Chapter 2

Literature review

2.1. MATERIAL SELECTION

Selective Laser Melting (SLM) process is a versatile process, suitable for processing wide range of metal, ceramic, composite as well as polymer materials. In which all the materials are supplied to the laser melting machine in the form of powder. Material parameters stated to be important for the laser melting process are viscosity, surface tension, particle size distribution, particle shape, thermal conductivity, specific heat, melting temperature, absorptance and emissivity (Agarwala et al. 1995). The goal of scientific research in SS316L is to provide the fundamental knowledge required to enable advances in future biomedical and surgical implants.

Stainless steel AISI 316L is still the most used alloy in all implants division ranging from cardiovascular to otorhinology. Montasser (2012) reported that the 316L stainless steel has been widely used in both artificial knee and hip joints in biomedical applications. The implants division and type of metals used are listed in Table 2.1. Moreover the average lifetime of artificial hip joints is about 10 years due to aseptic loosening of the femoral stem attributed to polymeric wear debris; however, there is a steadily increasing demand from younger osteoarthritis patients aged between 15 and 40 years for a longer lasting joint of 25 years or more. Ruidi et al. (2011) fabricated 316L stainless steel part with a pore gradient structure using SLM technique and reported that the tissue cell growth is favored with a high porosity. The properties of 316L stainless steel also plays a major role with respect to biomedical application which is mainly depending on the compacting pressure, melting temperature and the melting atmosphere as reported by Montasser (2012). Many researchers suggested that the porous 316L stainless steel is suitable for hard tissue implants (Hussein et al. 2013, Ruidi et al. 2012, Agarwala et al. 1995, Montasser 2012).
Table 2.1. Implants division and type of metals used. (Hendra et al 2011)

<table>
<thead>
<tr>
<th>Division</th>
<th>Example of implants</th>
<th>Type of metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular</td>
<td>Stent Artificial valve</td>
<td>316LSS; CoCrMo; Ti6A14V</td>
</tr>
<tr>
<td>Orthopedic</td>
<td>Bone fixation (plate, screw, pin) Artificial joints</td>
<td>316LSS;Ti;Ti6A14V CoCrMo; Ti6A14V; Ti6A17Nb</td>
</tr>
<tr>
<td>Dentistry</td>
<td>Orthodontic wire Filling</td>
<td>316L SS; CoCrMo; TiNi; TiMo AgSn(Cu) amalgam, Au</td>
</tr>
<tr>
<td>Craniofacial</td>
<td>Plate and screw</td>
<td>316L SS; CoCrMo; Ti; Ti6A14V</td>
</tr>
<tr>
<td>Otorhinology</td>
<td>Artificial eardrum</td>
<td>316LSS</td>
</tr>
</tbody>
</table>

Fig. 2.1. Selective laser melting working process (Encyclopedia Britanica 2012)
2.2. LASER MELTING PROCESS

Traditionally, SLM is an additive manufacturing process that uses a laser to fuse powder materials together. The industry standard term (chosen by the ASTM F42 standards committee) is laser sintering, although this is acknowledged as a misnomer because the process fully melts the metal into a solid homogeneous mass. The goal of additive manufacturing process is to produce a finished product from a three-dimensional (3D) CAD model in a single manufacturing process (Yan et al. 2014). Due to limitations in SLM, thin films cannot be produced based on the laser spot size and other effects. SLM can provide another technique for producing these types of parts without needing to braze or solder. Further, this process is carried out in a controlled atmosphere container with two chambers. One chamber is the feed chamber and the other is the build chamber. The feed piston is raised and the leveling roller transfers the powder to the build chamber. After each scan of the infrared laser, the building piston is lowered and the next layer of powder is transferred. This is done layer by layer until the part is completed as shown in Fig (2.1). Many different types of laser melting have been developed over the years. Some of the first processes used photosensitive resin, which created very brittle parts that could be used as visual aids and indirect moulds for casting (Katz and Smith 2001). Other version of the process used a metal-polymer powder mix to produce parts. The polymer had to be used as a binder for the metal powder and needed to be removed after laser melting. The porous structure was then filled with copper or bronze to fill the space left by the polymer (Erasenthiran and Dickens 2003). Further, a composite blend of metal has also been produced using this technique where one metal has a low melting temperature, while the second has a higher melting temperature. The lower melting point material would act as the binder in the matrix and hold the un-melted powder together (Su et al. 2013, Wang et al. 2012).

Many problems were associated with these processes, from brittleness to lack of heat resistance. For SLM to make fully functional components, the process needs to produce
parts that are similar in physical and chemical properties as the traditional powder metallurgy processed materials. This required that single metal powders be used with no binder. The powder would then have to be directly melted and fused to other layers of previously melted powder as reported by Morgan et al. (2001).

