CHAPTER 1

Introduction

1.1 Background

There are various surface treatment processes, like alloying, heat treatment and mechanical working [1], to improve the surface properties of metallic mechanical components which can work under high temperature, pressure, and adverse chemical atmosphere. Among these processes, alloying offers maximum variations, but is sometimes not economically justifiable as some of the alloying elements are not so cheaply available. Apart from the economic factors, improving the bulk properties was not technically necessary also, as most of the mechanical failures start from the surface of the material. Wear due to repetitive sliding friction in engine pistons and valves, erosion in turbine blades, corrosion in under-sea water structures and IC engine cylinders, all start and spread from the surface only. Several coating technologies developed with time to improve the surface qualities such as resistance to corrosion, erosion, abrasion, wear; to improve hardness, red hardness, high temperature strength, impact strength etc. The main branches of metallic coatings in the first half of the last century were hot-dipping, cementation, mechanical cladding, electroplating, vapour deposition and metal spraying [2]. These are still very important methods of metallic coatings to improve surface properties. Among these, the metal spaying method can be thought of as the predecessor of the laser deposition of metals, the topic of this thesis.

More focused research revealed that in most of the cases, not the whole surface but some localised part of the surface initiates failure and degrade the performance of the component. Instead of replacing the whole component, its repair and reuse had enormous commercial promise. Hence localised repair and improvement of the part became an important practice for the manufacturing industry. Apart from coating a virgin surface, metal spraying systems with conventional heat sources (flame, plasma arc, electric arc etc.) are also used in the repair shop to build up worn out or undersized parts.

Due to low energy density of flame/arc, the proportion of heat that goes to the base material is much higher, particularly during deposition of high melting point alloys. Thus, distortion of the base material and dilution of the deposited material are much higher with conventional metal spraying systems. These problems become acute for smaller components.

Development of high energy density sources such as electron beam, ion beam and laser beam during the second half of the last century helped in the emergence of new technologies based on these energy sources which could minimise the above mentioned problems to a great extent. Laser became one of the promising energy sources in this regard. In general, the use of a laser beam in surface treatments offers several advantages over conventional heat sources [3–5]:

- The energy supply can be well controlled. Several beam intensity profiles can be generated by optical arrangements.
- Very localised treatment is possible.
- Total heat input is low, resulting in minimal distortion.
- The heating and cooling rates are high, resulting in a fine microstructure and/or metastable phases.
- The treatment is a non-contact process. There is no tool wear, nor any mechanical force on the workpiece.
- Less after-machining, if any, is required.
- The process depth is well defined.
- Relatively easy to automate.

1.1.1 Laser surface modification processes

There are several laser surface modification processes based on basic mechanisms of heating, melting and vapourisation. The laser beam can vapourise, melt or just heat up a metal with or without phase change, depending upon the power density and laser-material interaction time. Various laser surface modification processes are shown in Fig. 1.1. Gross working range of power density and interaction time for a few laser surface modification processes are shown in Fig. 1.2. This research work falls within the group of surface modification technologies with material addition in the melting range. The additional material is generally supplied in the form of metal/ceramic powder.

