CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Additive Manufacturing (AM) process represent a family of technologies capable of producing physical models of any complexity directly from three-dimensional CAD software, using a swift, highly automated and flexible manufacturing procedure (Neal, 1994; Pham & Dimov, 2000; Cooper, 2001; Chua et al., 2010; Tiwari and Pande, 2013; Chua and Leong, 2014; Tiwari et al., 2015). Cucuruz et al. (2010) take up AM process as energy saving (up to 40% as compared to conventional manufacturing techniques) and highly productive and useful manufacturing technology used in various application fields. Diegel et al. (2010) reminded it as a sustainable manufacturing process. Campbell et al. (2011) found that the AM technology gives freedom to fabricate any kind of geometry without using any special tools, as required for conventional manufacturing processes. These technologies are also known as “Solid Freeform Fabrication”, “Layer Manufacturing” and “Computer Automated Manufacturing” (Beaman et al., 1997; Ilkgun, 2005; Tiwari et al., 2013).

AM systems operating on the principle of the layer-by-layer building (see Figure 2.1). It has been reported by Agrawal et al. (1995), Kumar & Dutta (1997); Chua et al. (2010), Gibson et al. (2010), and Wong and Aldo (2012) that AM process begins with creating CAD model of the part using CAD software or by special software which allows users to create CAD or STL (Standard Triangulation Language) data direct from CT or MRI scan (Chen et al., 2001; Caulfield et al., 2007). Furthermore, the CAD model either directly transferred by a computer interface to the AM machine or else through converting CAD model into additive processes usual STL file format which characterize the skin of the 3D model as a set of
triangles, storing the coordinates designed for the vertices and normal directions for each
triangle and slicing the CAD or STL file into thin layers (Tiwari and Pande, 2013). User
systematises the 3D model for build up by allocating the position and orientation of the part
in the machine, as part orientation impacts numerous parameters, including build time, part
strength and appearance. In addition, in the build up, slices of the model in form of thin
layers along the X-Y plane are laid one after another above each layer, moving upward in
the Z direction and building part one layer at a time physical parts to be created (Tiwari and
Pande, 2013).

AM technologies have a wide diversity of applications in various fields, including
aerospace, electronics, automobile, architectural modelling and biomedical engineering
(Tiwari et al., 2013). Therefore, they tender a unique and flexible process (Pham & Dimov,
2003; Salmoria et al., 2007). AM processes vary as of conventional manufacturing processes
in accordance with production time is shorter when using the conventional manufacturing
process and a wide range of materials can be used to a greater degree of accuracy and
precision owing to the additive, layered nature of AM process. The above AM characteristic
enables objects to be created with complicated internal features, which conventional
machinery cannot produce directly. Moreover, AM process builds parts by adding up
material layer-by-layer, thus avoiding tooling, reorientation and fixturing troubles (Campbell
et al., 2011). As the base layer is attached to a platform, the part is shaped exclusively of any
reorientation or refixturing required in the manufacture of parts. On the contrary to this,
conventional machining methods involve the subtraction of surplus or excess material from
a solid block. Generally, a critical shape object built by conventional machining requires that
multifaceted tooling and tool-path setting up to be designed and constructed in advance.
Besides, complex fixturing techniques and reorientation of complex objects are considered necessary in the fabrication process. With the development of AM techniques leads in addition to prototypes, and can also be utilized in tool-making (referred to as “rapid tooling”) and even in the fabrication of real end-use parts (referred to as “rapid manufacturing”) (King & Tansey 2003; Ilkgun, 2005, Eyers and Dotchev, 2010; Tiwari et al., 2015).

Additive Manufacturing (AM) techniques have been made commercially accessible in the market for the past 28 years. Since then, several AM techniques have been developed, however, merely some of them are extensively used and predominant in the market (Pham & Gault, 1998). The foremost AM technique Stereolithography (SLA) by 3D systems developed during the year 1988 and grows to be the pioneer in the AM market. Presently more than 50 vendors around the world marketing a large range of AM systems and each system have its own strengths, limitations and applications. Besides SLA, now, AM technologies presented in the market that may be classified as Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Fused Deposition Modelling (FDM), Laminated Object Manufacturing (LOM), 3D Printing (3DP), Electron Beam Melting (EBM), ProMetal, Laminated Engineered Net Shaping (LENS) and Polyjet (Wong and Aldo, 2012).

Moreover, AM technologies have been standardised and classified by the ASTM International Committee F42 on AM Technologies. The committee has classified AM process and their variants into seven main categories including photopolymer vat, material extrusion, powder bed fusion, direct energy deposition, sheet lamination, material jetting and binder jetting. The photopolymer vat process uses SLA and 2PP as AM technique and photo-curable polymer as material. The material extrusion process uses extrusion-free
forming techniques (i.e. FDM, MJS, PEM, PED, Robocasting, 3D-Bioplatting etc.). The powder bed fusion is one of the AM processes in which thermal energy selectively fuses the region of powder bed material. The powder bed fusion process includes SLS, SLM, EBM and SMS as AM techniques and polymer, metals and ceramics as a material to fabricate parts. The directed energy deposition AM process uses LENS and DMD as AM technique. Furthermore, this AM technique uses ceramics as well as metals as a material. The sheet lamination AM process uses LOM and UC as AM technique. Material jetting is AM process in which droplet of build material is selectively deposited layer by layer. Furthermore, the material jetting process uses DoD inkjet printing and PJT as AM technique and metals, polymers as well as ceramics as a material. Binder jetting is last AM process and in this process, liquid bonding ink is selectively spread to join solid powder material using 3DP as AM technique and polymers, metals and ceramics as a material (Chua and Leong, 2014).

In the subsequent sections, the following most common AM processes are presented:

Laminated Object Manufacturing (LOM)
Stereolithography (SLA)
Fused Deposition Modelling (FDM)
Three-Dimensional Printing (3DP)
Selective Laser Sintering (SLS)

All above technologies are explained briefly through an outline of their part building strategies. The work presented in this study focuses on SLS technology. In SLS process, a wide variety of materials can be used to create parts; therefore it has a gain over some of the other AM processes. Several SLS materials and their applications are presented herein study. Besides, some of the problems found during parts fabricated using SLS process are
stated, a description of previous studies of the development of composite materials used in SLS process is given, and finally, value engineering methodology is described which is a proven, effective and sustainable tool for continuous improvement and design enhancement.

![Figure 2.1: Layer-by-layer fabrication (Ilkgun, 2005).](image)

**2.2 Additive manufacturing growth trend and market status**

AM techniques have capabilities to create any type of geometry simply, economically and efficiently as a contrast to conventional manufacturing. This makes AM process fit in different fields of manufacturing. Chua et al. (2010) reported that the AM technique idea was to bring in the late 1980s. It has been reported in the year 2012 of an annual worldwide progress report, on AM and 3D printing state of the industry that the total yearly income for the AM industry for the year 2010-2011 was $1.7 billion and it is estimated to grow to $3.7 billion by 2019 (Wohlers, 2012). Wong and Aldo (2012) reported that the system sale for AM was approximate 2,800 unit machines in the year 2005 and over 6,000 unit machines in
the year 2010. The system sale for the year 2015 was 278000 units (Wohlers, 2016). Figure 2.2 shows the AM systems sales worldwide. The recorded growth for AM process was about 24 % in a year, 2010 and about 26 % compound growth rate until a year, 2010. Further, the recorded growth for AM process was about 48% in a year, 2016 (see figure 2.2 (c)). It has been reported that an estimated 26.3% of the entire industrial AM systems installed worldwide are in the region of Asia/Pacific. Furthermore, meanwhile 29.1% are in Europe and about 40.2% are in North America. The remaining 4.4% of AM systems are in Central America, South America, the Middle East, and Africa. The cumulative distribution of industrial AM systems in the Asia/Pacific region through the end of the year, 2016 is shown in Figure 2.3. It has been shown in the report that the majority of the AM systems are in Japan and China. The “Other” segment consists of Brunei, Indonesia, Mongolia, New Zealand, the Philippines, Singapore, and Vietnam Asia’s adoption of AM for modelling and prototyping applications and fewer organizations in this region are using AM to the manufacture of parts of final products (Wohlers, 2012; Wong and Aldo, 2012; Wohlers, 2016; Tiwari et al., 2016).

The use of AM for the direct production of parts that end up in final products continues to grow (see Figure 2.4). In previous nine years, it has gone as of virtually nothing to 24% of the total product and service incomes from AM process (Wohlers, 2012; Tiwari et al., 2016). Figure 2.5 shows the percentage of response for various AM processes (Wohlers, 2014). In addition, among all accessible AM processes as well as others like vacuum casting process, the percentages utilisation value of SLS process is very high and has about 25% as compression to the all others process.
(a) AM system unit sold till year 2015

(b) Printer sold and revenue generated in billions ($)

CAGR (2015-2018)
Printers sold: 91%
Revenue: 88%
(c) Growth rate per annum in percentage

Figure 2.2: AM growth trend (Wohlers, 2011, 2012, 2014, 2015, 2016).

Figure 2.3: Approximate AM percentage uses in the Asia/Pacific region by the end of year 2016 (Wohlers, 2016)
Figure 2.4: Use of AM for direct part production worldwide (Wohlers, 2012)

Figure 2.5: Percentage of response for different AM processes (Wohlers, 2012, 2016).
AM users in the market using AM process to fabricate products for different applications reported by (Tiwari et al., 2015). AM uses are about 31.7% in the automobile industry and up to 18.4% as a consumer product. The AM market status for different application is shown in Figure 2.6 (Wohlers report, 2016). The data reported by Wohlers (2012) about AM users in the market for various application show that AM applications have increased in the areas like medical industry, academics, aerospace, government/military and also in others and for the year, 2012 consecutive uses percentage for these is about 18.6%, 13.05%, 9.167%, 8.61% and 1.94% and uses decreased in areas of motor vehicles, consumer products and business machines, with the consecutive uses percentage about 20.57%, 17.23% and 10.83%. The AM systems have been mostly used in manufacturing industries such as automobile, medical field, aerospace industry electric home appliance and jewellery industry.

