Initially, both cases show a similar behaviour. The abrupt halt in heat input when the laser beam is shut off for the second case, caused an increase in the cooling behind, at and ahead of the laser beam area. A slightly higher rate was measured at the middle point of the intersection, as in this location heat further dissipates to the bulk of the first track. Cooling rates stabilised after the laser beam power was restored to the original level.
Figure 7.14. Modelled maximum cooling rates (solid phase) along the length of the second track of a cross-shape layer.

The optical micrographs in Figure 7.15 reveal the influence of these predicted cooling rates. Images correspond to the intersection of the cross-shape layer. Figure 7.15(a) shows an optical micrograph in the longitudinal direction of the second track for the case of a cross-shape deposited using constant laser power. The area observed corresponds to the intersection bump. Columnar dendrites can be observed in normal orientation to the interface and larger dendrites develop at the interface. Regularly sized grains are found in the bulk of the second track. A clear difference can be observed for the case of a cross-shape deposited using the strategy, as shown in Figure 7.15(b). As a result of rapid cooling, much finer grains are observed in the second track as compared to those in the first track as well as those in the second track of Figure 7.15(a). The interface between both tracks in Figure 7.15(b) is much clearer as the higher cooling rate prevented recrystallisation. The fine grain size in Figure 7.15(b) is a direct cause of rapid cooling due to the laser beam being reduced to 50 W. This is in line with the model prediction. In addition, the orientation of fine columnar dendrites in the upper region of the second track is roughly parallel to the heat flow, which broadly agrees with the model results.
7.6.1 Track direction change (corners)

Another case where a deposited layer can develop unevenness occurs where the deposition path changes direction such as at corners. Figure 7.16 shows a corner deposited using constant laser power and nominally constant scanning speed.

Excessive accumulation of mass developed at the corner, which lead to a protrusion rising above the nominal layer height. This is highlighted in Figure 7.18(a), as well as in the corresponding longitudinal profile in Figure 7.18(b). The model was used to determine a better strategy for uniform deposition at the corner.
After some simulations, it was determined that a possible strategy consisted of modifying the scanning speed and the laser power at the corner. A dwelling time of 30 ms for the laser beam was kept at the corner location to counter the end-of-track fall-off effect. After the dwelling time, the laser beam moves in the perpendicular direction but a laser deactivation time of 60 ms was set. After this, the laser was re-activated at the original laser power. This is depicted schematically in Figure 7.17.

![Figure 7.17. Offline control strategy for corner-shape deposition.](image)

This strategy was then applied in a real deposition case which is shown in Figure 7.18(c). The corresponding longitudinal profile in Figure 7.18(d) presents a smoother layer, although a small bump was still present. This is thought to occur due to the difference in the scanning velocity between the modelled and actual depositions. It is worth noting that a typical CNC motion system experiences velocity changes at any change of tool-path direction such as at a corner. This information was not available for the CNC system used in this work and so in the simulations constant velocity was assumed throughout. Nonetheless, the current results provided an approximately two fold improvement in controlling the layer height at a corner, which helps to demonstrate the proposed pre-emptive deposition strategy.
7.7 Conclusions

This chapter has presented an analysis of multiple-track deposition for the cases of lateral overlapping, vertical stacking and intersection of tracks. Advanced numerical simulations were produced using the flexible model developed in this work, some of which have not been attempted in any previous work. The model was able to simulate layers of realistic three dimensional shapes. Good agreement was achieved with corresponding experimental samples.

In lateral track overlapping applications, or surface layering, it was observed that the transverse layer profile does not hold a constant height. At low overlap ratios, the layer has a characteristic bumped profile, whereas at increasing overlap ratios, the layer tends to develop a transverse gradient. Since the model is able to predict this
behaviour, it could also be used to effectively determine the optimum beam offset to reduce track shape variability in any particular circumstance.

In applications of vertical layer stacking, or thin-wall deposition, an elongation in the melt pool was observed as layer height was gradually increased. This was accompanied by slight increases in the temperature of the melt pool. An effect of fall-off in height at the end of the wall was observed. This was related to end-of-track collapses in the melt pool, which accumulated after each new deposited layer. The model also predicted this phenomenon.

In applications involving track intersections or corner shapes, significant layer unevenness in the form of bumps was observed. The unevenness was caused by excessive mass deposition. The model was used to plan and assess alternative deposition strategies which were used to reduce deposition excess and hence bump formation. Results in cases of both intersections and corners, have shown that careful pre-planning of processing parameters such as laser power and scanning speed, can result in better layer geometry without the need to use sensor-based control systems.