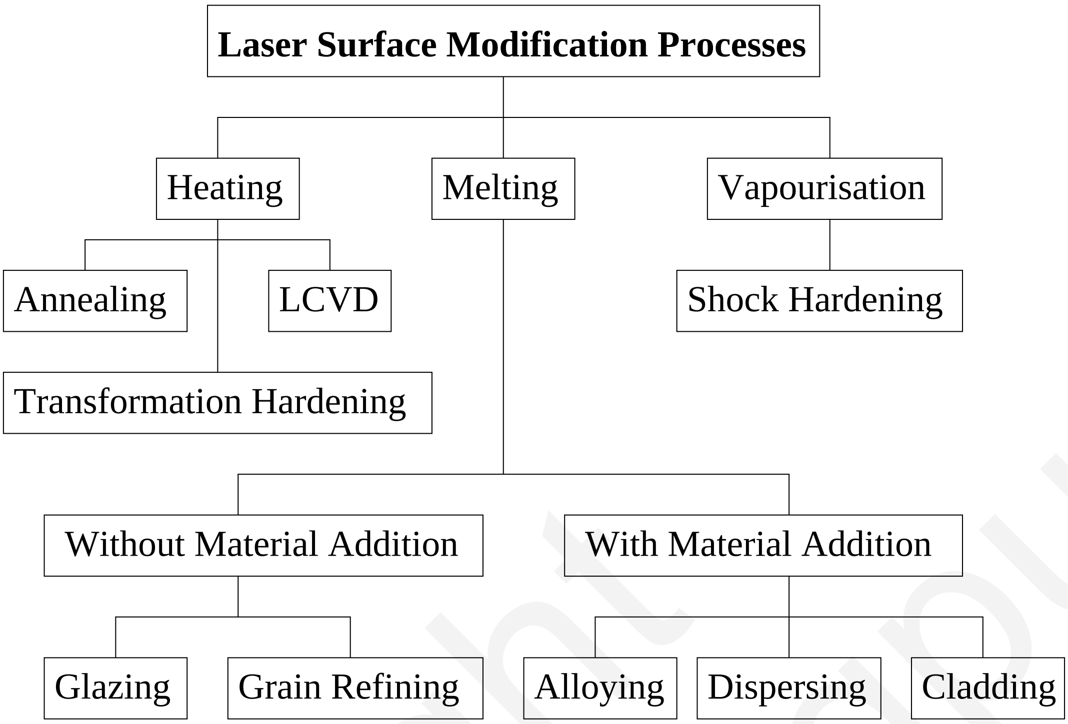

Figure 1.1: Various laser surface modification processes

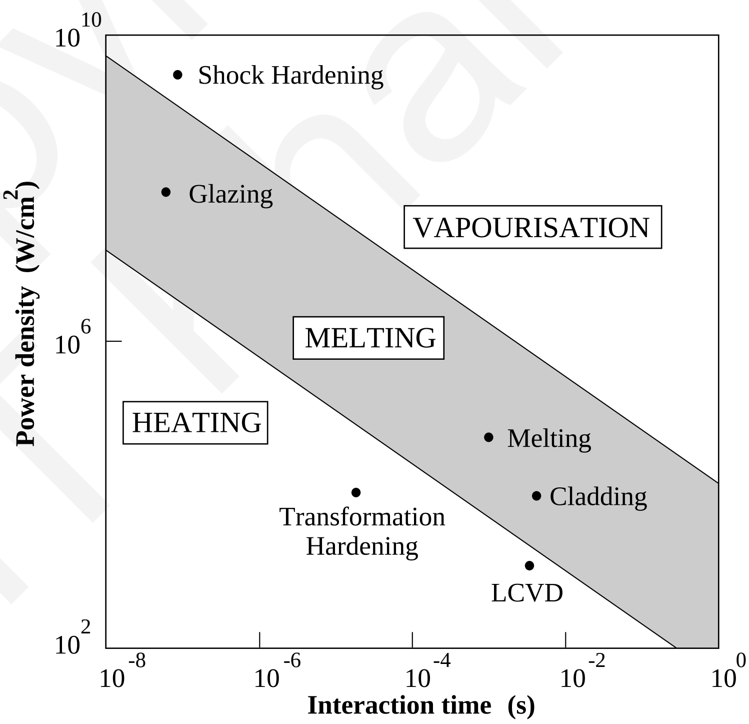

Figure 1.2: Power density and interaction time for laser surface modification processes [4]