![Figure 2.6: Percentage uses of AM in different applications (Wohlers, 2016).](image-url)
2.3 Classification of additive manufacturing technologies

In the subsequent sections, common additive manufacturing (AM) processes are classified. Also, a brief description of each, together with their building approaches and the key advantages and disadvantages of these approaches, are also presented.

2.3.1 Laminated Object Manufacturing

The sheet lamination process, one of the AM techniques is Laminated Object Manufacturing (LOM) that typically adopts the process of “laminated forming”. The thin layers of the laminate are used to build parts. The LOM process uses paper, plastic, ceramic and composites as a material but the most common material is paper. During the process the layers are bonded by coating the sheets with heat sensitive adhesives, allowing layer-by-layer bonding in the course of hot roller compression.

The sheets of material are provided and fed from a material supply roll and transmitted to a take-up roll positioned in a facing position (shown in Figure 2.7). The contours of every layer are cut with a CO₂ laser controlled through a CAD system. A laser beam is cautiously adjusted to penetrate exactly to the depth of one layer. Material which is not part of the specimen or product is trimmed into a rectangular profile by means of the laser to ease its removal while production of the part is then finished. The rectangular shape remains inside a place like an outside support in the part building process.

The LOM process usually has benefited over others AM technologies, such as the part does not need any support structure because it is supported by its own material. Furthermore, LOM process is easy to use and it does not affect the environment. Also, owing to the extremely low levels of internal tension within LOM parts, it avoids distortion, shrinkage and deformation of the parts. On the contrary to that a high level of effort is pertaining to
decubing, finishing and sealing parts. Common LOM process material i.e. papers are simply peeled off at the adhesion layer and bubbles can appear among layers. The part can either be burnt because of overheating or be caused to undergo addition failure due to deficient heat. In the Z dimension, the control of parts accuracy is quite complicated for paper LOM parts, owing to a swelling effect (‘Z-growth’). The remaining materials supporting the part are scrapped once the part building process is completed and the cost of such waste can be considerable (Mueller & Kochan, 1999; Pham & Dimov, 2003; Chua et al., 2010; Gibson et al, 2010; Choudha et al., 2012).

![Laminated object manufacturing process](image)

**Figure 2.7:** Laminated object manufacturing process (Liao et al., 2005).

### 2.3.2 Stereolithography

The Stereolithography (SLA) is an AM technique based on photopolymer vat process where the part building process is based on photosensitive liquid resins which shape a solid polymer while exposed to Ultraviolet (UV) light. SLA systems comprise a build platform
located in a vat of resin and a UV laser. Initially, the platform is kept on the top of the surface of the resin, prior to being lowered to the planned thickness of the initial layer of the part, where it is imaged on the resin surface through the laser by using information get from the 3-D solid CAD model. Choudha et al. (2012) illustrates that once a UV laser has drawn the layer structure lying on the surface of the resin thereafter the scanned resin is allowed to polymerise and solidify. The subsequent layer is then scanned, so one more layer can be built. The process is going over until the part is fully fabricated (see Figure 2.8). The vat and excess resin are drained and the part takes out from its build-platform. The parts produced using SLA process have overhangs problem which needs support structures to avoid them from swaying and turn out to be deformed in the liquid environment. Further, supports are removed once the part has been completed. In a few cases the support structures are not removed, such as, where a making part has inner cavities with hardly any or no access points (Kietzman, 1999; Pham & Dimov, 2000; Chua et al., 2010, Gibson et al., 2010, Choudha et al., 2012; Chua and Leong, 2014).

Figure 2.8: Stereolithography process (Kietzman, 1999; Choudha et al., 2012).
2.3.3 Fused Deposition Modelling

Fused Deposition Modelling (FDM) is an AM technique based on material extrusion process in which nozzles tip to build the part and a base platform for support and building are required. Thermoplastic filament or wax is used in this process as material to fabricate the parts. As shown in Figure 2.9, the filament material is fed through a temperature-controlled extruder to eject and deposit the material onto a platform during a layer-by-layer fabrication process (Chua et al., 2010). Thereafter on completion of the first layer, the base platform is lowered and then the subsequent layer is deposited and thermal fusion of material causes bonding of all added layer to the previous one. Therefore, the part building process needs to be maintained at a temperature nearer to solidification point to ensure proper bonding between subsequently added layers. The object is designed and fabricated as a physical part from 3-D solid or surface models because AM course of action based solely on the precise deposition of thin layers of the extrudate. The Road Width (RW) is controlled by setting flow parameters at a temperature over the melting point of the thermoplastic material and in addition by using the precise dimensions of the nozzle tip (Jamal, 2001; Castle, 2008; Chua et al., 2010, Choudha et al., 2012; Mohammad, 2012; Wong and Aldo, 2012).

![Diagram of FDM process](image_url)

**Figure 2.9:** Fused deposition modelling process (Castle, 2008; Choudha et al, 2012).
2.3.4 Three-Dimensional Printing

Three Dimensional Printing (3DP) is an AM technique based on binder jetting process which employs processing of powder during the building of parts. The 3DP process uses many types of powder material from metals, ceramics and polymers. As shown in Figure 2.10, the main part of the 3DP machine includes a print-head which’s X–Y axes is suspended over a vertical piston plate, providing control over three directions of motion. After spreading a thin layer of powder onto a piston plate levelling is done through a roller. In the 3DP process to facilitate selectively print droplets which bind the powder particles together, the binding material goes by a nozzle attached to the fast axis carriage with a back and forwards motion above the powder bed. Thereafter, the piston plate lowers the piece of work and then roller spreads the next layer of powder. This process of part building is repeated until the final part is not made. Figure 2.10 shows the illustration of the 3DP process. After completion of the part building process, the excess powder which has been supporting the part is detached to reveal the made-up part (Katstra et al., 2000, Choudha et al., 2012; Wong and Aldo, 2012).
Figure 2.10: Three-dimensional printing process (Xpress 3D, 2005; Wong and Aldo, 2012).

2.3.5 Selective Laser Sintering

The powder bed fusion process one of the AM technique is Selective Laser Sintering (SLS). SLS process developed by Carl Deckard in 1987 and originally patented by the University of Texas, Austin, and further, it was licensed to the DTM Corporation (Tiwari and Pande, 2013). DTM corporation, company pioneer in the AM market bring in the first commercially available SLS system in year, 1992 (Neal, 1994; Pham & Dimov, 2000; Chua et al., 2010; Gibson et al. 2010, Chua et al., 2014, Hasmi, 2014, Tiwari et al., 2015). Other than this now there are few other vendors around the world marketing a large range of AM systems and each AM system having its own strengths, limitations and applications (Choudha et al., 2012). A summary of specifications for EOSINT P 395 & FORMIGA P 110 is given in Table 2.1. SLS uses powder processing during the building of parts. It uses many types of powders which include polymers, metals, ceramics, and composites. SLS parts are fabricated while the surface tension of particles is overcome in the presence of heat of an IR laser beam and they then fuse together. Furthermore, during the process the powder is supplied through two feed-cartridge units which distribute a thin layer of powder over the build-area, using a layering roller. The part build area is also supported through a movable piston (see Figure 2.11) (Pham & Dimov, 2003; Chua et al., 2010; Gibson et al., 2010; Tiwari and Pande, 2013; Hasmi et al., 2014; Tiwari et al., 2015).

Chua et al. (2010) and Gibson et al. (2010) stated the SLS working process which begins with creating a 3-D CAD model of the part with CAD software or special software permits users to create CAD or STL data from CT or MRI scan transferred to the SLS machine or through converting CAD model into additive processes standard STL file format which
correspond to the skin of the 3D model as a set of triangles, i.e. coordinates for three vertices and normal directions for each triangle, slicing the CAD or STL file into thin layers as shown in Figure 2.1. In addition, process parameters and manipulation of the laser are controlled using data processing with the computer system. Moreover, the computer system is used to control the supply of nitrogen inside part building chamber for creating an inert environment in order to eliminate the possibility of powder oxidation and explosion. The process continued with heating of the powder depending upon kind of material selected for processing just below the melting point temperature using a heater positioned above the part bed. Heating of powder material causes minimization of thermal distortion, reducing of heat stress to the lowest possible degree and also prevents the fabricated part from warming. Thus, fusion to the previous layer is too facilitated. Further, during the process, the temperature of the powder feed cartridge units are controlled, therefore, powder to be transferred freely by a layering roller. During the build process, a very thin layer (between 100 μm to 125μm) is spread by the roller in the part build chamber. The transverse speed of the layering roller is a regulating machine parameter (Kumar & Dutta, 1997; Jain et al., 2006; Yusoff, 2007; Custom Part Net, 2012; Wong and Aldo, 2012; Tiwari et al., 2015).

The SLS machine uses a CO₂ laser having capacity up to 50 watts (Chua et al., 2014; Hasmi, 2014; Tiwari et al., 2015). Two mirrors having onto the surface of the powder build area used to guide the laser beam, thereby enabling it to scan particular areas of powder corresponding to a particular slice of the objects as per chosen design geometry (see Figure 2.11). The contact of the incident laser beam with the powder fuses the powder particles to fabricate the first layer of SLS parts (Neal, 1994; Yusoff, 2007; Gibson et al, 2010; Hasmi, 2014). Then the part-build cylinder lowers slightly and one of the feed-cartridge unit rises in
order that the next layer of powder may be added. The process continues in this way until the part is not fully fabricated (Tiwari et al., 2015).