Full melting has the main advantage to produce almost full dense products in one step. Nevertheless, it also has general problems like internal stresses, part distortion due to high temperature gradients and shrinkage. Typical process defects associated with SLM processes are porosity, residual powder and non-connected layers. However there is a more substantial problem is balling phenomenon (Yasa and Kruth 2011). Balling is the formation of small spheres approximately the diameter of the beam and may result in the formation of discontinuous scan tracks (Agarwala et al. 1995). The risk of balling of the melt pool may also result in bad surface finishes (Kruth et al. 2005, Yasa et al. 2011). The processed material can also suffer from the effects of vaporization. Using a shielding atmosphere or pre-heating the powders to higher temperatures may help to overcome these problems. Also powders with bimodal distributions for optimum packing and using additives to reduce surface tension also suggested for decreasing process defects (Agarwala et al. 1995, Wang et al. 2011). The other form of problem in SLM process is non-uniform density in powder bed due to balling phenomenon. Su et al. (2013) and Tolochko et al. (2004) stated that the laser initially scans the surface of the cold powder bed, there is an initial ball that forms from the high surface tension of the bed. The surface tension creates a steep contact angle, limiting the wettability of the liquid pool (Agarwala et al. 1995, Bourell et al. 1992, Beaman et al. 1998, Marcus et al. 1992, and Barlow et al. 1995). In addition, the oxides in the powder also influence the surface tension as reported by Morgan et al. (2004) and Simchi et al. (2006). The high surface tension causes the bead to form on the surface of the powder bed instead of penetrating into the bed. The beads then begin to develop pores in between each pass, because the roots cannot be reached by the laser (Zhang et al. 2007). The initial balling and any other balling that can occur in the track will deplete powder from the surrounding powder bed, which leads to more problems with non uniform density, as seen in Figure (2.2).
Further, thermal stresses are major issues in laser melting process. Most often this means that the part is not dimensionally correct and needs further machining to be a useable part. Many thermal issues are inherent with the process; some thermal issues are dependent on the part being made. The issue of curling has been very apparent in tracks that are made without a support base plate. When parts require long tracks to be made, there is an issue with distortion, cracking, and Christmas tree defects (Simchi et al. 2006). The non-uniform heating causes these problems to occur. Cracking is commonly seen and it is possible to have the delaminating of layers from the thermal stress. Preheating the bed has shown to help alleviate the effect of the thermal stress (Morgan et al. 2001).

Beal et al. (2006) found out that by using different laser strategies may lead to reduce thermal stresses, porosity and shrinkage. Maintaining part accuracy is another factor which makes further complications when using high power lasers. Despite the advantages of the SLM technologies, some restrictions exist regarding the use of different metal materials and the achievable building speed. Therefore, the economic use of this technology is limited in the aerospace industry and in the medical technology. For an industrial use, it is necessary to solve the described difficulties. The factors that need to be considered when selecting and processing unique materials and the research that has been carried out to date, focusing on laser melting, which is one of the

---

Fig. 2.2 Balling phenomena during SLM process (a) cross section, (b) top surface
most established and widely used additive manufacturing approaches. It also examines
the limitations of current laser melting systems in relation to the processing of different
materials. The effect this has on the development of new and improved materials for laser
melting is evaluated, in addition to the difficulties experienced in maintaining consistency
with current laser melting (Goodridge et al. 2012).

Song et al. (1994) reports on the process development of SLM for direct melting of
bronze as a low-melting metallic powder on a laboratory test facility. The experimental
investigations with single spots, lines and layers on the powder bed indicate successful
direct melting of bronze powder without polymer binder or preheating. Researchers also
found that besides the process parameters such as laser beam power, scanning speed and
hatching distance, material parameters such as particle size distribution exert an influence
on the melting behaviour and should, therefore, be considered in terms of further process
development. Further, they indicated that the principle of SLM for metals is based on
melting and not on diffusion. Because of the counter tendency existing between surface
quality and curl, any attempt to optimize the process must involve a trade-off between
these parameters. Besides the process parameters, powder parameters such as particle
size distribution, homogeneity in the particle size, density of the powder, constituent of
the powder influence the melting behavior and should, therefore, be considered in any
effort to enhance surface quality. Further process development of SLM will require
optimization of the process itself as well as of material parameters.

2.3. PHYSICAL ASPECTS OF LASER MELTING PROCESS

2.3.1. ENERGY DENSITY

The geometric characteristics of the part are influenced by the laser energy density.
Rüsenberg et al. (2011) reported that the maximum part density is obtained at higher
energy densities. Yusoff et al. (2008) stated that in order to produce a good functional
SLM part, it is important that the powder on the part bed surface receives a sufficient
amount of energy through the laser melting process. The reason is that sufficient energy
density is produced when the energy input increases and is applied to the part bed
surface, this in turn causes a higher temperature at the powder interface and thus creates a
better melt flow. However, too high an energy density causes a hard part cake, which in
turn results in the operator having difficulty in taking parts out of the build as well as increased surface roughness, and a light brown colour being seen on the part surface due to overheating.

2.3.2. ABSORPTIVITY
Absorptivity of a material can be defined as the ratio of absorbed radiation to the incident radiation. When the incident laser beam comes into contact with the powder layer, part of its energy is absorbed and another part is reflected. The factors which affect the absorption of heat energy are the wavelength of the laser beam, the powder material, homogeneity in the particle size, density of the powder, constituent of the powder etc, (Verhaeghe et al. 2009 and Gusarov et al. 2009).

The researchers also describe the laser melting of a single-component powder is a rather complicated process because the processing window of melting is very narrow. The particles either do not melt at all for a given power density or undergo a complete melting at a higher power density. The liquid surface melts contracts to minimize its surface energy, resulting in resolidified droplets. This phenomenon becomes more pronounced for materials possessing a high melting point. For this reason, high-melting point powders are usually blended (mixed) with low-melting point binding powder materials. Unlike dense materials, only part of the incident radiation is absorbed by the outer surface of the particles in loose powder materials. Another part of the radiation penetrates through the inter-particle spaces (pores) into the depth of the loose powder interacting with the underlying particles (Tolochko et al. 2000).

The laser beam interaction with the powder bed at SLM consists of coupled radiation and heat transfer in a thin powder layer deposited on a dense substrate. It was observed that the melt pool formed around the laser beam contacts the substrate by its central part only. Furthermore Gusarov et al. (2009) validated the model for coupled radiation transfer and thermal diffusion with experimentation. The absorbed fraction of laser energy $1 - \rho =0.3$ was used in calculations is expected to be the most uncertain model parameter where $\rho$ is the reflectivity of the dense material. It was noted that the absorptivity of metals
generally tends to increase with temperature. The limitation of this model is that the negligence of the Marangoni convection in the melt pool. Also the researchers recorded that the laser radiation can penetrate into powder by an open pore system until the substrate and create a volumetric heat source. The melt pool formed around the laser beam contacts the substrate by its central part only. Such a complex shape of the melt surface can produce its deformation driven by surface tension. Moreover, the balling effect at high scanning velocities is explained by the Plateau–Rayleigh capillary instability of a liquid cylinder.