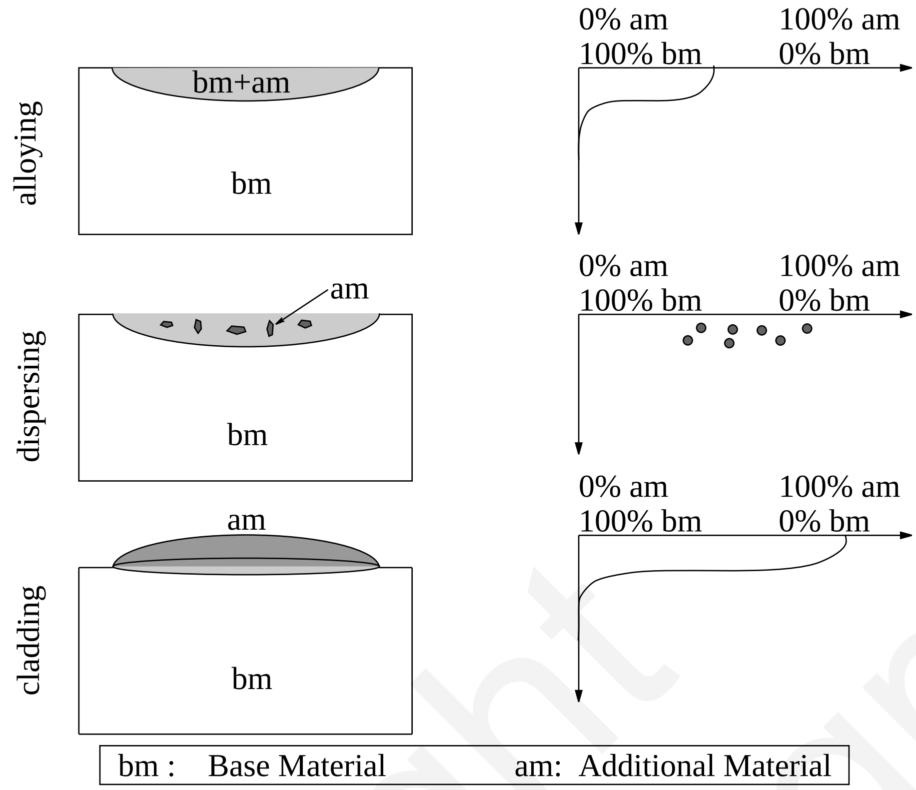

Figure 1.3: Different laser surface modification processes with material addition. The vertical axis in the right-side figures indicates the percentage of added material (am) in the base material (bm) with depth at the centre.

There are broadly three types of laser surface modification technologies with material addition as depicted in Fig. 1.3, such as (1) Laser alloying, (2) Laser dispersing and (3) Laser cladding.

1. **Laser alloying:** In laser alloying, the additional material completely melts and fully dissolves in the comparatively large substrate melt.

2. **Laser dispersing:** In laser dispersing, the additional material in the form of particles does not melt or partially melts and remains as dispersed solid particles after the substrate melt solidifies. The reasons for not melting may be due to large particle size of the additional material, its high melting temperature or less process time.

3. **Laser cladding:** In case of cladding, melting of both substrate as well as the additional material are essential for strong metallurgical bond but the substrate melting is required to be as little as possible for minimum dilution of the coating layer. The thickness of a single clad layer may vary from 0.1 to 2 mm [6].

It is to be noted that laser cladding also adds geometrical dimensions to the substrate apart from modification of surface properties. Therefore, for the dimensional repair of worn out or corroded components along with surface modification, laser cladding is suitable. In this regard, laser cladding offers some advantages over conventional thermal coating techniques [3, 5, 7, 8]. The combination of a controlled minimum dilution of the substrate by the coating material, and a very strong fusion bond between them, is a unique feature of laser cladding. Porosity in the coating can be prevented entirely, and a homogeneous distribution of elements can be achieved .

1.1.2 Techniques of metal deposition

Depending upon the material addition techniques, basically there are two methods of laser deposition of metals:

- Two stage process, and
- One stage process.

Two stage process

In two stage technique the material to be deposited is preplaced over the substrate and then the laser is scanned over it. Laser melts the preplaced material layer as well as the substrate which on solidification forms a deposited layer with strong metallurgical bond with the substrate. Examples are the laser melting of flame and plasma sprayed layers [8–10], preplaced powder [11–17] and preplaced plates or chips [18].

One stage process

In one stage method, the material to be deposited, and the laser energy are supplied together onto the substrate. The process starts with the formation of a melt pool on the substrate. Simultaneously, coating material is fed into this pool and it melts; a strong fusion bond between the coating material and the substrate is achieved immediately. Two methods of material feeding are available:

- wire feeding, and
- powder feeding

Wire feeding [19, 20] can be useful for the cladding of rotationally symmetric products that can be clad in one continuous track.

The injection of powder into a laser generated melt pool is a much more common method compared to wire feeding [21, 22] or preplaced method [6]. This method is also called ‘blown powder laser cladding’ [4]. This method is more flexible; it allows the on-line variation of clad dimensions and composition. Powder injection cladding is a more robust method than wire cladding because there is no direct contact with the melt pool, and the laser beam can pass through the stream of powder particles instead of being obstructed by the wire. Many more elements and alloys are available as powder than as wire.

