Literature Review

Based on this knowledge the work of others relating to selective laser sintering (SLSLM) of metal is reviewed, leading to a statement of aims for this PhD project. Provides background information to explain the importance of the SLS process for rapid manufacturing applications. SLS is discussed alongside other processes used in rapid manufacturing. The process is described with reference to hardware, materials and the manufacture of freeform structures. Machine parameters and the characteristics of parts. Concentrates on modes of heat transfer in the SLSLM process. Equations describing heat transfer mechanisms are reviewed. The effect of laser heaton SLSLM [P. Jacobs, 1992] materials is examined full potential of this emerging manufacturing. Some rapid manufacturing methods are described, and the nature of output parts is discussed.

Needs of Manufacturing Industry

New technology and new working practices have affected the contemporary industrial product design process in many ways. The integration of new technology and practices has helped manufacturing industry to meet its evolving needs. Described below is the current state of the product design process, which leads to an understanding of why technologies such as the type researched in this work have been so quickly adopted by manufacturing companies across the world. From the scale of a single-piece child's toy to automobile comprising thousands of parts, manufacturers are perpetually involved in the business of product development. A team of people is assigned a specific product development task to complete in a given time, using given resources. Teams are multi-disciplinary, consisting of engineers, industrial designers, purchasers and marketers amongst others. All groups must bring their specialized knowledge to bear on the product, in order to define the details of its form and function. The product is then brought to the manufacturing stage, before being released to market. What has been identified is that multiple, rapid repetitions of the early product development loop (analyze, evaluate and refine) are required. This loop may involve visualization and testing in the computer environment, but will also require rapid realization of 3D CAD [X. Yan, P. Gu, 1996] geometry, i.e physical model-making. This will facilitate communication of design developments to a broad range of people, and will allow limited product testing, both of which can drive future design iterations. Such a group of methods for CAD data realization has recently become available, collectively known as solid freeform fabrication (SFF)[ Karapatics N., 1999] methods. Their ability to quickly create solid objects has attracted interest from people inside and outside manufacturing
industry, leading to many novel applications. Discussed in the next section is the value to manufacturing industry of technology not only for creating prototypes, but also for generating mass production forming tools.

**LS and Layered Manufacturing**

LS, as one of the material additive manufacturing techniques, has shown tremendous potential for different fields of applications such as coating [D. Bunnell, 1995] rapid prototyping [Chua, K. Leong, 2003] and parts repair. Using LSFF, a fully functional near-net-shape three dimensional (3D) object can be fabricated directly from its CAD model by successive layer-by-layer metallurgic ally bonded deposition of metallic materials. In this process, a laser beam is utilized to melt a thin layer of a moving substrate and powder particles, deposited on the process domain, to form a small track. Each track (clad)[ J. Pinkerton, 2004] is created by rapid solidification of the additive materials together with a thin layer of the moving substrate, or previously deposited tracks.

**Important SLSLM Process**

**Stereo lithography**[D.T. Pham, R.S. Gault, 1998]:- It is the most widely used rapid prototyping technology. Stereo lithography builds plastic parts or objects a layer at a time by tracing a laser beam on the surface of a vat of liquid photopolymer.

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**Fig.1(a) Steorolithography**
Laser Engineered Net Shaping™ (LENS ®) [C.P. Paul, 2007][P. Kulkarni, 2004] and similar laser powder forming technologies are gaining in importance and are in early stages of commercialization. A high power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head.

FDM is the second most widely used [D.T. Pham, R.S. Gault, 1998] rapid prototyping technology, after stereo lithography. A plastic filament is unwound from a coil and supplies material to an extrusion nozzle. The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off. The nozzle is mounted to a mechanical stage which can be moved in both horizontal and vertical directions.
Selective Laser Sintering [M.M. Sun, J.J. Beaman, 1991]: The process is somewhat similar to stereo lithography in principle as can be seen from Fig. 2. In this case, however, a laser beam is traded over the surface of a tightly compacted powder made of thermoplastic material (A). The powder is spread by a roller (B) over the surface of a build cylinder (C). A piston (D) moves down one object layer thickness to accommodate the layer of powder. The powder supply system (E) is similar in function to the build cylinder. It also comprises a cylinder and piston. In this case the piston moves upward incrementally to supply powder for the process. Heat from the laser melts the powder where it strikes under guidance of the scanner system (F). The CO2 laser used provides a concentrated infrared heating beam.

![Fig. 2 Selective Laser Sintering](image-url)
Model of the SLS process

The physical processes associated to the SLS process are mainly the heat transfer and sintering of powder. Based on previous work done by Sun and co-workers [M.M. Sun, 1991], the modeling and numerical simulation of the SLS process includes optical, thermal and rheological processes. The optical behavior is commonly referred to the interactions between the laser light and the powder bed surface. Phenomena considered in the optical model are reflection, transmissions, absorption, etc. The thermal behavior refers to the heat transfer mechanisms [Storch, S., 2003] that occur due to the laser light penetrating the powder bed. Phenomena considered in the thermal model are conduction, convection and radiation. The rheological behavior refers to the sintering model due to the surface tension driven viscous flow [J. Liu, 2005] of molten material.