**Table 2.1: Specifications of mostly used EOS systems (EOS INT P395 & FORMIGA P110)**

<table>
<thead>
<tr>
<th>Model</th>
<th>EOS INT P395</th>
<th>FORMIGA P110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>SLS</td>
<td>SLS</td>
</tr>
<tr>
<td>Laser type</td>
<td>CO₂</td>
<td>CO₂</td>
</tr>
<tr>
<td>Precision optics</td>
<td>F-theta lens</td>
<td>F-theta lens</td>
</tr>
<tr>
<td>Laser power (W)</td>
<td>50W</td>
<td>30 W</td>
</tr>
<tr>
<td>Power consumption (nominal)</td>
<td>2 kW</td>
<td>Maximum 5 kW / typical 1.4 kW</td>
</tr>
<tr>
<td>Layer thickness (Material-dependent) (mm)</td>
<td>0.06 – 0.10 – 0.12 – 0.15 – 0.18 mm</td>
<td>0.06 – 0.1 – 0.12 mm</td>
</tr>
<tr>
<td>Scan speed (mm/s)</td>
<td>up to 8 m/s</td>
<td>Up to 5 m/sec</td>
</tr>
<tr>
<td>Support structure</td>
<td>Not necessary</td>
<td>Not necessary</td>
</tr>
<tr>
<td>Effective building volume (mm)</td>
<td>340 mm x 340 mm x 620 mm</td>
<td>200 mm x 250 mm x 330 mm</td>
</tr>
<tr>
<td>Building speed (material-dependent)</td>
<td>Up to 31 mm/h</td>
<td>up to 20 mm height/h</td>
</tr>
<tr>
<td>Nitrogen generator</td>
<td>Integrated (optional)</td>
<td>Integrated (optional)</td>
</tr>
<tr>
<td>Compressed air supply</td>
<td>Minimum 5,000 hPa; 6 m³/h</td>
<td>Minimum 6,000 hPA; 10 m³/h</td>
</tr>
<tr>
<td>Computer system</td>
<td>Current Windows operating system</td>
<td>Current Windows operating system</td>
</tr>
<tr>
<td>Power supply</td>
<td>32 A</td>
<td>16 A</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Software</td>
<td>EOS RP Tools; EOSTATE 1.2; Magics RP (Materialise)</td>
<td>EOS RP Tools (optional); Desktop PSW</td>
</tr>
<tr>
<td>CAD interface</td>
<td>STL. Optional: converter to all common formats</td>
<td>STL (optional: converter to all common formats)</td>
</tr>
<tr>
<td>Network</td>
<td>Ethernet</td>
<td>Ethernet</td>
</tr>
</tbody>
</table>

**Figure 2.11:** Selective Laser Sintering process (Tiwari et al., 2015).

2.3.5.1 SLS process parameters

The Selective Laser Sintering process has various fabrication parameters and their combinations determine the quality of sintered parts, such as geometric problems, mechanical and physical properties. Depending upon selected powder properties and the
requirements of the application different process parameters are settled (Gibson & Shi, 1997&1999). Thus, the default values for every process parameters based on the material used during the process for the fabrication of the parts have been specified by SLS system manufacturer as EOS, Germany and DTM Corporation.

The better part properties are obtained by the proper selection of process parameters for considered SLS materials and by taking account major factors which can influence the SLS processed parts quality are classified into two groups:

- Issue related to the process.
- Issue related to the material properties.

1. Issues related to the process

The powder material properties, fabrication parameters, build part orientation and post processing of the fully fabricated parts determines the mechanical properties and look of SLS fabricated parts (Blattmeier et al., 2012; Gibson and Shi, 1997). In addition Gibson et al. (2010) reported that the fabrication parameters, specifically, powder bed temperature, laser power, laser beam spot size, laser scan speed, thickness of layer, hatch distance and scanning pattern have to be combined taking in account optimal condition for each factor to get the greatest surface finish, appearance quality, part build rate and mechanical properties. Furthermore, it has been reported by Gibson and Shi (1997) that after optimising the fabrication parameters, build part orientation, and post-processing parameters, the mechanical properties and made part appearance solely depend on the selection of the material. The polymers glass transition temperature ($T_g$) and melting point temperature ($T_m$) decide part bed chamber temperature ($T_b$) and fill laser power ($P$) during SLS (Gibson and Shi, 1997). To obtain repeatable end results the powder bed temperature must be kept
uniform and constant. High part bed temperature and high fill laser power grouping makes dense parts, however, it results in part growth. Combinations of low part bed temperature and low fill laser power produce parts having improved dimensional accuracy, lower density part with layer delamination tendency. In addition, low part bed temperatures and high fill laser power combinations give an increased tendency for non-uniform shrinkage and also the build of residual stresses end results in curling of fabricated parts (Gibson and Shi, 1997; Gibson et al., 2010). By increasing laser stays time in a particular location, a larger melt pool diameter and sintering depth can be achieved and in the condition of low laser power during part fabrication, only by keeping low scan speed proper fusion of power particle is possible (Gibson et al., 2010). Other fabrication parameters such as scan spacing and scan size choice are based on powder properties (such as particle size, density, etc.) and specific application requirements (Gibson and Shi, 1997). The incremental trend of energy density can be achieved by decreasing the Scan Speed (SS) and Scan Spacing (SCSP) and increasing fill laser power. High energy density conditions correspond to parts of high tensile strength, part density and it tends to limit value, while more increasing fill laser power. Uniform temperature distribution during sintering is achieved by taking shorter scan vector, as shorter scan vector takes less time to scan the subsequently part without too much loss of heat. The similar condition corresponds for better binding of the part (Tiwari and Pande, 2012). Also, Simchi (2006) has reported the similar combination for attaining better binding of the part. The mechanism of densification during the sintering of metals follows the first order of kinetic laws and sintering rate is the function of the input laser energy. Furthermore, the sintering density of metal powder must be an exponential function of the input laser energy. During direct SLS of metals quantity of oxygen present in sintering
affects densification, whereas the presence of oxygen allows surface oxides to form. The absorption rate of CO$_2$ laser radiation increases due to the formation of an oxide layer on the surface of powder particles and changes the temperature – time history of sintering and also increases the melt volume. Better mechanical properties in fabricated parts can be obtained at the middle of the building height level in comparison to the extreme position; moreover, the part dimensions increases with the increasing energy density level in every case regardless of the part build orientation (Caulfield et al., 2007). Further, through HIP and post processing (such as infiltration, coating and surface finishing) improves density, mechanical properties as well as SLS fabricated parts appearance quality (Gibson et al., 2010; Kruth et al., 2010). A flat sectional sintering geometry is obtained at higher beam scanning speed (Deny et al., 1992). In other words, increasing laser duration time gives a better value of sintering depth and vice-versa. The lower scanning speeds with higher laser power produce the larger values of the sintering depth as well as sintering width, whereas improved fabricated parts quality is obtained by increasing powder packing density. The work on SLS part characteristics is reviewed by Kruth et al. (2010) and they stated that the higher density of fabricated part is attained at zigzag scanning pattern; moreover, the surface quality is improved through re-melting of parts 12 times and optimal process parameters with controlled microstructure is a basis for better part characteristics. Kumar (2003) reported that understanding of computational modelling concept and applying it to optimise varying process parameters results in improved efficiency of SLS process machine.

Gibson and Shi (1997) have given the relationship for SLS fabrication parameters and material properties as discussed below.

SLS fabrication parameter and material properties relationship (polymer),
\[ P \, (\text{watt}) = \frac{BS \cdot \rho \cdot D_b \cdot h \cdot [C \cdot (T_m - T_b) + l_f]}{(1 - R)} \]  \hspace{1cm} (Eq. 2.1)

where \( \rho \) is powder density, \( C \) is specific heat, \( l_f \) is latent melting heat, \( D_b \) is the diameter of the laser beam on part bed and \( R \) is a reflectivity.

\[
\text{Energy density (cal/cm}^2\) = \frac{P \cdot f}{(BS \cdot SCSP)} \hspace{1cm} (Eq. 2.2)
\]

where conversion factor is \( f \).

To process the material on SLS process, following typical values of processing parameters for polymer materials are to be taken as part bed temperature \( (T_b) \) should be close to \( T_g \) for amorphous materials, whereas it is kept 3–4°C below melting point temperature \( (T_m) \) for perfectly crystalline material; fill laser power \( (P) \) is to be taken between 50 W to 18 KW depending upon material; Scan Spacing \( (SCSP) \) must be kept either below the laser beam diameter on the part bed or closer to it i.e., \( (\leq 0.8 \text{ mm}) \); slice thickness \( (h) \) should be kept in between 0.07 mm to 0.5 mm, also the largest slice thickness is restricted by \( D_p \) of the powder. In addition, the scan size value is usually taken in between 55 mm to 85 mm.

2. Issues related to the material properties

The density of the SLS processed part by using the mixture of powders of different sizes can be increased. Simchi (2006) reported that finer particles which are smaller in size have larger surface area to absorb more laser energy, which results in an increase of working temperature and consequently the sintering kinetics. To facilitate preferential melting of material keep binder particle smaller than the structural particles. On the other hand, for instance, preferential binder melting possibly neutralised with the higher reflectivity or lower absorption of a metallic binder material i.e. \( (\text{Cu or Co}) \) as compared to the structural
material which is either ceramic or any other hard material. Kruth et al. (2007) reported that the better packing with small pores is to be attained in a combination of small binder particles and larger binder particles which favour fast spreading of the molten binder through capillary force and rapid rearrangement of the particles. In addition, initial packing density of the powder material influences the density of SLS fabricated part in which the high sintering density part with the rigid network of high melting point solid particles limits the flow of low melting point particles and also prevents rearrangements of the particles, whereas in a lower sintering density part, the liquid is free to flow and rearrange the solid particles and consequently results in densification of parts (Zhou et al., 2009).