Gusarov et al. (2009) solved numerically the radiation transfer equation in a layer of homogeneous absorbing scattering medium, which is equivalent to the powder bed, irradiated with a normally incident laser beam of an axially symmetric profile to estimate the spatial distribution of the deposited thermal energy. The scattering and lateral transport of laser radiation is shown to decrease the intensity of the heat source at the axis and to produce its weak tail around the laser spot. Further, the author also stated that this decreases the maximum temperature in the powder bed. Narrowing the laser beam to increase the precision of selective laser melting becomes ineffective when the beam radius approaches the extinction length in the powder because it does not adequately narrow the zone of energy deposition.

Jianhua et al. (2009) studied a sequential addition packing algorithm to generate 3-D random packing of spherical particles with the same or different sizes. Then, a Monte Carlo based ray tracing algorithm is formulated to simulate the radiation heat transfer in the bimodal random packing structures. In addition, they investigated the influences of particle surface emissivity and population ratios of larger particles to smaller particles on the radiative transfer process are discussed. The researchers found that a bimodal packing structure, in which larger particles are less than smaller particles, can achieve a higher radiative heat flux level in the packed bed.

Florenzia et al. (2010) derived theoretical heat transfer equation established that both laser beam and material properties contributed to the energy intensity obtained by the powder during melting process. The influential material properties were found to be thermal conductivity, thermal diffusivity, specific heat, powder reflectivity and effective
absorption coefficient. In addition, the predominant laser beam properties were laser power and scan speed, which built on and confirmed previous works regarding these parameters. Heat distribution in SLM can be studied through the optical and thermal behaviour of the SLM process. Optical behaviour governs the relation between laser beam and powder bed surface. Energy transfer relating to light scattering and absorption by powder bed was addressed by the optical behaviour. The optical properties of the biomaterial, such as index of refraction, are coupled with the laser beam properties to estimate the amount of energy absorbed by the powder bed.

An analytical ray tracing model is developed by Wang et al. (2002) to model the energy absorption and penetration during the selective laser melting of metal powders. The proposed model was applied to a Fe-Cu powder mixture. Model gives an evaluation of the energy absorption and penetration and an estimation of the melting zone dimension. The model simulations always help to understand the physical phenomena involved, to identify the processing window and to optimize the SLM process.

The absorption of the powder bed is described by the total energy incoupling. It is defined as the ratio between the absorbed and the total input energy:

\[
\text{Total Energy Incoupling} = \frac{\text{Absorbed energy}}{\text{Input energy}} \times 100(\%) \quad (2.1)
\]

The total energy incoupling into the powder bed should be distinguished from the material absorption coefficient. It accounts for multiple reflection/absorption of the light in powders and is influenced not only by the laser source through its wavelength but also by the powder bed itself through the powder material.

In the laser beam scanning simulation of a single line melting, the real laser beam is represented as a bundle of parallel rays, equally spaced. The energy of each emitted ray is calculated from the energy distribution in the irradiated zone. This distribution depends on the power density, scan speed and other parameters. The energy distribution \(e\) for the uniform distributed cylindrical laser beam is given by:
where \( P \) is total laser power, \( d \) is the spot diameter of the laser beam and \( v \) is the scan speed of the moving laser beam. The total energy of any emitted ray is calculated by integrating the energy distribution around its initial position in \( x-y \) plane according to its representing zone (Kruth et al. 2009).

During the laser beam scanning simulation, the absorbed energy of each individual particle is accumulated to get its total absorbed energy \( (E_i \) for \( i^{th} \) particle). At the same time, the energy necessary to fuse this particle, calculated respectively for both materials according to the following equation:

\[
E_m = (c_p \times \Delta T + c_l) \times \rho \times V \tag{2.3}
\]

where \( c_p \) (KJ/KgK) is the specific heat, \( T \) (K) is the temperature rise needed for melting, \( c_l \) (KJ/Kg) is the latent melt energy, \( \rho \) (kg/mm\(^3\)) the density and \( V \) the volume of the spherical particle. At the end of the simulation, a simple comparison of the absorbed energy \( E_i \) to \( E_m \) will determine whether any particle absorbs enough energy to melt or not. The melting zone dimension is evaluated from the most side-wise molten particles.

Kharanzhevskiy et al. (2013) developed a two-dimensional transfer of laser radiation in a high-dispersive heterogeneous powder media. In the model, the size of particles is comparable with the wave length of laser radiation so the model takes into account all known physical effects that are occurred on the vacuum–metal surface interface. It shows that in case of small particles size both morphology of powder particles and porosity of beds influence the absorptance of the solid phase. Therefore the laser radiation penetrates deep into the area of geometric shadow. Intensity of laser radiation is described as a function corresponded to the Beer–Lambert–Bouguer law.

2.3.3. MARANGONI CONVECTION

Marangoni convection, also called surface-tension-driven convection or thermocapillary
**2.3.4. MELTING AND SOLIDIFICATION**

Melting and solidification are major physical mechanism happening during laser melting process. Different mathematical models have been proposed by various researchers on
melting and solidification. Carolin et al. (2011) proposed a 2D lattice Boltzmann model to investigate melting and re-solidification of a randomly packed powder bed under the irradiation of a Gaussian beam during selective beam melting processes. Ruidi et al. (2011) found out that during melting process the low recoil pressures facilitate the flattening of the melt which creates high pressures and further cause the material removal by melt expulsion. Moreover, Kruth et al. (2004) inferred that due to a higher degree of melting the density of the consolidated samples increased when the laser was operated in pulsed mode. Further, researchers found out that during solidification process the marangoni flow caused by different surface tension and thermal buoyancy significantly alter the solidification process and make the molten pool wider and shallower (Yang et al. 2001 and Kruth et al. 2004). Various mathematical formulations to numerically solved solidification and melting problems are categorized by Henry et al. (1996). Gordeev et al. (2011) also stated that the characteristic time of the cycle "heating-melting-solidification-melting" depends on the annealing mode. If a pulsed laser is used then this time is about 1 μs. The authors stated that it is difficult to control the melting process. Also becomes a tough issue for proper selection of processing parameters.