1.2 Laser Deposition of Metals with Powder Feed

Laser deposition of metals with powder feed is basically the blown powder laser cladding process. The working principle of the blown powder laser cladding is melting a substrate surface by a moving laser beam and adding pneumatically delivered metal/ceramic powders into the melt pool which subsequently melt; as the laser beam moves away the melt solidifies to form a continuous built-up layer over the substrate. Due to the simultaneous melting and then resolidification of a thin substrate layer as well as the additional material, a strong metallurgical bond forms between the substrate and the build-up layer. Materials are deposited in a single layer on the scanning track. For wider areas, adjacent tracks are scanned as shown in Fig. 1.4. For three dimensional manufacturing, layer-by-layer deposition method is practiced, i.e. several layers are deposited, one upon another, to get the height as shown in Fig. 1.5.

1.2.1 Applications

Laser deposition of metals with powder feed is one of the emerging technologies having multiple applications in manufacturing industry; ranging from surface repair and modification with superior coating over a mechanical component to direct fabrication of three-dimensional metallic components [23]. Two broad groups of applications are:

- Surface repair & modification applications, and
- Low volume manufacturing applications.

Surface repair & modification applications

From its early developmental period, surface repair and modification remain as one of the main areas of thrust for laser material deposition with powder feed. Injecting pre-alloyed fine metal powders in a melt pool on a substrate by a moving laser source, and formation of controlled microstructure on solidification are the keys to surface modification [24]. There is a large body of literature reporting these studies [25–33]. These studies show the formation of fine microstructure [27], quasi crystalline structure [28], metastable phase [29], inter-metallic compounds [30], glass [31] etc., resulting in improved mechanical and chemical properties like higher hardness and erosion resistance, lower coefficient of friction, improved Young's modulus and higher corrosion resistance [32, 33].