It has been reported by the Shi et al. (2004) that the viscosity of the material is dependent on the molecular weight and influences density of SLS fabricated parts. Also, the density of the fabricated part is more at higher viscosity (Haworth et al., 2013). The quality of the fabricated SLS part varies with the melting of the used material, whereas increasing crystalline nature of material has an effect on the shrinkage and precision. High dimensional accuracy and precision are attained when a difference among melting peak and the crystalline peak is more. The minimum thickness of the layer is determined by the particle size of the material and it controls the accuracy of the part. Moreover, a smaller particle size is ideal which can be easily oxidized because of the presence of more surface area contrast to larger particles (Higa, 2011; Oliveira et al., 2014). The ratio of absorbed radiation to the incident radiation is absorptance of a material and it is especially important to consider it for SLS process in sintering of two component powder mixture. Tolochko et al. (2000) found that in sintering, only a part of the incident radiation is absorbed by the outer surface of the particle within a loose powder and rest part of radiation penetrates through the inter-particle
spaces into the depth of the loose powder interacting with the underlying particles. Usually, the laser absorption is higher in the solid material due to multiple reflections of laser beam trapped in the gap of the layer (Kruth et al., 2003), whereas multiple reflection effects among the powder particle are likely to have higher optical penetration depth compared to bulk material (Simchi, 2006). In SLS process, CO\textsubscript{2} and Nd: YAG lasers are mostly used as energy sources. The laser absorption depends on the laser wavelength for various kinds of materials and produces a considerable effect on the consolidation of the particles. The CO\textsubscript{2} laser is best suited for sintering polymer powders as it depicts high absorption at long wavelength. The wavelength of the CO\textsubscript{2} laser is 10 μm. The CO\textsubscript{2} laser is also best suited for oxide ceramic, whereas for carbide ceramic the Nd: YAG is the best option. The Nd: YAG has a wavelength of 1.06 μm. In addition, for metal Nd: YAG laser is also best suited available laser option because of the fact that metal absorbs much better at a shorter wavelength (Kruth et al., 2003; Tolochko et al., 2000). The reflectivity of the material mostly depends on its electrical conductivity. Furthermore, the metals have generally higher reflectivity and require high energy density. On the other hand, a greater depth of fusion penetration with no thermal shock or cracking is to be attained for material which has high thermal diffusivity (Higa, 2011; Yuan et al., 2013). Figure 2.12 shows the SLS process parameter.
Figure 2.12: SLS process parameter (Tiwari et al., 2015).

Furthermore, the most common fabrication parameters separately are described in the following section.

2.3.5.1.1 Fill laser power

The fill laser power is an important SLS parameter and during part fabrication available to the CO₂ laser beam at the part bed surface. Ilkgun (2005) reported that the fill laser power input value solely depends on the type of material and appropriate layer thickness is required to build the parts. To allow bonding between adjacent powder particles by heating powder at part bed surface close to its melting point temperature, a fill laser power is needed to be set. Gibson & Shi (1997), Jamal (2001) and Aldahsh (2011) have fabricated the test parts using various levels of laser power in order to determine the optimal laser power for the material used in SLS. Furthermore, since the part bed temperature is close to the melting point of the
material thus a relatively low laser power is useful to sinter the powder in each successive slice of the part. Moreover, too much laser power energy will cause large thermal penetration into the powder, as a result of which it affects powders beyond the cross section of the part and consequently cause growth. On the other hand, insufficient laser energy will not fuse the powder completely, thus affects the quality of SLS fabricated parts and produces the porous and weak parts (Alimardani, 2009; Chua et al., 2010; Gibson et al., 2010; Tiwari et al., 2015). Fill laser power \( P \) can be calculated by equation 2.1.

### 2.3.5.1.2 Laser beam speed

The scan speed of laser movement across the surface of the part on the part bed powder is laser beam speed and it causes to fuse the powder particles together. Pham & Dimov (2000) and Chua et al. (2010) reported that laser speed used for the most part builds is very fast and ranging between 1m/s to 5m/s. Also, it depends on other parameters such as laser power and scan spacing to fabricate the parts by a better energy density leading to low porosity, good surface finish and good mechanical properties (As per Equations 2.1 and 2.2).

### 2.3.5.1.3 Laser beam offset

Laser beam offset is an essential parameter which influences the accuracy of SLS parts. Beam offset consists of laser spot diameter, deflection angle during the laser scan and the area of the powder surface is affected by heat. In addition, Wang (1999), Jamal (2001) and Aldahsh (2011) stated that the dimensions of the laser spot diameter vary at different points on the surface of the powder, depending on the deflection angle of the laser beam from the scanning mirror. As shown in Figure 2.13, the laser spot has the smallest diameter \( D \) at \( \alpha = 0 \), and hence the laser spot can focus most effectively on the scan surface. When the value is
\( \alpha > 0 \), the diameter of the laser spot on the scan surface is \( D' = D / \cos \alpha \). The difference of \( D' \) and \( D \) is expressed as:

\[
\delta = D \left( \frac{1}{\cos \alpha} - 1 \right) \tag{Eq. 2.3}
\]

\( D \), however, increase in direct proportion to \( \alpha \) but the increase in diameter is not expected to be significant (about 5.4% at the highest value of \( \alpha = 19^\circ \) and \( D = 0.42 \text{mm} \)). The effect of this increase is thus generally ignored.

![Diagram of laser focus system](image)

**Figure 2.13:** Changes in laser spot diameter (Wang, 1999).

### 2.3.5.1.4 Scan spacing

Figure 2.14 describes the Scan Spacing (SCSP) process parameter in which the laser-path movement during scanning is shown. It is the distance between two adjacent, parallel, scanned vectors. During scanning, the SCSP distance should be kept smaller than the effective laser beam diameter, otherwise, adjacent scanned paths could not be bonded together properly. Therefore, the final fabricated part will be very fragile. In addition, the
surface of the part may be uneven at too small scan spacing distance (Ilkgun, 2005; Gibson et al., 2010; Aldahsh, 2011; Hasmi et al., 2014).

Figure 2.14: Scan spacing (Ilkgun, 2005).

2.3.5.1.5 Scanning strategy

Ilkgun (2005); Gibson et al. (2010); Aldahsh (2011) and Hasmi et al. (2014) stated that, the scanning strategy of the laser beam used for building a layer is controlled through a machine operator which possibly “fill only” (i.e. a strategy which can produce the part faster but less accurately), or a strategy which both “fills and outlines” (i.e. to produce a part more slowly but with greater accuracy) (see Figure 2.15). Ilkgun (2005) reported that the laser scan proceeds by a “fill” or a “fill and outline” method depending on the slice (layer) geometry obtained from the STL file.
2.3.5.1.6 Energy density

One of the important SLS fabrication parameters is energy density. It is energy transferred to the surface of the SLS part bed. Laser power, laser scanning speed and scan spacing are factors on which energy density depends. To produce functional SLS parts having good quality, it is required that the powder lying on the surface of the part bed will get a sufficient amount of energy density during the SLS process. The energy density can be determined by the following equation 2.2. The presence of high energy density of a laser beam results in better fusion of polymer particles, consequently ensuring decreased porosity and enabling a more dense structure to be built. Moreover, very high energy density leads to degradation of the polymer, hard part cake, difficulty while removing the build part, more surface roughness, and a light brown colour on the surface of the part appears due to overheating. In contrast, the part is likely to have insufficient bonding among powder particles and then
higher porosity resulting in the fabrication of weaker part at low energy density levels (Caulfield et al., 2007; Pham et al., 2008; Beal et al., 2009; Tiwari and Pande, 2013).

2.3.5.1.7 Slice thickness

Slice thickness is the powder thickness of each layer in the part build cylinder which decides the depth to which the part piston lowers for each layer and the height at which the roller counter rotates from one of the feed cartridge units to other onto the SLS part bed. In addition, slice thickness is a vital factor which affects, both the building time of the SLS process as well as the surface roughness of the fabricated part. The fabrication of parts with thinner slices can reduce surface roughness, however, the building of parts takes more time. Though thicker slices can save time, however, they might diminish the fabricated parts dimensional accuracy with a stair step effect as shown schematically in Figure 2.16. In the EOSINT P395 system, slice thickness is kept in between 0.06mm to 0.15mm and the default setting is 0.12mm (Gibson & Shi, 1997; Jamal, 2001, Tiwari and Pande, 2013). Roller counter rotations may affect slice thickness, that is to say, high rotation speeds may cause powder being pushed in front of the roller. Moreover, setting too low roller speeds, on the other hand, increases part processing time. The greatest slice thickness is limited by the penetration depth ($D_p$) of the powder. Consequently, penetration depth ($D_p$) is based on laser power, energy density and material properties such as particle size, powder density, specific heat and thermal conductivity. Therefore an appropriate slice thickness of the powder must be set to fulfil the requirements of the application (Gibson & Shi, 1997).
2.3.5.1.8 Heater control

The powder in the SLS machine is heated with a specific device (i.e. heater) to a temperature just below the melting point of the material prior to exposure, in order to decrease heat stress to the lowest possible degree and for better sintering using the laser beam. To maintain and control the temperature of the powder during this process three heaters are employed in the SLS system. The heaters are positioned above the part bed and two feed cartridge units. Out of three heaters, one is the part heater which controls the powder part bed area and others two are the right and left heaters which are used to control the right and left powder feed cartridge units respectively. To monitor temperature at the surface and to adjust the heaters automatically, an IR sensor is used. The SLS system having one IR sensor monitors the only temperature at the top surface of the part bed, while thermocouples are used to adjust both the right and left heaters. Usually; in the SLS system material processing to build the parts takes place in three stages (Chua et al., 2010; Hasmi et al., 2014).

A. Warm up stage

During the SLS, the warm-up stage is the first step in the heating process and it stabilizes the temperature in the process chamber, part build area and in feed cartridge units to set the
level of temperature (see Figures 2.17 and 2.18). Depending upon the material to be used, the set temperature levels are adjusted for the part as well as for feed conditions by the SLS machine operator. Generally, warm up stage takes approximately 2 hours and at that time the roller does not initially travel to spread the powder. However, the part bed piston guides downwards while the SLS machine roller distributes 25.4 mm thickness of powder from the right and left feed-cartridge units to the part build cylinder (Yusoff, 2007; Aldahsh, 2011; Vasquez, M., 2012; EOS, 2013).

During this stage, to reach the set levels, the part bed powder temperature slowly rises as of 10°C to 12°C below the material melting point temperature. The set part bed heater temperature level detected once the surface powder in the part bed begins to varnish. Also, the temperature of the feed powder is gradually increased to its maximum possible level and reaches set temperatures at which it can still flow freely. The part feed heaters temperature set is found out once, surface powder in the part feed bed begins to crack. Small values of cracks are acceptable. At condition when the cracks are excessive, under such conditions temperature should be reduced in increments of 1°C until merely small cracks are visible. This limits the level of thermal shock, or cooling, from the feed cartridge powder lying on the part bed (Yusoff, 2007).