Melting and re-solidification are the mechanisms of metal powder-based SLM to bond powder particles to fabricate a functional part (Tiebing et al. 2010). During the SLM process of the two-component metal powder system, only the low melting point metal powder goes though melting and re-solidification, whereas the high melting point metal powder remains solid in the entire process. Significantly density change due to the shrinkage occurs during melting in the melting process because the high melting point powder alone cannot support the structure of the powder layer when the low melting point powder melts. Zhang et al. (1999) analytically solved a one-dimensional melting problem in a semi-infinite powder bed containing a two component powder mixture subjected to a constant heat flux heating, of which the shrinkage is considered. Chen et al. (2006) obtained an analytical solution of one-dimensional melting of the two-component metal powder layer with finite thickness. A two-dimensional steady-state laser melting problem using an Alternating Direction Implicit (ADI) method scheme with a false transient formulation was solved by Basu et al. (1988). A two-dimensional transient model of laser-melting problem associated with a moving laser beam in which the
interface energy balance was neglect (Chan et al. 1984). Melting and re-solidification of a sub-cooled semi-infinite two-component metal powder bed with a moving Gaussian heat source was simulated by Zhang et al. (1998). The author also modeled a three dimensional melting process of two-component metal powder with stationary and moving laser beams. Olakanmia et al. (2011) stated that the role of processing parameters (Laser power, laser speed and spot size etc.,) play a major role on the densification mechanism and microstructural evolution in laser sintered powder. It was established that both the densification mechanism and microstructural evolution in laser sintered powder were controlled by the specific laser energy input. The author also found out that at the highest energy density, there is the potential for greater melt superheat, so it takes longer for the initiation of solidification. A lower temperature gradient may result giving rise to a lower cooling rate. Su et al. (2013) investigated that argon atmosphere during laser melting process enhances better solidification rate. The author pointed out that oxidation of powder can create impurity and during solidification it can cause colour change to the material.

2.3.5. BALLING

Balling effect is the formation of large spherical liquid droplets at the surface, which degrade the structure of the powder due to surface tension forces (Tolochko et al. 1995). The absence of the balling effect may be understood by considering the soft laser irradiation conditions where the temperature increases gradually. Under such conditions the melt appears inside the initially sintered powder. Droplets are more likely to be created at rapid heating under intense laser irradiation, when the period of solid state melting before melt formation is very short and the strength of necks between the solid particles is insufficient to resist the surface tension of the melt (Tolochko et al. 2003). Low laser power leads to the first kind of balling characterized by highly coarsened balls possessing an interrupted dendritic structure in the surface layer of balls. A limited amount of liquid formation and a low under cooling degree of the melt due to a low laser input was responsible for its initiation. The second kind of balling featured by a large amount of micrometer-scaled (10 µm) balls on laser sintered surface occurred at a high scan speed. Its formation was ascribed to laser-induced melt splashes caused by a high capillary instability of the melt. Feasible control methods were proposed to alleviate
balling phenomena. It shows that increasing the volumetric density of energy input, which was realized by increasing laser power, lowering scan speed, or decreasing powder layer thickness will decrease the tendency of balling (Dongdong et al. 2009). Porosity also plays a major role in balling effect. The severe impediment to the smooth spreading of the fresh powder on the previously sintered layer and tends to cause delamination induced by poor inter-layer bonding in combination with thermal stresses, handicapping the completion of a multi-layer component.

Dongdong et al. (2008) found out that using a higher scan speed leads to the ‘shrinkage-induced balling’, because of a significant capillary instability effect. The ‘self-balling’ prevails at a high laser power combined with a low scan speed, which is ascribed to an excessive liquid formation and a too long liquid lifetime.

Several researches have been carried out to know about balling phenomenon as a typical SLM defect. It was found that the SLM balling phenomenon can be divided into two types generally: the ellipsoidal balls with dimension of about 500 μm and the spherical balls with dimension of about 10 μm. The former is caused by worsened wetting ability and detrimental to SLM quality; the latter has no obvious detriment to SLM quality (Li et al. 2012). Many researchers have found that the oxygen content plays an important role in determining the balling initiation, which can be considerably lessened by decreasing the oxygen content of atmosphere to 0.1% (Das et al. 2004, Li et al. 2009 and Kruth et al. 2013). A high laser line energy density, which can be obtained by applying high laser power and low scan speed, could enable a well-wetting characteristic. The effect of scan interval on balling initiation is not obvious as long as the scan track is continuous. The surface re-melting procedure can also alleviate the balling effect in a certain extent, due to the melting and wetting of metal balls. Li et al. (2012) describes about the two types of zones creates after the laser melting process, they are stability zones and instability zones. Researchers also found out that stability zones formed continuous track. Whereas instabilities appear at low scanning speed in the form of distortions and irregularities and on the contrary, excessively high speed gives rise to the balling effect. Furthermore the report discusses about the range of the optimal scanning speed which is larger for higher laser power and it narrows for material with high thermal conductivity. Yadroitsev et al. (2010) noted that the penetration into the substrate
provides an additional stabilizing effect for melting of continuous individual tracks. Tiebing et al. (2010) showed that the ‘balling’ can be avoided by scanning at very high intensity with very small beam spot sizes. Authors also claimed that the two-component powder approach, which uses two types of the metal powders possessing significantly different melting points, has been used successfully in SLM processing metals as another way to avoid “balling” phenomenon. The high melting point powders never melt in the melting process and play a role as the support structure necessary to avoid “balling” in the melting process. The particular material properties and methods of material analysis of the metal based powder system for selective laser melting applications are addressed by Storch et al. (2003).