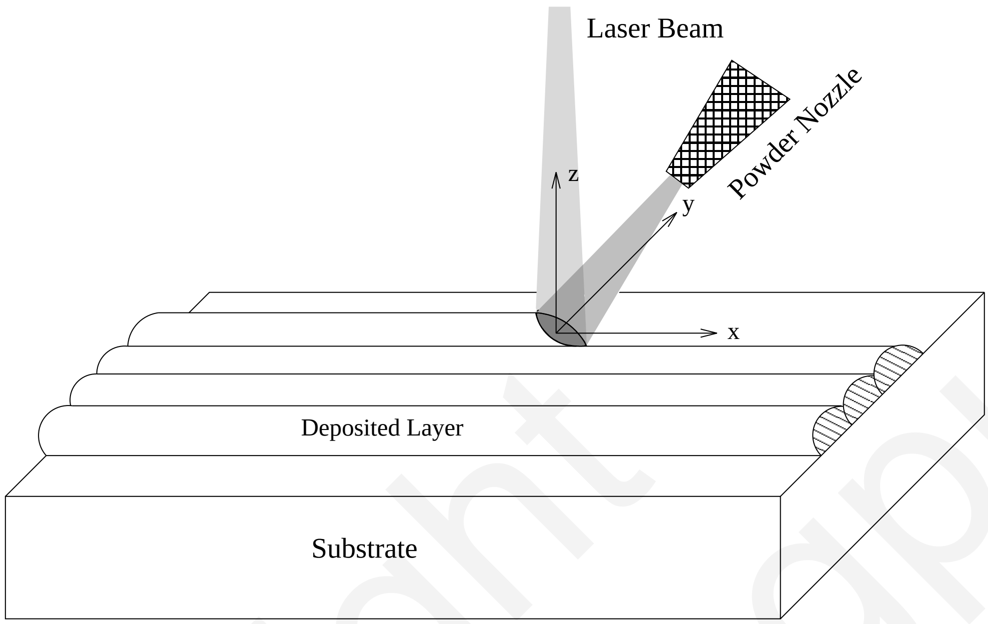

Figure 1.4: Deposition of adjacent tracks

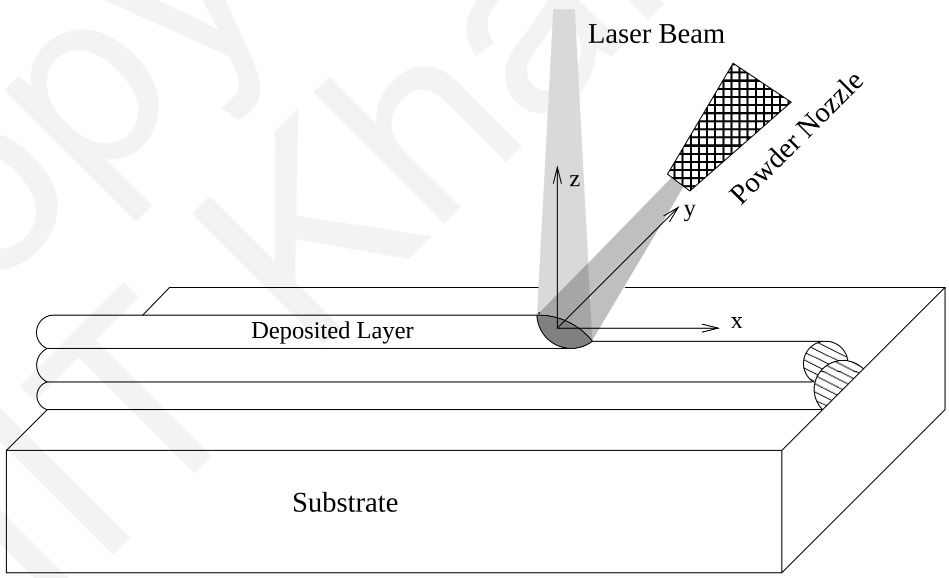

Figure 1.5: Layer-by-layer deposition

The applications are vast, ranging from repair and modification of automotive valves, valve seats, extruder screw, turbine blades to aerospace components [34–38].

Low volume manufacturing applications

Three-dimensional metallic mechanical components of small size from simple to complex geometry can directly be fabricated by layer-by-layer deposition of metal powder by laser beam [23, 39, 40]. Direct light fabrication (DLF) and laser engineered net shaping (LENS) are such technologies based on this principle [41, 42]. The computer controlled deposition path is guided directly from a CAD solid model of the component in these technologies. The components are fabricated near net shape and require very little after-machining. Integration of laser deposition of metals with powder feed system with CNC milling, EDM machining or other techniques gave birth to hybrid technologies such as shape deposition manufacturing (SDM) [43] which can directly make a functional product. These components have many unique properties derived from the advantages of finer grain size due to rapid solidification. Abrupt as well as gradual change of composition are possible by varying the powder material during the process. Fabrication of functionally graded material and joining of dissimilar materials by gradual change in composition are among many uses of these technologies [44, 45].

1.3 Literature Review

Most of the studies on laser material deposition with powder feed generally deal with the metallurgical aspects — the relationship between the microstructure and properties, usually hardness & corrosion resistance of the built-up surface layer for a series of added materials [25–33]. Parametric studies relating the process parameters such as laser power, scanning speed, powder feed rate etc., which ensure a successful deposition in a desired way such as complete mixing in alloying, low dilution in cladding etc., are generally missing. Very few literature are there in this regard. The literature reviewed during this research work is spread through out this thesis. However, in this chapter, in the following section literature on parametric studies are presented.

1.3.1 Experimental aspects

It is of great importance to find the range of process parameters for a low dilution, pore free and continuous deposition. Steen [4] has given one process parameter chart, showing power density and interaction time, for general laser surface modification processes (see Fig. 1.2). For cladding of Ni-Al bronze on Al alloy, Liu et al. [46] have given a process chart on laser power requirements for different build-up heights and showed that the laser power required for good deposition is in between discontinuous track and large dilution range. Qian et al. [47] and Sun et al. [48] have shown that increased powder flow rate causes lower dilution and higher build-up height. Frenk et al. [49] have shown that build-up height increases with powder feed rate and decreases with scanning speed; global absorption and attenuation of the beam increase with powder feed rate. Kathuria [50] has shown that shorter interaction time produces finer microstructure and higher hardness. Oliveira et al. [51] have reported the process window for thick deposition of Ni-Cr based powder on a steel substrate using co-axial laser cladding by continuous Nd-YAG laser. Their studies show that an optimal laser power and powder particle velocity zone exist for efficient deposition; build-up height increases linearly with powder feed rate & the powder deposited per unit distance along the scan direction falls within a band; and deposition width increases linearly with laser power.

1.3.2 Thermal modelling aspects

Experimental investigations are generally very expensive and time consuming (but more accurate) and true for the set of experimental input parameters. There is necessity of theoretical investigations. There are extensive theoretical studies on surface melting, alloying and welding with laser or other sources of energy in the literature spanning from early 1980's till date [52–65]. In a recent paper Mackwood and Crafer [66] have reviewed more than two hundred papers on laser welding and related processes. These are very useful articles in developing models of several thermal processes and studying temperature profile, melting-solidification, melt pool convection, solute distribution etc. The main difficulty in modelling laser deposition of metals with powder feed lies in its complex build-up geometry. There are very few articles dealing with this problem.