**B. Build stage**

This stage corresponds to keep constant, the temperature of the powder in the part bed and feed cartridge units (see Figures 2.17 and 2.18). The Part bed powder temperatures are generally close to the melting point of the material; hence relatively low laser power is required to melt the powder in each successive layer in the production of parts. Too much laser power will affect powder having in outside the part boundary and cause growth. On the
other hand, inadequate laser power will not fuse powder particles completely, thus resulting in the fabrication of weak parts which have too much porosity. Further, when build platform is lowered; the fabricated part is covered by the feed powder which subsequently cools it to the part bed temperature. The rate of cooling depends on the part’s geometry and its orientation during the build. Also, a variation in density of the part affects the cooling rate. The heating of the top of the part bed piston is made by piston heater and allows slowing the cooling rate of the first set of parts built and then reduces the thermal gradient and prevents distortion of the fabricated parts. If the rate of cooling is too slow, it may result in growth and on other hand if it is too high, warming and curling of the parts may occur (Yusoff, 2007, Vasquez, M., 2012; EOS system manual, 2013; Haerst et al., 2015).

C. Cool-down stage

This stage is the last process which allows the sintered parts to cool sufficiently in order that the fabricated parts and un-sintered powder can be taken out and separated from the part bed cylinder, as shown in Figures 2.17 and 2.18. Only after when the temperature falls below that of the glass transition of the material, the fabricated parts may be removed from unsintered powder. If not, they could curl and warp or deform. The period of this stage depends on the volume of the part which is to be build and the degree of the cylinder and piston heat. The cool down stage which takes more time will affect the properties and usability of the material, thus un-sintered powder which has been exposed to an extended period of cool down needs to be refreshed by an adequate amount of new powder (i.e. virgin powder) so as to produce good quality SLS parts (Chua et al., 2014; Aldahsh, 2011).
2.3.5.2 Consolidation mechanisms

In SLS, the densification of the powder particles is achieved through several binding mechanisms such as Solid State Sintering (SSS), Chemically Induced Binding (CIB), Liquid
Phase Sintering (LPS) – Partial Melting (PM) and Full Melting (FM). These consolidation mechanisms directly affect the microstructure and fabricated part characteristics (Kruth et al., 2005).

1. **Solid State Sintering** (SSS) is one kind of binding mechanism which takes place at a temperature between half of the melting point temperature and the melting point temperature of the material. Throughout sintering process physical, chemical reaction and diffusion neck formation between adjacent powder particles take place. Particle growth together results in sintering thereby lowering the free energy. In addition, the solid state sintering mechanism binds and consolidates a variety of materials through volume diffusion. By preheating of powder material, the limitation of slow solid state sintering process rate is avoided to get essential laser scanning velocity.

2. In **Chemically Induced Binding** (CIB), heating particles are at very high temperature, the partial disintegration of the mixture takes place where free form acts as a binder (e.g., Sic, Al$_2$O$_3$ and SiO$_4$).

3. The **Liquid Phase Sintering–Partial Melting** (LPS-PM) is classified as, different binder and a structural material; and no distinct binder and structural material.

(a) In the case of different binder and structural material type liquid phase sintering–partial melting consolidation mechanism, the structure material remains solid while binder material is melted.

The LPS-PM consolidation mechanism is furthers classified as,

(i) Separate grains type binding mechanism - In this type LPS-PM consolidation mechanism, the structural material is either metal or ceramic and the binder material is
mostly metal wherein binder particles are small in size as compared to structural particles. The similar type mixture of material gives better packing with small pores and drives high capillary force for rearrangement of particles during SLS. Porous green parts are formed which may be post-treated in furnace and further to get fully dense part infiltrating with low melting point material (e.g. metal-metal composite as Fe-CU, stainless steel –Cu and metal-ceramic composite as WC-Co, WC-CuFeCo, TiC-Ni/Mo, ZrB₂ –Cu and TiB₂-Ni etc.).

(ii) Composite grain type binding mechanism has high green density and high surface texture (e.g., WC-Co and glass filled polymer powder).

(iii) In coated grain type binding mechanism LPS-PM both binder and structural material are coated with structural material within the binder phase. This is done to make sure that the laser power is completely absorbed by the binder material during SLS process.

(b) In no distinct binder and structural material type consolidation mechanism only difference is in between molten and non-molten areas which take in single phase, partial molten and fusing powder mixture.

4. In full melting binding mechanism polymers as well as metals are completely molten with objective to fabricate dense part with better mechanical properties and to avoid post processing of parts. The full melting type binding mechanism category comprises of types as, single component single material powder-partial, single component alloyed powder and fusing powder mixture to fabricate fully dense part (Kruth et al., 2005, 2007, 2008, 2010).

2.3.5.3 Materials used in SLS and their applications

One of the main advantages of the SLS process as compared with other AM techniques is its capability for making parts using different, non-toxic multiple materials, as basically any
material which is in powder form may be used, such as thermoplastics, metals, ceramics and composites through direct sintering, or indirectly by using a low melting point binder (Hon & Gill 2003). Usually, the SLS process uses a finer particle size to fabricate a thinner layer, better resolution, lower surface roughness and less shrinkage of the part (Kurth et al., 2003). The varieties of materials with different properties have been developed to meet the requirements of different applications. Materials usually used in the SLS process are given here (Boivie, 2000; Pham & Dimov, 2000; Cooper, 2001; Paramount, 2009; Chua et al., 2010; Chua et al., 2014; Tiwari et al., 2013; Tiwari et al., 2015).

2.3.5.3.1 Polyamide 12

Polyamide 12 is a semi-crystalline polymer material which is most commonly used to fabricate the parts through SLS process. It has low processing temperatures, melting flow control and ease of production during the SLS process. Additionally, the semi-crystalline polymers have proportion of shrinkage about 3%-4% and this is because of the fact that the SLS process involves a thermal stage (Pham et al., 2000; Jamal, 2001; Kurth et al., 2003; Chua et al., 2010; Gibson et al., 2010; Thomas et al., 2011; Hasmi et al., 2014; Haerst et al., 2015; Yuan and Bourell, 2015). The Polyamide 12 powder has spherical particle shape and is irregular to a considerable degree. The average size of the particles is about 60 micrometers. Further, Polyamide 12 material has good physical properties, such as a high melting temperature because of strong hydrogen bonding. Polyamide 12 is used in SLS process to create models; prototypes and nowadays for making end-use parts (Kotlinski, 2014). The parts made using Polyamide 12 deliver good long-term stability, offering resistance to most chemicals and it is also harmless to the environment and safe to use with foodstuffs. Moreover, the made-up parts are durable and offer good heat-resistance. The fine particle
size produces good quality dense parts (Zarringhalam et al., 2006; Yusoff, 2007; Tiwari and Pande, 2013).

2.3.5.3.2 Metal

The metallic materials such as, steel, aluminum, alloys and composites can also be used in the SLS process. The SLS of metals is done through indirect and direct methods. During indirect SLS, the metal powder being mixed with a thermoplastic binder to fabricate the ‘green part’. The green part is porous, and thus to obtain a completely dense part, it may be infiltrated with copper or bronze. The direct SLS (DMLS) process employ metal powder blends without any binder material. Preprocessing and post processing stages are eliminated by using DMLS. Generally, metal is used in the SLS system to create a mold cavity and core inserts for tooling. It gives superior material properties; hence the metal is strong enough to produce more than 50000 parts when used for rapid tool moulds. Apart from that metal posses very good corrosion resistance and mechanical properties and is widely used in different fields of applications (Das et al., 1998; Karapatis et al., 1998; Dewidar & Dalgarno, 2001; Cooper, 2001; King and Tansey, 2002 & 2003; Kumar, 2003; Kruth et al., 2004; Kobryn et al., 2006; Bertrand, 2007; Higa, 2011; Chua et al., 2010 & 2014; Hasmi, 2014).

2.3.5.3.3 Polystyrene / CastForm

Polystyrene is an amorphous polymer widely used in the SLS process. CastForm is ‘investment-caster’ compatible powder that possesses low ash content and is friendly with standard foundry practices. The processing of CastForm involves two main phases: a green part produced by SLS and followed by wax infiltration. The green part is 45%, consequently is very brittle, because of its limited material properties. Further, the part fabrication is completed by dipping the made part into molten red foundry wax. CastForm material
patterns involve few modifications to standard foundry practices, and are rapidly and simply removed. Low density polystyrene and high quality foundry wax guarantee a clean pattern. In addition, CastForm allows a fast track route to metal castings, such as titanium, aluminium, magnesium, and zinc. On the contrary, CastForm has a few disadvantages in that it is very complicated and risky to clean away loose powder, as the part strength is very low at this stage and some features possibly will deform and break (Gubbels et al., 1994; Pham et al., 2003; Dotchev & Soe, 2006; 3T AMD, 2008; Paramount, 2009).

2.3.5.3.4 Polycarbonate (PC)

Polycarbonate is an amorphous thermoplastic which has been used widely in the SLS process. The PC powder is supplied by 3D Systems. In addition, PC powder has a broad size distribution and irregularly shaped particles with a mean diameter of 90 micrometers. PC reveals good thermal stability characteristics and can fabricate parts with extremely superior dimensional accuracy, feature resolution and surface finish. The parts produced using PC have moderate strength and durability attributable to the porous structure, so they are only valuable for applications that do not require part strength and durability. To further improve mechanical properties, parts can be infiltrated with an epoxy resin. PC is usually considered as a polymer which is to be used for sacrificial patterns during investment casting, as the porous structure of the PC parts put off them from expanding succinct of ceramic shell cracking (Nelson et al., 1993; Jamal, 2001; Kruth, et al., 2003; Fan et al., 2005; Berzins et al., 2007).

2.3.5.4 Common problems related to the SLS process

SLS fabricated part quality depends on SLS process parameters. These parameters are set differently in relation to powder properties and the requirements of the application.
Moreover, optimized process parameters can reduce many problems, reduce geometrical inaccuracies and improve fabricated part properties by observing part-build; therefore suitable process parameters can be established satisfying the application requirements. However, Changes in some process parameters may affect other parameters and needs adjustment. Reason being based on the materials used, the SLS manufacturers have specified default values for all process parameters. Frequent problems regarding the SLS process, together with a brief description, and the causes, results and corrective action are presented in the following section (Yusoff, 2007; Jamal, 2001; Aldahsh, 2011).