The model could be used for LMD optimisation and improvement through the study and development of improved deposition strategies for various deposition applications which could be implemented in commercial deposition systems. This could be one step further than the CNC tool path and LMD deposition path planning systems that can be found on some current commercial systems.
Chapter 8

Conclusions and future work recommendations

8.1 Conclusions

This thesis presented the development and application of a new CFD model of laser metal deposition which calculates the different fundamental phenomena occurring at the different stages of the process, such as flows of assistive gases in the coaxial nozzle, flow of powder particles through and after the coaxial nozzle, interactions between the laser beam and powder stream through powder heating and laser attenuation, melt pool formation/solidification and mass addition from powder to the melt pool. The integration of these aspects in a unified approach is carried out for the first time. This allows for a robust simulation of the LMD process which incurs in fewer assumptions than previous models. The resulting model is flexible and can be used to simulate a variety of track and layer geometries in a three dimensional environment. This is used for predicting track morphology and providing additional understanding on the processes of track formation.

Numerical and experimental studies of the laser metal deposition process were reported, and concluding remarks were presented in each chapter of this thesis. However, some important outcomes and conclusions are revisited in this section. They are summarised as follows:

- A new flexible model of the laser metal deposition process was developed using CFD software. This model applied a hitherto untried approach of integration of the different stages of the process into a unified structure, considering aspects occurring from the powder stream formation through the
coaxial nozzle, up to the solidification of the deposited track. This work represents a step further from existing numerical works on laser metal deposition.

- A numerical study of the powder stream was carried out with using the powder stream model, which takes into account phenomena of gas and powder motion through and after the coaxial nozzle as well as powder heat transfer to and by the powder. The inclusion of the substrate was a feature which was not considered in previous powder stream models. This allowed the investigation of three-way interactions between the powder stream the laser beam and the substrate.

- The trajectory of powder particles which comprise the stream is mainly determined by wall collisions inside the nozzle cavity and drag forces from the assistive gases. These gases have a slight effect of powder consolidation. Whereas the carrier gas tends to favour better stream consolidation, the inner gas tends to distance the powder stream consolidation further from the nozzle.

- The effect of standoff distance on powder stream formation was found. Mass concentration increases with reducing standoff distance due to the bouncing of particles from the substrate back into the bulk of the stream.

- It was found that standoff distance which maximises the rate off mass deposition does not necessarily coincide with the laser focal plane. The adequate standoff distance should be located at the location of the powder stream consolidation.

- A numerical study of track formation was carried out using the laser metal deposition model. This model has the capability of analysing a variety of deposition applications in different scenarios.

- Track formation was simulated in a variety of situations and the mechanisms of track formation were studied. It was observed that track irregularities such as top waves or lateral undulations are produced by combined phenomena of melt pool fluctuations, uneven mass addition rates and mass redistribution.
Advanced applications of multiple-track deposition were also studied, including layering and wall formation.

- Advanced simulations of track intersection and corner scanning were carried out. Significant layer unevenness due to excess of mass deposition was predicted.

- The model was used to test and simulate deposition strategies which reduced layer unevenness. These were applied successfully in real deposition cases. It was shown that the model could be used as a potential tool for process improvement and as a possible complementing control tool for closed-loop systems.
8.2 Future work recommendations

- The developed model has been used to study the deposition of 316L stainless steel. Additional studies could be carried out using other common deposition materials such as Ti-6Al-4V or Inconel 718. A further step on this direction would be to build a material database. In addition, the model is currently designed to simulate deposition of powder and substrate of equal materials. An area of improvement would be the deposition of two different materials. This would require accounting for mixture of properties and alloying phenomena.

- Curved or inclined surfaces are not uncommon in LMD. Studies could be carried on deposition over inclined surfaces, as well as on horizontal surfaces or deposition in vertical from bottom situations. Moreover, the deposition of overhang features could also be investigated.

- The experimental observations revealed the presence of unmelted particles stuck on the deposited track. The model could be improved to account for this phenomenon, which would allow to predict splatter formation and micro roughness.

- The wire feed technique in LMD is still popular. The replacement of the powder stream with a wire rod as a mass source could be implemented in the model. This would result in a new comprehensive model of LMD using wire, which could also have applications in laser welding.

- The capabilities of the current model for accurate three-dimensional morphology prediction and heat transfer could be used as input for further modelling of residual stresses in the deposited track and original substrate.

- A promising area of further work would be to carry out additional studies of geometrical deposition control using the developed model. This could potentially lead to the creation of a knowledge database of best-deposition-strategies which could be implemented in commercial LMD systems. In addition to this, the control capabilities using the model could be expanded to other areas such as solidification control.
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