2.3.6. WETTING

Wetting is described as how a liquid deposited on a solid (or liquid) substrate spreads out. Wetting phenomena have a major role in the field of material science which strongly determine both processing and properties of materials (Elham et al. 2009). Author developed a new algorithm to simulate 2D dynamic wetting phenomena using the single phase lattice Boltzmann method.

Das et al. (2001) noted that oxidation is a serious problem at the higher processing temperatures necessary for melting metals of interest (typically exceeding > 1000°C). These phenomena severely degrade material properties and part geometry. Poor wetting of an oxide substrate by a liquid metal is explained by the interfacial thermodynamics involved. The equilibrium of a liquid in contact with non-interacting solid and gaseous phases is shown in Fig (2.3). To ensure good wetting and successful layer-by-layer consolidation direct SLM of metals, processing must be conducted in a vacuum or protective atmosphere using high purity inert gases.

Fig. 2.3 Three phase equilibrium for wetting and non-wetting systems (Das 2003).
Takayuki et al. (2009) describes the wettability with respect to energy input phenomenon during SLM process. The author inferred that the SLM process is sufficiently large, full densification with the density comparable to those of the corresponding wrought steels due to increased wettability. Xue et al. (2010) proposed an effective method to fabricate BaO–B2O3–SiO2 glass/ceramic composites with different microstructures that depend on the high-temperature wetting affinity. The experimental results of Xue et al. (2010) showed that the wetting affinity between oxide ceramic and the BaO–B2O3–SiO2 glass matrix could strongly affect the driving force of densification and crystallization and finally the microstructure of the glass/ ceramic composites. It was found that suitable amounts of alumina powders could obviously increase the driving force for melting of glass by increasing the capillary pressure. In this case, the contact angle between alumina and glass matrix is about 248° at high temperature and a densified and homogeneous microstructure of glass/alumina composite was obtained.

The fundamentals of equilibrium wetting phenomena have been well explored by many researchers (Gennes et al. 2004, Powell et al. 1997 and Wang et al. 1995). Generally, equilibrium wetting is described by Young's equation is represented in Figure (2.4) and the equation is given below (2.4).

\[
\sigma_{SG} - \sigma_{SL} = \sigma_{LG} \cos(\theta_{eq})
\]  

(2.4)

Where \( \sigma \) denotes the surface tension and the index S, L, G denotes the solid, liquid, and gas phase, respectively. The equilibrium wetting angle \( \theta_{eq} \) is the result of the force equilibrium at the triple-point is represented in Fig 2.5. However, the dynamic process which is particularly important for many practical applications and Blake et al. (2006) stated that the phenomenon is not clear. However several numerical methods are available. In order to simulate the complex hydrodynamics of wetting, computational fluid dynamics was used and the most famous ones are the Volume of Fluid (VOF) (Fukai et al. 1995, Pasandideh et al. 1996 and Bussmann et al. 1999) and the lattice

![Diagram of equilibrium contact angle](image)

Fig. 2.4 Equilibrium contact angle of a liquid droplet wetting a plane solid (Carolin et al. 2011)

Young's equation (2.4) describes the equilibrium state where the interfaces are not moving and the phase boundary line stagnates. If a phase boundary is in motion, such as in the case of a spreading droplet, the contact angle differs from the equilibrium value and is denoted as dynamic contact angle $\theta_d$. If $\theta_{eq} \neq Q_d$ there is a force $F$ acting at the triple-point trying to move it in such a way that $\theta_d \to \theta_{eq}$. The x-component of the force equals:

$$F_x = \sigma_{SG} \sim \Sigma_{SL} - \sigma_{LG} \cos(\theta_d)$$

(2.5)

By inserting equation (2.4) into equation (2.5), the x-component of the force acting at the triple-point is given by:

$$F_x = \sigma_{LG} \cos(\Theta_{eq}) - \sigma_{LG} \cos(\Theta_d) = 2\sigma_{LG} \sin\left(\frac{\Theta_d + \Theta_{eq}}{2}\right) \sin\left(\frac{\Theta_d - \Theta_{eq}}{2}\right)$$

(2.6)

This force, which we call wetting force, vanishes when the dynamic wetting angle is equal to the equilibrium wetting angle. In order to describe dynamic wetting we have to take the force $F_x$ into account. It is also suggested to bring this force into this model as an additional capillary force. That is, a virtual extrapolation of the gas-liquid interface into the solid wall as depicted is shown in Fig (2.5). The curvature at the triple-point cell was determined in such way that the x-component of the capillary force equals the wetting force.
\[ F_s = n_s \sigma L G k \]  \hspace{1cm} (2.7)

\[ n x \sigma L G k = 2 \sigma L G \sin \left( \frac{\Theta_d + \Theta_{eq}}{2} \right) \sin \left( \frac{\Theta_d - \Theta_{eq}}{2} \right) \]  \hspace{1cm} (2.8)

Fig. 2.5 Calculation of the curvature at the triple-point cell (Carolin et al. 2011).

Yadroitseva et al. (2013) reported that during wetting process the adhesion between the solid and liquid is greater than the cohesive force of the liquid. For laser melting, wetting implies that the molten powder spreads on the substrate or previously sintered layer, instead of balling up on its surface.