Kar and Mazumder [67] developed a one dimensional diffusion model to determine the composition of extended solid solution formed due to rapid cooling. This model considered mass and heat transfer by diffusion in a semi-infinite solid. Hoadley and Rappaz [68] developed a two-dimensional finite element model considering conduction mode of heat transfer. Powder addition into the melt pool is considered as heat sink and the melt pool free surface is modeled as circular arc in this model. Picaasso et al. [69] proposed a rather simple model from global energy balance among beam, powder and substrate. In this model the melt pool shape is calculated using a three dimensional analytical model assuming that the powder is predeposited. Zhao et al. [70] have solved a three dimensional conduction equation for the temperature field using finite element method to find out the effect of various process parameters (laser power, scanning speed and powder preheat) on dilution. By a similar approach Toyserkani et al. [71] have presented a characteristic curve representing effective energy versus effective powder deposition densities for good quality deposition. Hu and Kovacevic [72] have used ANSYS finite element software to solve three-dimensional heat conduction equation to predict the melt depth, length, temperature and cooling rate for laser based additive manufacturing. Han et al. [73] have solved two-dimensional fluid flow and energy equations to predict the peak melt pool temperature and melt pool length for different laser powers. Level set algorithm is employed to get the melt pool free surface shape in this model. In a recent paper Pinkerton and Li [74] have used a simpler model based on mass and energy balances for one-dimensional heat conduction in the substrate to explain why deposition width is more than the melt pool width for higher powder deposition rates.

Studies on the effect of laser-powder interaction

Before reaching the melt pool the powder particles cross the laser path. The effect of this interaction on the overall process have got attention of the researchers from the early 1980's. Weerasinghe and Steen [75] considered powder heating due to absorption and the shadowing effect of powder particles over the substrate. They found slight distortion of the energy distribution profile and no significant increase in total absorption by the workpiece. Considering optical and thermal processes, Pustovalov and Bobuchenko [76] have shown that overall deposition efficiency can increase by increasing powder preheating. Considering the shadowing effect of powder particles over the substrate and neglecting the intersecting shadows, Picaasso et al. [69] have found that total attenuation and heat absorbed by the powder are proportional to the powder feed rate and inversely proportional to the average powder radius and velocity. Fu et al. [77] have extended this approach by considering Gaussian beam and a diverging powder stream along the gas jet coming out of a nozzle whereas Liu et al. [78] have considered Gaussian distribution of powder particle number density [79]. The attenuation was found to be increasing exponentially with powder feed rate, radius and velocity. Frenk et al. [49] have arrived at a similar solution as that of Picaasso et al. [69] for power attenuation from the first order approximation of the exponential relation using Mie's theory [80] of scattering of light through a particle cloud.

Studies on the melting of powder particles in melting-solidification zone

Powder particles after striking the surface of the melt pool are carried inside the melt pool by the pool convection. Depending on the particle velocity and the local melt pool temperature powder particles melt instantly/gradually inside the melt pool. The rate of melting of these particles depends on the rate of heat transfer from the surrounding superheated liquid. Melting of a metal spherical particle in a superheated fluid of same or different materials has been studied extensively. Kreith et al. [81] performed an experimental and theoretical investigation of rotating metallic spheres in liquid mercury and suggested a correlation for forced convection. Hsu [82] has given expression for the theoretical Nusselt number for the cases of heat transfer to liquid metals flowing past a single sphere, and past an elliptical rod considering potential flow around the solid object. Anselmo et al. [83] have presented the theoretical and experimental results on the melting of both fully and partially immersed silicon spheres. Numerical and experimental investigations on the melting time of solid sphere immersed in liquid aluminium and steel have been carried out by Argyropoulos and Mikrovas [84], Argyropoulos et al. [85]. They have given correlations for forced and natural convection based on the measurement of the melting times of the spheres. More recently Melissari and Argyropoulos [86, 87] have conducted an extensive numerical and experimental analyses of the melting of pure aluminium and AZ91 magnesium alloy in the liquid bath of same material. They found out the melting time of the immersed sphere by recording the change in electrical resistance between the tip of a wire inside the sphere and the bath. In another paper Melissari and Argyropoulos [88] found the correlation for forced convection heat transfer by correlating the Nusselt number to Reynolds and Prandtl numbers. Although they have considered a wide range of fluids with different Prandtl numbers for simulation but the study was limited to small values of Stefan number signifying the low superheat ($\leq 100^0$C) of the surrounding liquid. However in practice (e.g. laser cladding process) surrounding fluid temperature can go close to evaporation temperature resulting in higher value of Stefan number.