2.3.5.4.1 Powder fluff

Powder fluff is an observable fact identified when the powder material has a higher packing density at the bottom of the feed powder cartridge units than it has on the top (see Figure 2.19). This phenomenon takes place when powder is not uniformly consolidated in the loading process as a result of short feeds in the initial part of the build, thus resulting in low quality parts.

![Powder Cartridge Filled](image)

**Figure 2.19:** Schematic view of powder fluff (Aldahsh, 2011).
It has been recommended as a corrective measure to minimise powder fluff by compressing the powder by a flat plastic or heavy cardboard plate, the same size and shape as the feed-cartridge. This is pressed down onto the cartridge (Boivie, 2000; Zhou, 2009; Aldahsh, 2011).

2.3.5.4.2 Cracking of part bed and feed cartridge

The surfaces of the part bed and feed cartridge can crack open when the roller moves across them (see Figure 2.20). This occurs because of an excessive heating rate from the part bed and feed heaters, causing partial melting of powder on the part bed and feed surfaces. Consequently, the part cracks if it is built above the seam area that is cracking. To avoid this problem it has been suggested that the part bed and feed heaters set points are decreased in increments of 2°C until the crack disappears (Aldahsh, 2011).

Figure 2.20: Cracking appears in part-Bed and feed-cartridge (Aldahsh, 2011).

2.3.5.4.3 Clumping

Clumping refers to agglomerated powder on the powder-bed surface, before the roller as it moves across the part-bed. These results in streaks or cracks of powder part-bed surface
become visible behind the roller (see Figure 2.21). Agglomerated powder builds up due to moisture, recycled powder, overheated powder in the feed-cartridges, also inadequate sifting. It results in streaks, that become visible behind the roller, and uneven powder thickness, which may cause growth or insufficient melting and poor quality parts. It has been suggested that the set temperature points for the left and right feed-heaters are reduced and that recycled powder is systematically sifted before use in order to avoid this problem (Abid, 2009).

![Figure 2.21: Schematic view of clumping (Abid, 2009, Aldahsh, 2011).](image)

**2.3.5.4.4 Crystals and condensation**

Crystals and condensation obvious in small amounts of volatile material which vaporise in SLS processing (see Figure 2.22). This phenomenon takes place because of extreme part-bed temperatures and can result in crystals or condensation forming on the lens of the IR sensor, which may subsequently cause incorrect part-bed temperature readings, with an extremely difficult or impossible break out and melting of the part-bed. Crystals or condensation on the laser window can also decrease the amount of laser power delivered to
the part-bed surface, resulting in weak or curled parts. As a corrective measure, EOS recommends cleaning the IR sensor and laser window before, but not during, each build. Once the build has started, however, no corrective measures are taken (EOS operating manual, 2013).

![Image of IR sensor and laser window with crystals and condensation](image)

**Figure 2.22:** Crystals and condensation on the lens of the IR and laser window (EOS operating manual, 2013).

### 2.3.5.3.5 Bonus Z

Bonus Z is a phenomenon identified while the laser melts a part beyond the specified depth (generally about 0.004 inch (0.1 mm)) in the first few scans and causes vertical growth in the Z axis. The distinction between growth and bonus Z is that growth may occur on any part edge, while bonus Z occurs merely on downward-facing surfaces (see Figure 2.23). This phenomenon takes place because of the laser penetrating the un-sintered powder below the part boundary, resulting in a part dimension outside the tolerance range of the Z-axis. To avoid this problem, the chance of bonus Z should be minimised by reducing the temperature time relative to the powder bed and the fill-laser power for the first few layers (between the
first and fourth layers). Constant offset in the Z dimensions of the STL file is applied by the offset. The Z offset has an effect on only downward-facing surfaces by moving them upward, in line with the specified distance (Ho et al., 2002; Dewidar et al., 2003; Aldahsh, 2011).

![Schematic View of Bonus Z](image)

**Figure 2.23:** Schematic View of Bonus Z (Ho et al., 2002; Dewidar et al., 2003; Aldahsh, 2011).

### 2.3.5.4.6 Curling “in-build”

Curling is a phenomenon identified while the edges or corners of the part rise above the powder part-bed surface. The parts may get thinner in the Z-axis, as shown in Figure 2.24. This phenomenon takes place because of temperature difference and the part temperature dipping too low after the feed-powder is added. Curl can also occur if the part-bed temperature is too low (Jamal, 2001; Min Hur et al., 2001). Consequently, parts are not flat, particularly where large surface-area cross-sections are concerned and the part may approach the part-bed while the roller passes over if the curling is severe. It has been recommended to increase the set point values for the left and right feed heaters to the highest possible temperature at which the powder can still flow freely to avoid curling “in-build”,

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Increasing the powder-bed temperature may also reduce heat transfer from the build to the powder part-bed. In addition, reducing left and right feed distances may also cut down on curling “in-build” (Jain et al, 2009; Aldahsh, 2011).

**Figure 2.24:** Schematic view of curling “In-Build” (Jain et al., 2009; Aldahsh, 2011, EOS operating manual, 2013).

**2.3.5.4.7 Curling “post-build”**

Curling “post-build” is identified while the final product is not flat, however, the Z dimensions are still correct. These cases are thus unlike from curling “in-build” (see Figure 2.25). Here, curling takes place because of too much cooling rates when the heater temperature decreases quickly and the part is prematurely removed from the process chamber. Consequently, parts are not flat, particularly where cross-sections with a large surface area corresponding to the correct Z dimensions are concerned. To avoid this problem, it is recommended that the temperature of the powder-bed and left and right feeds
should be increased. The part-cake should be allowed to cool for longer inside the SLS machine and then left to cool fully outside the machine prior to parts are removed from SLS machine (Jamal, 2001; Aldahsh, 2011; EOS operating manual, 2013).

![Figure 2.25: Schematic view of curling “Post-Build”](image)

**Figure 2.25:** Schematic view of curling “Post-Build” (Jamal, 2001; Aldahsh, 2011; EOS operating manual, 2013).

### 2.3.5.4.8 Growth

Growth is a phenomenon identified while additional powder sinters on the part, results in changing its dimensions. Growth is mainly evident in fine detail or small apertures. The distinction between growth and bonus Z is that growth may occur on any part edge, while bonus Z occurs exclusively on downward-facing surfaces (see Figure 2.26). Growth occurs because of too much laser power and part bed temperatures, therefore leading to heat diffusion beyond part boundaries and resulting in extra-large parts and parts which possibly difficult or even impossible to break out. To avoid this problem, reducing part-bed
temperature and fill-laser power is suggested (Shi et al., 2007; Aldahsh, 2011; EOS operating manual, 2013).

**Figure 2.26:** Schematic view of “Growth” (Shi et al., 2007; Aldahsh, 2011; EOS operating manual, 2013).

2.3.5.4.9 Missed-scan

A missed-scan is recognised while the laser beam does not entirely scan the fill area of a part (see Figure 2.27). Missed-scans happen when an error in the STL file received from the CAD model does not have correctly connected with surface patches. This problem is not material-related but will cause incorrect part geometry and possibly poor part properties. It has been suggested to verify that the STL and CAD files are correct, or else to create new files, as a corrective measure, (Chen et al., 2001; Dimov et al., 2005, EOS operating manual, 2013).
**Figure 2.27**: Schematic view of a “Missed-Scan” (Chen et al., 2001; Dimov et al., 2005, EOS operating manual, 2013).

### 2.3.5.4.10 Weak parts/porosity

This problem is recognised when parts emerge porous and solid, which means that the part will subsequently be brittle and have low density (see Figure 2.28). These cases occur when the laser window is covered by crystals and laser power is therefore inadequate. Also, they occur when laser speed is very high. This causes for low strength and density in the parts fabricated. Corrective performance comprises, cleaning the laser window, increasing fill-laser power in the build, raising part-bed temperature with decreasing the laser speed (Hon, 2003; Schmidt, 2007, EOS operating manual, 2013).
2.3.5.5 Previous studies of composite material used in SLS

2.3.5.5.1 Glass-filled polyamide 3200

PA 3200 GF is a composite material formed by addition of glass bead with polyamide. The glass bead filler particles are of regular shape and have about 50μm an average particle size. The material has a high-melting-point. However, Polyamide 12 used in composite acts as a binder and the glass particles acts as a structural material. During sintering of PA 3200 GF composite in SLS machine, the Polyamide 12 particles are fully melted, and the glass particles remain solid. Glass-filled polyamide has greater mechanical properties, such as rigidity and flexural qualities as comparison to Polyamide 12. Besides, the glass bead is selected to reinforce the Polyamide 12, as a result improved strength, dimensional stability, rigidity and heat resistance is achieved. The glass-filled blend is suitable for fabricating rigid parts proposed for production in advanced, engineered thermoplastics, and is the exact choice for functional testing (Childs & Tontowi, 2001; Cooper, 2001; Mazzoli et al., 2006; Abid, 2009). In contrast, one of the drawbacks of PA 3200 GF marketed by EOS is that it is more costly than Polyamide 12, which is also supplied by EOS.
2.3.5.5.2 Aluminium-filled polyamide (Alumide™)

Alumide, a new composite material consisting of two materials, polymer as base material and aluminium as filler is developed by EOS GmbH. The aluminium filler has an average particle size of 45 μm and the particle size distribution (90% volume distribution) is in the range 26–75 μm with an elevated melting point about 660 ºC (EOS, 2008; Mazzoli et al., 2006; Yan et al., 2009). In this composite system polymer particles acts as binder because they have a low melting point. Alumide™ has a high dimensional accuracy, can stand at high temperatures and has improved mechanical properties, such as tensile and flexural modulus. Besides, Alumide™ gives a greater surface finish, also improved finishing properties for many functional prototypes. The aluminium-filled polyamide powder was developed owing to the need to manufacture models with outstanding dimensional accuracy and resistance to mechanical stress, particularly bending strength and the ability to withstand high temperatures (Mazzoli, 2006). A typical application for Alumide™ is the fabrication of stiff parts, with a metallic appearance, mainly in the automobile industry (e.g. wind tunnel tests), tool inserts for injecting and moulding small production runs, education, also in high accuracy medical models. Furthermore, the surface of Alumide parts can be refined by grinding, polishing, or coating. Further, low tool-wear machining is possible for this material (e.g. milling and drilling) (Subramanian et al., 1995; Mazzoli et al., 2006).