### 2.3.7. HEAT TRANSFER

During laser melting process of metal powders, the heat transfer plays a major role in the formation of necks between particles in the powder bed. Researchers also found out that the necks often remain small as compared to the particle size (Roberts et al. 2009 and Gusarov et al. 2003). Various results indicated that the heated regions undergo rapid thermal cycles that could be associated with commensurate thermal stress cycles. Deposition of successive layers and subsequent laser scanning produces temperature spikes in previous layers. More over it was noted that the resultant effect is a steady
temperature build-up in the lower layers as the number of layers increases (Roberts et al. 2009 and Gusarov et al. 2003)

Many researchers developed the analytical models to predict the temperature rise occurring in a body when a laser like heat source is applied (Bechtel et al. 1974, Cline et al. 1977, Scherer et al. 1977, Carslaw 1959, Chen et al. 1983, Sanders et al. 1984 and Festa 1987). These authors assumed the heated body to be semi-infinite and isotropic, with constant material properties. None of the models incorporated surface heat loss. Heat propagation occurred by conduction in the solid and it is described by Fourier's equation (2.9). The laser intensity surface distribution was assumed to be Gaussian equation (2.10), or constant within a zone of a certain shape. Most models assumed exponential attenuation with depth equation described in equation (2.11). For moving sources, the relationship between beam speed and heat diffusion speed is key: if the ratio $U/(d. K)$ is low enough, the temperature profile for a moving source resembles that for a stationary source. If $U$ is high enough, the depth profile of temperature becomes similar to that of irradiance. The effect of the beam diameter $d$ and attenuation depth $Z_p$ are considered. Carslaw (1959) describes the model equations for heat sources applied to solid bodies. One example is described here, the variation of temperature with position and time in an infinite body due to a line heat source. In order for the line assumption to be applied to SLM, the ratio $U/(d. K)$ must be above a certain value. The body is infinite in size with constant properties, at an initial temperature of zero throughout. The heat source of strength $Q$ is applied instantaneously at $t=0$.

Temperature is described by:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - \left(\frac{\partial C}{k}\right)\frac{\partial T}{\partial t} = 0$$

(2.9)

$$I(r) = I_c \cdot e^{-\frac{2r^2}{w_0^2}}$$

(2.10)
Where $I(r)$ is the beam irradiance at a radial position $r$, $I_c$ is the peak irradiance and $w_0$ is the beam radius, equal to $d/2$.

$$I_z = (1 - R) I_0 e^{-bz}$$  

(2.11)

Where $I$ is irradiance, $R$ is the powder reflectance, $b$ is the extinction coefficient of the powder and $Z$ is depth into the bed. Subscripts $Z$ and 0 mean at $Z$ depth and at the surface respectively.

For simulating heat transfer in laser melting process various models have been developed already. An innovative simulation technique known as element birth and death, in modelling the three-dimensional temperature field in multiple layers in a powder bed was developed by Roberts et al. (2009). One of a model to develop 3D transient temperature field are as follows

$$\int_\Omega \rho Ud\Omega = \int_S qdS$$  

(2.12)

$$-k_e \frac{\partial T}{\partial Z} |_{z=L} = h(T_a - T_{z=S}) + \varepsilon R \sigma (T_a^4 - T_z^4 = s)$$  

(2.13)

$$-k_e \frac{\partial T}{\partial Z} |_{z=0} = 0$$  

(2.14)

Where $\rho$ is local density of powder bed during melting; $\Omega$ is volume of powder bed, which is related with its surface S; $U$ is heat conduction, which is related with specific heat capacity and position in the space, etc.; and $q$ is thermal flux density of laser per area. where $k_e$ is local effective thermal conduction coefficient; $h$ is convection heat exchange coefficient; $T_a$ is pre-heat temperature; $\varepsilon_R$ is emissivity of powder; and $\sigma$ is Boltzmann factor. The other border condition related to the situation when no thermal loss is produced at the thermal conduction of inner powder bed (Jian et al. 2013).

Dongdong et al. (2009) developed transient three-dimensional finite element model to simulate the phase transformation during the selective laser melting process; taking into
account the thermal and melting phenomena involved in this process. A bi-level structure integration procedure is chosen, in which the temperature dependent thermal conductivity, specific heat, and density are integrated at the outer level then used as material constants for the integration of the heat equation in the inner level.

In a one-dimensional system with an internal point heat source, of strength \( q \), located at \( x \), equation (2.15) describes the energy distribution in the medium. \( \delta(n) \) is the Dirac delta function which is exactly zero for all \( n \) not equal to zero. To transform equation (2.16) into the equation of a moving heat source, the location ‘\( x' \) is set equal to \( x_0 + vt \), where \( x_0 \) is the initial position of the point source, \( v \) is the velocity of the source and \( t \) is time. For moving heat source problems there are two solution types. The first type is an exact solution which is valid for all times. The second is referred to as a quasi-stationary or quasi-steady state solution. The later solutions are developed by assuming: the coordinate system moves with the heat source, the length of medium is exceedingly large compared to the heat-affected zone and that after an initial transient period the temperature distribution around the heat source, as observed from the heat source, does not change. Thus, the time dependence of the temperature can be set to zero, eliminating the time variable from the differential equation which describes the temperature distribution in the medium. Eliminating the time dependence affords simpler solutions to the differential equation.

\[
q \delta (x - x') \quad \text{(2.15)}
\]

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad \text{(2.16)}
\]

Carslaw and Jaegar (1959) presented solutions for numerous problems of stationary and moving heat sources by integrating the solution for an instantaneous point source in an infinite medium over the appropriate time and space variables. This solution strategy is referred to as the heat source method. The differential equation for heat transfer in an isotropic material with a temperature independent thermal diffusivity (\( \alpha \)). Equation (2.17) given an instantaneous point heat source in an infinite medium, \( Q \) is the strength of the
point source which is located at the point \((x', y', z')\). be: \(Qpc\), where \(p\) is the density and \(c\) is the specific heat. As \(t \to 0\) the temperature at all points is zero except at \((x', y', z')\) where the temperature approaches infinity.