1.4 Process Parameters and Research Issues

Laser deposition of metals is a complex technique defined by a plurality of parameters. The major ones among these are given in Table 1.1. Optimizations of the input parameters with respect to the output parameters are the subject of research. Experiments as well as mathematical modelling are required for this purpose. This research addresses some of the parameters listed in the Table 1.1.

1.4.1 Outline of the thesis

Development of a heat transfer model for parametric studies on laser deposition of metals with powder feed is the main work of this thesis. This thesis consists of seven chapters. A brief description of each chapter is given below.

Chapter 1: This chapter consists of general background of historical necessity of development of laser surface modification processes, overview of laser surface modification processes in general & laser deposition of metals with powder feed in particular and literature review.

Chapter 2: A theoretical model for laser deposition of metals with powder feed, based on thermal processes, is developed in this chapter. Phenomena like absorption

Input parameters	Output parameters
(i) *Process parameters* • Laser power and beam intensity profile. • Scanning speed. • Powder feed rate. • Size and distribution of the powder particles. • The point and angle of injection. • Powder-gas and shielding gas flow characteristics. (ii) *Property parameters* • All the thermo physical properties (α, T_m, Δh_{sl}, ν, σ, $d\sigma/dT$, β etc.).	• Deposition rate • Deposition geometry (Height, width etc.) • Dilution level • Melt pool temperature • Microstructure quality • HAZ • Residual stress

Table 1.1: Important parameters for laser deposition of metals with powder feed

of laser energy, formation of melt pool, addition of preheated powder to the melt pool, its subsequent melting, resolidification & formation of build-up layer and melt pool convection due to the surface tension gradient over the melt pool free surface & density gradient in the bulk of the melt pool have been considered. The governing equations along with boundary conditions are developed and these are normalised using appropriate scaling analysis.

Chapter 3: A simplified conduction model has been deduced from the generalised governing equations developed in Chapter 2. The dimensionless governing equation for the conduction model is solved by finite volume method in a multiblock non-orthogonal grid system with collocated variable arrangement [89]. Role of different process parameters such as laser power, scanning speed, powder deposition rate and laser beam intensity profile is investigated using two dimensional and three-dimensional conduction models and a process map, showing the working range of scanning speed and powder mass deposition rate for a feasible laser cladding process, has been developed in this chapter.

Chapter 4: In this chapter, the coupled fluid flow and energy equations are solved for a two dimensional simplified case by finite volume method using SIMPLE [90] algorithm in a multiblock non-orthogonal grid system with collocated variable arrangement [89]. The role of melt pool convection on the process characteristics, dilution and temperature field, is investigated and a process map has been developed. Since the solution of three-dimensional Navier-Stokes and energy equations are time comsuming, only a few set of input parameters have been considered for this case. Based on the three-dimensional results a process map is presented which predicts the form and scale of the microstructure of the solidifed clad track.

Chapter 5: In this chapter the heat transfer characteristics of melting of a metal spherical particle in its own liquid have been presented. The coupled fluid flow and energy equations are solved for a two dimensional axisymmetric case by finite volume method using SIMPLE [90] algorithm in a multiblock non-orthogonal grid system with collocated variable arrangement [89]. A critical number comprising Reynolds number, Prandtl number and Stefan number has been introduced below which effect of convection on the heat transfer rate can be entirely neglected without significant error.

Chapter 6: In chapter 3 and chapter 4 it is assumed that the solid powder particles are distributed uniformly after injection into the melt pool and thus behave as uniform heat sink during melting. This assumption may not always be true. Therefore, in this chapter, we have accounted for the non-uniform melting of powder particles inside the molten pool. For calculating the melting rate of a solid particle in the melt pool we have used the correlation equation obtained in chapter 5.

Chapter 7: Summary of the whole thesis is in this chapter. The basic conclusions are drawn. The direction of future work has been presented.

Some of the results of Chapter 3, Chapter 4 and Chapter 5 are published in references [91–95].