2.3.5.5.3 CarbonMide®-Carbon fibre-filled polyamide

CarbonMide is a new composite material commercial marketed by EOS. In this composite system, a carbon as a filler and polyamide is as binder to produce black parts. CarbonMide has an additional commercial name, Windform XT, which has nearly the same characteristics. The parts manufactured through the SLS process using CarbonMide possess
excellent mechanical properties characterized by high stiffness levels, high tensile strength, and also tensile modulus. In addition, they possess low density, electrical conductivity, a smooth finish and a sparkling look. A typical application for CarbonMide is the fabrication of fully functional prototypes having high-end finish for applications in the automobile industry, such as wind tunnel tests or other aerodynamic applications. Blocher, the managing director of FKM (2008) has explained that CarbonMide has a great potential in the manufacture of large, mechanically loaded parts for racing and sports cars (Jain et al., 2006; EOS, 2008).

2.3.5.5.4 Silicon Carbide/Polyamide

SiC/Polyamide composite has been developed to fabricate part of superior functionality by SLS. The SiC/Polyamide composite material consists of two materials, polyamide as a base material and silicon carbide as a filler material. The silicon carbide selected for reinforcement to form particulate composite has an average particle size about 44.5 μm. Furthermore, filler is angular in shape as compared to the polyamide; also possess a high-melting-point about 2700 °C. The polyamide powder is thus used as a binder due to its low melting point (Gill & Hon, 2004). At optimized parameters, simple and complex shapes are easily fabricated with this material. Further, SiC/Polyamide composite can be infused with metal by means of using an infiltration process to produce both metal matrix as well as ceramic matrix composites, such as by infiltrating aluminium matrices into SiC during a nitrogen atmosphere and at temperature about 750-850° C, wherever the polymer was removed by heating. The loadings of Silicon Carbide near 45vol. % are usually achieved. At this vol. % of Silicon Carbide, properties reported as moduli about 180GPa and a 4-point bending strength about 275MPa. Besides, the composite have the ability to form complex
geometries that are not obtained by a casting process with shrinkage of less than 1%, also possess minimum machining after infiltration (Vail et al., 1993; Beaman et al., 1997; Gill & Hon, 2004).

**2.3.5.5 Copper polyamide (CuPA)**

Copper polyamide is a metal-plastic composite of a copper powder and polyamide blend developed by DTM in year, 1998 to use during the SLS process for fabrication of parts (Pham & Dimov, 2000). Tooling inserts are formed with a layer thickness of 75μm. In addition, it is essential to finish the tools prior to their integration in the tool base. Further, unfinished tool inserts can be produced in a day, also no furnace cycle is required. CuPA composite is developed to make tooling for short production runs of equivalent plastic parts having conformal cooling, good thermal conductivity, heat resistance and durability. CuPA composite material is able to be built into mould tool inserts by the SLS machine as like PA materials (e.g. PA2200). Furthermore, the advantages of using CuPA are many. It is significant and appropriate for injection moulded inserts used for producing several hundred parts (100–400 parts) from familiar plastics such as polyethylene (PE), polypropylene (PP), polystyrene, ABS, also PC/ABS. In addition, the surface of parts fabricated using CuPA can be easy to machine and finish the part. However, the parts fabricated using copper polyamide is costly because material cost is too high (Pham & Dimov, 2000; Levy & Schindel, 2002; King & Tansey, 2002).

**2.3.5.6 Nanoclay/PA2200**

Nanoclay/Polyamide 12 composite has been developed by Jain et al. (2009) to use with SLS process. In study of SLS process of blended powder of polyamide (PA), and organically modified nanoclay, the effect of nanoclay on the sintering parameters, and mechanical
properties of sintered parts were investigated (Jain et al., 2009). It has been observed that the ultimate tensile strength, elongation at break, and other properties of the PA/clay composite SLS specimens degrade relative to pure PA2200 SLS specimens. It has also been suggested that the suitable part bed temperature needed to be optimized for the blended powder to avoid part curling (Jain et al., 2009). The tensile modulus achieved at 2wt% addition of Nanoclay in PA12. The inclusion of Nanoclay (more than 5wt %) in PA12 become difficult so it good to add lesser wt% (<5wt %) of Nanoclay filler in PA12 to get better part properties.

2.3.5.5.7 Cement/Polyamide 12

Cement/Polyamide 12 composite has been developed by Aldahsh (2011) for use with SLS. It consists of two materials, polyamide 12 and cement as filler rigid particles. The cement filler has an average particle size of 15μm and is irregular in shape when compared to the polyamide, with a high-melting-point of around 1400 ºC. The polyamide powder is therefore used as a binder because of its low melting point (Gill & Hon, 2004). Simple and complex shapes are easily produced with this material by using optimized parameters. The proportion of cement filler added in polyamide 12 was (0-40%). The tensile strength achieved maximum (about 51.5MPa) at 10wt% cement filler addition while further addition of cement filler in PA12 decreases the tensile strength of the part fabricated through SLS process. The addition of cement filler in PA 12 gradually decreases the elongation at break % of SLS parts while tensile modulus increases and it is about 2800MPa at 40wt% addition of filler in PA12. Also addition of cement filler in PA12 increases the flexural modulus and it is maximum (2500MPa) for 40wt% filler. The maximum flexural strength and compressive strength (about 60MPa) is achieved at 40wt% filler.
2.3.5.8 Flame retardant polymer material

It has been reported by Laoutid et al. (2009) that improving the flame retardant characteristic of polymer is new concern to fulfill the requirements of the various field of application and it is achieved through the polymer nanocomposites, i.e. polymer matrices filled with specific, finely dispersed nanofillers, which will give excellent thermo-mechanical performances with enhanced flame retardant behavior. The nanofiller materials used as filler are metal hydroxide, phosphorous, silicones, silica, nanoclay, carbon nano tubes and nano scale particulate additives.

2.4 SLS process research group

Worldwide many researchers have dedicated much of their research activities in engineering, medical, and material development for the SLS process. To make this process more viable, researchers are working together with the close integration of engineering, material science and medical disciplines. The partial list of research groups and their areas of research have been listed (Tiwari et al., 2015). Although the list majorly belongs to university research formed groups, however some industrial research groups working in this field have also been included. Every part of information provided in this section was collected from their web pages, articles, and AM annual reports. Also, the list is not comprehensive; there may be numerous other groups in the process of research activities listed below.

2.4.1 SLS medical application research group

The groups of AM that are keenly involved in medical applications are classified in several subcategories.

1. Research groups involved in surgical planning
o Rapid Prototyping Centre, Milwaukee School of Engineering, USA: This group uses Duraform Flex, Durform PA, and ALM GF for surgical application.

o Design and New Product Development Group, De Montfort University, UK: The persons of this group are involved in Maxillofacial and orthopedic surgery.

o Pontific Catholic University of Rio Grande do Sul, Brazil: The people of this group is involved in surgical planning for medical research.

o Rapid Prototyping Digital Modeling & Realization, Manufacturing ZGroup, Department of Mechanical Engineering, National University of Singapore: This group is keenly working in the orthopedic surgery.

o Biomedical Modeling Inc: This group produces the models for CT & MRI scans used in surgical planning and implant fabrication.

2. Research groups involved in prosthetics and implants

The major groups involved in this area are:

o Virtual reality and Additive Manufacturing Laboratory, Missouri University of Science and Technology, USA: This group works in the direction of developing a bone surgery simulation system which involves the integration of VR technologies and biomechanics models to provide high-fidelity graphic displays and realistic haptic feedback in real time, during synthetic surgical operations.

o Industrial and System Engineering, North Carolina State University, USA: Herein group, medical imaging, CAD and AM technologies are used to develop and fabricate customs, medical implants, prosthetic devices, also medical instruments.
- Department of Mechanical and Materials Engineering, Queens University, Canada: This group is mostly involved in the fabrication of artificial joints, in knee mechanics and gait analysis.

- Design and Rapid Prototyping Lab, University of Florida, USA: This group is working on bone mechanics.

- Speed Scientific School, University of Louisville, USA: This group is working towards AM fabricated implantable strain sensors for spinal fusions.

- National Centre for Biomedical Engineering Science, National University of Ireland, Galway: This group is working to create parts for implantation and investigating the interaction of tissues with the materials using PMMA, PEEK, HA as material and SLS as a process.

- Medical Imaging Group, University College London, UK: This group is involved in the fabrication of titanium implants.

- OrthoCAD Network Research Lab, Indian Institute of Technology (I.I.T.), Bombay, India: The persons of this group is working on an interdisciplinary project to develop orthopedic implants and surgery planning software, focusing on Total Knee Prosthesis (TKP). The team comprises, engineers, surgeons and scientists from I.I.T. Bombay; Tata Memorial Hospital, Mumbai; Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad, India is also working on the same project.

Others:

- Indian Institute of Technology (IIT), Madras, India.

- Engineering Materials Research Group, University of Southampton, UK.
Additive Manufacturing Research Group (AMRG), School of Mechanical and Manufacturing Engineering, Loughborough University Leicestershire, UK.

Paulo Ferreira Research Group, University of Texas, USA.

3. Research groups involved in scaffold fabrication for tissue engineering

Substantial numbers of research groups are actively working herein area. The list of major groups working in this area is given below:

- Centre for Rapid and Sustainable Product Development (CDRSP): This group is a unit of Polytechnic Institute of Leiria, Portugal. In addition, this is actively in the process of developing a new solution for sustainable manufacturing and tissue engineering.

- Drexel University, USA: This group is involved in project titled “An Innovative Bionic Manufacturing System for 3-D Bone Scaffold and Tissue Structure” with the objective to construct composite bone scaffold, which integrates biomaterials research, bionic modelling, solid free-form fabrication, systems and control, also bone scaffold tissue engineering in one intelligent system.