\[
T(x, y, z, t) = \frac{Q}{8(\Pi \alpha t)^{\frac{3}{2}}} e^{-((x-x')^2 + (y-y')^2 + (z-z')^2)/4\alpha t} \quad (2.17)
\]

The authors presented a solution for heating of an infinite medium moving at a constant velocity in the \(x\)-direction by a point heat source, which releases heat at a rate \(q\), located at the origin. The solution to this moving heat source problem follows from equation (2.17) is obtained by equating the strength of the instantaneous source, \(Q\), to the amount of heat released by the moving heat source over a time interval \(dt\), thus \(Q=q \ \text{dt}\). Since the point heat source is located at the origin \(x_0=y'=z'=0\). To account for the motion of the medium, \(x\) is equated to \(-v \ (t-t')\). The solution for the temperature distribution in the moving medium is given by equation (2.18), which cannot be evaluated analytically.

\[
T(x, y, z, t) = \frac{q}{4\Pi k(x^2 + y^2 + z^2)} e^{-v((x^2 + y^2 + z^2)-x)/2\alpha} \quad (2.18)
\]

Following similar logic, the authors presented a solution for heating of a semi-infinite solid by a strip heat source, with dimensions \(-b<x<b, -\infty<y<\infty\), moving at constant velocity in the negative \(x\)-direction in the \(z = 0\) plane. The authors present plots of the
dimensionless surface temperature as a function of normalized distance as predicted by equation (2.19) for several different values of the Peclet Number. The Peclet Number, equation (2.20), is a dimensionless group which relates the rate of energy delivery per unit area to the rate of heat diffusion into a medium per unit area. Large values of Pe represent a rapid rate of energy delivery as compared to the rate of heat diffusion, thus the maximum temperature occurs at the trailing edge of the strip heat source. As the value of Pe increases, the length of the heat-affected zone ahead of the strip decreases.

\[
T(x, z, t) = \frac{Q}{\Pi k} \int_{-b}^{b} e^{v(x-x')/2\alpha} K_0(v((x-x')^2 + Z^2) / 2\alpha) dx' \]  
(2.19)

\[
P_e = \frac{vb}{2\alpha} \]  
(2.20)

Festa et al. (1990) compared one and two-dimensional heating of a semi-infinite body by constant intensity thermal fluxes. In the one-dimensional problem, the entire upper surface is subjected to a constant flux for time greater than \( \tau \) (not the characteristic relaxation time). The solution to the one-dimensional problem is given by equation (2.21). In the case of one-dimensional heating the quasi-steady state condition is always satisfied since there is no conduction in x- and y-directions. In the two-dimensional case, the surface is heated by a moving heat source, of width 2b, moving in the positive x-direction. The goal of Festa et al. (1990) was to develop a simple model which could be used to determine the depth to which solid state phase transformations occur in laser and electron beam surface hardening.

\[
T_{1-D}(z, t) = \frac{2q_0a^{1/2}}{k} \left( i^{1/2} \text{erfc} \left( \frac{z}{4\alpha(t-\tau)} \right) - U(t-\tau)(t-\tau)^{1/2} i^{1/2} \text{erfc} \left( \frac{z}{4\alpha(t-\tau)^{1/2}} \right) \right) \]  
(2.21)
The authors also compared the solutions of the one- and two-dimensional problems by comparing the maximum dimensionless hardening depth, function of Peclet number for various dimensionless transformation temperatures. The dimensionless transformation temperature is determined by $T_{x-D}$ which is in equation (2.22). Agreement between the one- and two-dimensional solutions is good for dimensionless transformation temperatures less than 0.15. For dimensionless transformation temperatures greater than 0.15, the prediction of one-dimensional solution exceeds that of the two-dimensional solution. For Pe greater than ~0.8 the dimensionless hardening depth predictions by both models are in agreement for all transformation temperatures. Specifically, the one-dimensional model over predicts the hardening depth for small Peclet numbers (Pe <0.8) when the dimensionless transformation temperature is greater than 0.15. The analysis presented by the authors is strictly applicable to second order phase transitions, which by definition have no enthalpy change associated specifically with the transformation.

$$T^+_C = T_{x-D} \frac{k}{2bq_0}$$

Hou and Komanduri (2000) developed general solutions for moving and stationary plane heat sources based on the heat source method. Surface heating of a semi-infinite medium by elliptical and rectangular plane heat sources with uniform (square-wave), parabolic and normal (Gaussian) intensity distributions were considered. The solutions presented are exact not quasi-steady state. However, the solutions involve integrals which must be evaluated numerically. The authors present plots of dimensionless temperature as a function of normalized distance for several normalized depths into the medium for elliptical heat sources with uniform and normal distributions. Pe is equal to 5 for both intensity distributions used by the authors, thus minimal heating is observed ahead of heat source. The shape the surface temperature distribution for the uniform heat source matches that of Carslaw and Jaeger, as would be expected. For the normal distribution, the surface temperature distribution resembles the shape of the intensity distribution of the source. The authors estimated the time required to reach a quasi-steady state
temperature distribution is shown in equation (2.23).

\[ t_{\text{quasi-steady}} = \frac{20\alpha}{v^2} \]  

(2.23)

2.3.8. SHRINKAGE

Additive manufacturing is emerging as a rapid manufacturing technique, which produces the functional parts in small batches, particularly in aerospace application and rapid tooling (Raghunath et al. 2007). However, the accuracy of an SLM process is difficult to predict as it is a function of many different factors, some of which are interdependent also. The factors that influence accuracy of SLM are accuracy of tessellation from the CAD model, slicing algorithm, data transfer, device motion resolution, powder granulometry, beam offset and the shrinkage (Wang et al. 1999 and Karapatis et al. 1998). One of the major causes of part inaccuracy in SLM is shrinkage during melting which does not occur in a uniform manner (Wang et al. 1999 and Pham et al. 1999). The shrinkage of a new layer can be constrained by the existing part substrate. In addition, areas at high temperatures tend to shrink more than those at lower temperatures and part geometries such as thick walls or sections can increase the shrinkage. To compensate for shrinkage, a material shrinkage coefficient is calculated and a scaling factor is applied in each direction to the STL file (Pham et al. 1999). The resulting geometry can be slightly oversized compared with the nominal geometry, depending on the scaling factor used. Wang et al. (1999) discussed the two most important parameters namely shrinkage and beam offset for the SLM process. Formula for shrinkage and beam offset has been derived in his work which can be used for scaling up the CAD models.

Nelson et al. (1993) developed a one-dimensional heat transfer model of SLM process for predicting melting depths in polycarbonate powders. They also conducted experimental studies to validate their simulation findings. Williams and Deckard (1998) used analytical and experimental methods to study the effect of energy density, spot diameter and delay on average density and strength of SLM parts. Their findings show that with the increase in energy density and spot diameter there is increase in density and strength of SLM
parts. However there exists a range of delay time which gives maximum density and strength. Wang et al. (1999) investigated the relationship between post-cure shrinkage and the various process parameters for stereolithography by using least-square method. They concluded that, as the curing degree of the green-state prototype increases, the shrinkage reduces. They also found that curing degree is a function of laser power, layer pitch, scan pitch and scanning speed.

Liu et al. (2011) reported that the discrepancy in the porosity between the stacking structure and the sintered structure also shows that a small amount of volume shrinkage takes place after solidification from the partially or completely melting of the powder.

2.4. OVER VIEW OF LITERATURE SURVEY

Many researchers have investigated the SLM process on polymer based as well as metallic based material by experimentally as well as numerically. Further, it is evident from the available literature that this process has been successfully used in many industries.

In the recent past, the alloy AISI 316L mainly focused by many researchers, since it is widely used in biomedical application particularly in both artificial knee and hip joints (Montasser et al. 2012). However this materials having good biocompatibility and corrosion resistance, very few attempts have been made on the developments of laser melting of stainless steel 316L powders. Kharanzhevskiy et al. (2013) developed a two-dimensional heat transfer of laser radiation in a high-dispersive powder heterogeneous media. Carolin et al. (2011) proposed a 2D lattice Boltzmann model to investigate melting and re-solidification of a randomly packed powder bed under the irradiation of a Gaussian beam during selective beam melting processes. Yadroitseva et al. (2013) reported that during wetting process the adhesion between the solid and liquid is greater than the cohesive force of the liquid. Ruidi et al. (2012) found that the oxygen content plays an important role in determining the balling initiation, which can be considerably lessened by decreasing the oxygen content of atmosphere to 0.1%.

Yin and Emi (2003) experimental results found out two types of marangoni flow the thermal Marangoni flow and solutal Marangoni flow. The thermal Marangoni flow will lead to a clockwise flow pattern (defined as source flow), whereas the solutal one does the opposite (defined as converging flow); the clockwise thermal component is weaker.
than the counterclockwise solutal flow. Jean et al. (2004) found out that at low scanning speeds, the liquid pool becomes larger than the beam diameter if sufficient power is applied, and the development of Marangoni eddies leads to a widening and deepening of the pool. When the scanning speed increases, the transverse eddies disappear whereas those in the longitudinal plane get bigger. Junke et al. (2008) conducted a numerical simulation on thermal stress and temperature distribution by using finite element analysis. It was concluded that the thermal stress can be reduced by means of the dual-laser-beam method. Ning et al. (2005) formulated a equation to find out the percentage of shrinkage during laser melting process. Laser sintered sample of Ti6Al4V was subjected to porosity studies by Das et al. (2003). The influence of laser processing parameters on mechanical properties and microstructure of pure titanium models made by laser melting was investigated by Edson et al. (2006). Experimental results of Fisher et al. (2009) suggests that at average powers between 10 W and 15 W the powder size of 30 µm obtains smooth and regular plates and above 60 W, the plates are distorted and irregular. Microstructural studies were performed by Fisher et al. (2009) for continuous sintered and pulsed sintered titanium. Compared with continuous wave interaction, the authors found out that pulsed wave interaction obtained stronger consolidation. Mechanical behaviour studies and microstructural studies were performed by various researchers on laser sintered parts on different materials both polymers and metallic materials by changing the laser parameters and powder characteristics.

2.5. GAPS IN LITERATURE
Very limited work has been reported on laser melting of stainless steel 316L, although it has been widely used in biomedical applications. The quality of fabricated parts can be affected by many factors such as materials properties, powder bed characteristics, and process parameters. The process parameters such as beam power, scanning speed and laser beam spot diameter needs to be studied in detail. The simulation can be used to determine the optimum parameters of laser melting including beam power, scanning speed, and laser spot diameter. The validation of numerical model with experimental should be performed so as to optimize the process parameters. In order to get more accurate results, it is
necessary to include further physical phenomena in the model, such as absorbance, radiation, marangoni effect and evaporation. It would be desirable to simulate the process in 3D and also to perform longer simulation runs in larger domain, since most of the reported works are performed in 2D. Comparison of numerical and experimental validation on geometric characteristics of the laser melted part is lacking in the literatures. Absorbance of the powder bed also one of a major factor needs to be addressed for different porosity percentage in the powder bed. The metallurgical defect mainly balling a common defect in laser melting process also needs to be studied for different process parameters. Microstructural studies on the laser melted tracks were not much discussed in many of the literatures hence studying the morphological characteristics of laser melted track will get a better understanding on how the laser process parameters will affect the microstructure of the melted track.