- Direct Digital Manufacturing Laboratory, Georgia Tech University, USA: This group is in the process of computational design, fabrication and characterization of scaffolds for bone tissue engineering having predictable mechanical and transport properties.

- Mechanical Engineering Department, Babol University of Technology, Iran: This group is working in the fabrication of biodegradable tissue engineering scaffolds with FDM and SLS technologies.
Engineering Materials Research Group, University of Southampton, UK: They are in the process of 3D printing of PEEK and HA/beta-TCP Tissue Engineering (TE) Scaffolds.

Others:

- National University of Ireland – Galway (Nat Centre for Biomedical Engineering Science).
- Selective laser sintering Research Group, University of Applied Sciences Mittweida, Germany.
- Industrial and Manufacturing System Engineering, University of Hong Kong, Hong Kong.
- Department of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore.

4. Research groups involved in orthodontics and hearing aids

- The Institute of Material Science, University of Connecticut, USA.
- Paulo Ferreira Research Group, University of Texas, USA.

2.4.2 SLS material development research group

Following groups are keenly involved in material development for SLS process:

- Advanced Laser Material (ALM) based in Temple, Texas, USA: This group is involved in the development of newer grades of material for AM processes which include unfilled and filled nylon 11 and 12 materials. Also, some of which for high performance, fire retardant, high heat deflection temperatures (HDT), and for functional part fabrication applications.
- CRP Technology based in Modena, Italy: This group is involved in the development of a variety of grades of Wind WindForm® materials for SLS process used in the fabrication of high performing parts of wind tunnel applications, also used for fabrication of finished and functional prototypes.

- Exceltec based in Chassieu, France: The group is involved in the development of newer grades of the material of Innov PA series of polyamide powders used in automobile parts fabrication, also for making parts through SLS process used in HDT and fire retardant application.

- EOS, Germany: This group is involved in developments of PrimePart®, EOSPEEK, PA, PrimeCast® series of powders. Also, engaged in for development of metallic and composite powders used in to fabricate parts of medical, aerospace, automobile, rapid tooling, architecture and consumer goods application.

- MTT Technology, UK: The pure titanium, titanium alloys, aluminium alloys and tool steel and stainless steel powders for high strength, rapid tooling and medical applications are developed by this group.

- 3D Systems, USA: This group is in the process of development of a variety of materials like DuraForm®, CastForm™, etc. for testing prototypes, functional use, rapid tooling and rubber-like application.

- Arkema Inc., France: This group is in the process of development of the materials like, Luperox® Organic Peroxides line of products which are essential to produce plastics as PVC, PS, LDPE, PS, PMMA, UPR, etc. for various applications.

- iSQUARED, Germany: This group is in the process of development of AMAX and B30 materials for SLS and FDM process.
o Praxair Surface Technologies, Austin, USA: This group is in the process of development and providing gas material for SLS process.

o SIBCO Inc., Ferndale, USA: This group is in the process of development of Somos® series powders for SLS process.

o Solid Composites GmbH, Germany: Solid Composites GmbH involved in the development of new powder material solutions derived from PP and POM and functional filler material for SLS process.

o EnvisionTEC GmbH, Germany: This group is in the process of development of materials for various application including, medical, aerospace, manufacturing goods, sporting goods, also many others. Material developed by this system includes ABS and high temperature like polymer, polypropylene, also others.

o Additive Manufacturing Research Group (AMRG), School of Mechanical and Manufacturing Engineering, Loughborough University Leicestershire, UK: This group is in the process of development of composite materials and functionally graded materials for fabrication of parts used in aerospace, automotive, sports, also medical equipment.

o Additive Manufacturing and 3D Printing Research Group, University of Nottingham UK: This group is in the process of the development of next-generation multi-material and multi-functional laser sintering technology for aerospace, automotive, also for various medical applications.

o The National University of Ireland, Galway (Nat Centre for Biomedical Engineering Science): This group involved in the synthesis and characterization of new polymers
and composites materials which have the potential for using it to fabricate new
devices for medical application.

- Engineering Materials Research Group, University of Southampton, UK: They are
  keenly in the process of development of nanostructure material for implants and
  medical applications.
- The Institute of Material Science, University of Connecticut, USA.
- Department of Mechanical and Aerospace Engineering, Nanyang Technological
  University, Singapore: They are in the process of development of biomedical
  materials.

2.5 Value Engineering methodology

SLS technology has made considerable strides over the past 28 years, however, challenges
are still having with this process. These are mainly associated with materials and process
(Tiwari and Pande, 2012). To cope up with these challenges Value Engineering (VE)
methodology is used. VE is an established, effective, and sustainable tool for continuous
improvement and design development. VE aims to identify redundant cost associated with
any product, material, parts, component, system, or service through analysis of functions,
and efficiently eliminating them without impairing the quality and functional reliability,
which leads optimality (Mahajan, 2007). VE take account lowest life cycle cost, to realise
the essential function consistently, and cultivate the possibility to reduce the cost, and find
out the ways to improve the value of the product (USA Defense Department, 2011;
Mukhopadhyaya, 2013). We are users, and in user’s point of view, using value engineering
analysis principle and method to guide, organize and appraise innovation, to learn how to
enhance the quality of products, and how to reduce the cost, subsequently to design new
product or the oddness product with high quality which could meet the customer’s requirements. Thus, enterprise or company possibly will make more profit; the enterprise’s technological innovation could have the explicit direction which will direct enterprise competence. The relation between cost, value and function is expressed as:

\[
\text{Value (V)} = \frac{\text{Function}}{\text{Cost}} = \frac{F}{C} \quad \text{Equation (2.4)}
\]

where Function = The exact work that a design or a product or part must perform.

The equation 2.4 of VE indicates that Value depends on the combination of the function and the cost. Here are two ways to improve products value, one by decreasing production cost and other by removing products unnecessary functions. By critically examination of the above VE formula, it has been identified that there is several ways to improve product’s value i.e. function maintains, cost reduces; cost maintains, function increases; function decreases a little, cost decreases more in fact; cost increases a small, while function increases more in fact. While the customer appraises the mechanical product which he wants to obtain, he always considers the value in terms of the utility of this product and if it worth to buy. Merely combine the product function with its cost, combine the technical indicator with an economic indicator, can we make high-quality and low-price products, and make extra profit. In recent years, some studies have been limited to apply VE in only, management information system, architectural field, customer value analysis, government bid procurement etc (Mukhopadhyaya, 2013). Particularly, very little attention has been in the optimisation of material for selective laser sintering (SLS) process of AM. The purpose to use value engineering is to validate, the design and material of the assembly or subassembly or part of the product, and to step back and look at the total image and function for SLS process. Thus, the specific objectives of this work are to undertake a study to adopt
the VE method in SLS process for reducing the cost of material without impairing the function of the product.

In this regards approach is made to get the answer of questions associated, what is the item? What function does it perform? What does it cost? What else will do the function? What will be the cast?

VE method steps consist of, orientation phase, information phase, functional analysis phase, development phase, presentation phase, implementation phase, and last step are follow-up phase.

Phases of VE: Different VE phases are described below.

- Orientation phase: It involves identification of problem very obviously, selection of project, stating objective and target and in detail training of all the members.
- Information phase: This phase begins after clearly identifying what is to be accomplished. Herein phase all the significant information, like material, drawing and technical specification, manufacturing processes, detail cost break, performance/failure report, quality, procurement and production problem are collected in short.
- Functional analysis phase: This phase involves analysis and identification of functions of the products.
- Creative phase: This phase is the core of VE. In this phase, the entire likely alternatives are generated. This can be achieved through brainstorming and other creative techniques so as to generate a large number of ideas associated with material for attaining the functional requirement.
Evaluation phase: This phase involves analysis of probably developed alternatives. Further, the cost of each idea is also estimated. The critical evaluation of every point of the solution is carried out. The idea, related to material which promises greatest saving are screened and shortlisted using short listing techniques like feasibility ranking etc.

Development phase: This phase engage examination of shortlisted ideas in depth to arrive at an optimum and practical solution.

Presentation phase: The presentation phase involves the presentation of preferred alternatives to the decision makers for consent and implementation.

Implementation phase: This phase involves execution of results of above phases which is definite, specific and tangible solution accepted to all.

To stimulate creative ideas in VE, a test checklist is issued, which is consisting of a subject, basic questions analysis, and answer. Because the subject is of material so the basic question is asked what is the material specification? , and analysis is done by asking subsequent questions like as, Can less expensive material be used? Can a more expensive material have easier machining properties? Are the newly developed materials can be used advantageously? and can the size or weight of material be reduced?. Subsequent to that will get answers. Figure 2.29 shows the depiction of VE job plan phase and VE savings potential during the life of a typical material selection system (Mukhopadhyaya, 2013). By continuously applying VE technique in the product can result, saving in materials, saving cost and increase in functionality, acceptability, sustainability reliability and durability of the SLS fabricated products obtained (USA Defense Department, 2011; Mukhopadhyaya, 2013).
Figure 2.29: Depiction of value engineering job plan phase.
The cost per part for SLS system is calculated through a formula which includes the factor as like; use full life of machine in years, depreciation cost per year, hours per year, machine cost per hour etc. Moreover, after finding out the part function and cost per part for various material, design and parameters, the value of the part can be analysed, and the part material, parameter, and design which impart superior value with lesser cost can be adopted for fabricating part in SLS process.

2.6 Summary
This chapter presents a brief description of AM process, AM market trends, common AM processes with the focus on SLS technology for EOS Systems. SLS is considered one of the most popular AM techniques. In the SLS process, the main fabrication parameters which influence the quality of sintered parts are described. The consolidation mechanism which influences the sintering of parts is also described. Some of the common materials employed to produce RT and RM parts by SLS are presented. The main problems with using Polyamide 12 powder produced through SLS are highlighted, followed by a description of previous studies of composite material used in SLS. The various research groups around the globe working in the field of AM material developments and medical application is described. Finally, an optimisation technique “Value Engineering” is described.