Optical sub-model

The SLS workstation uses a powerful CO2 laser [J. D. Kim, K.H. Kang, 2004] as a thermal energy source for inducing selective fusion. In general, laser energy is characterized by a large heat flux contained in a small area. The distribution of laser intensity across the beam diameter follows nearly a Gaussian relationship [M.M. Sun, 1991].

Thermal sub-model

In the SLS process where only an external heat flux $q$ per unit area flowing into the body is considered, the heat transfer behavior can be described by the basic energy balance equation [Manzur, 1996].

Applications of LS

As pointed out in the first chapter, LS under different names has effectively been used for different applications: namely, coating, part repair, and rapid manufacturing. Since there are many published articles and research reports documenting developments, challenges, advantages, and disadvantages of the LSFF process in its various applications, here the discussion will be limited to the potential of the LSFF process for fabrication of functionally graded parts or heterogeneous structures. Heterogeneous components are usually made of different materials (in this thesis, heterogeneous structures and functionally graded parts are considered the same and they represent structures made of different materials). Due to new fabrication technologies, the use of heterogeneous objects has shown a rapid increase in the past decade [K. Cooper, 2001]. In many different engineering applications such as biomedical and geophysical applications, conflicting material properties are required in order to enhance mechanical properties and functionality of an object. For instance, it is possible to fabricate a heterogeneous component with low thermal expansion and a relatively high heat transfer rate. Conventional
methods cannot create objects in which materials change gradually from one to another. Sharp interfaces between different materials cause stress concentrations that ultimately create delaminating and cracks between layers. Another major problem in fabrication of heterogeneous objects is controlling the variation of the different desired materials. Most of the time, a large number of unknown variables are involved in the process which have to be considered together [K. Cooper, 2001]. LSFF technology allows the creation of parts with the deposition of different materials (multi-material deposition) in one specific layer or different layers (i.e., material composition varies from layer to layer or from one point to another point). The gradual change from one material to another reduces stress concentrations between the interfaces of subsequent deposited layers, and as a result, dramatically enhance the performance of the fabricated part. However, this variation should be carefully linked with the overall thermal expansion of the mixed materials to prevent cracks or delaminating due to a large difference in the thermal expansion coefficients of the constituent materials.

**LSFF Process Parameters**

In LSFF, a large number of operating parameters govern the process. Understanding the relationships between these parameters and their effects on the process are crucial to the geometrical and physical qualities of the fabricated parts. In general, the parameters are classified into two groups. The first group refers to those related to the properties of the powder and the substrate such as the thermal properties of the materials used. The second group contains parameters specific to the equipment used in the process [Simchi, A., 2003]. These parameters are summarized. Some of the process parameters affect each other or are affected by the environment of the process (they are sensitive to the external disturbances). Furthermore, they are highly sensitive to variations of the working parameters as well. Since the quality and geometrical accuracy of a clad depends on the process parameters, they should be kept within certain tolerance ranges throughout the fabrication process to guarantee the results. For example, the desired temperature of the melt pool and consequent temperature distribution over the substrate is a function of process parameters including material properties, laser power density at the process zone, and scanning or traverse speed. These also determine the cooling rate at the liquid-solid transient boundary that has a crucial effect on the solidification process and microstructure of the fabricated parts. The temperature distributions (temperature gradients) also determine the thermal strains and therefore thermal stresses across the process domain.

**Main Process Parameters**

Laser Motion device Powder feeder Material
- Average power
- Spot size
- Wavelength
- Pulsed/CW
Beam profile

**Powder stream**

On the other hand, any disturbances or sudden changes of these parameters may cause a totally different outcome. For instance, various interaction times, as a function of traverse speed, result in completely different product in terms of the mechanical and metallurgical characteristics. In laser material processing, different interaction times and laser power intensities result in three different physical phenomena: vaporization, melting, and heating. Each of these three categories, depends on the interaction time and laser power intensity, also produces different outcomes. LSFF, which is in the melting class, requires approximately an interaction time of $10^{-2}$ to $10^{-4}$ s, and a laser power intensity of $10^3$ to $10^4$ W/mm$^2$. In the same zone (melting class), by increasing the laser power intensity, from $10^3$ to $10^8$ W/mm$^2$, and decreasing the interaction time, from $10^{-3}$ to $10^{-8}$ s, the process condition will be appropriate for welding, alloying, and glazing, respectively [L. LU, 2001]. Therefore, the sensitivity of LSFF to the process parameters and complexity of its involved physical phenomena makes it difficult to produce consistent results which meet all desired mechanical and geometrical requirements even under the same operating parameters. However, the associated limitations and drawbacks can be overcome efficiently by understanding the process and consequently developing a comprehensive control plan to monitor and control the main process parameters.

**Parts Quality**

Despite all demonstrated advantages of LSFF compared to conventional manufacturing techniques, LSFF has not been widely employed in industry due to several limitations associated with this manufacturing technique. In the LSFF process, delaminating, crack formation between deposited layers, and variations in the mechanical and metallurgical properties across the structure of the produced parts are some of these limitations and drawbacks. There are several reported research programs that address the related physical phenomena, specific process parameters, and material properties of a specific product. Some of these research programs have been conducted to characterize the melt pool properties and understand the effects of the process parameters on the LSFF process [J. Pinkerton, 2004]. The interaction between the laser beam and the powder stream [M. Zhong, 2004], the effect of laser characteristics on the process, and the metallurgical and mechanical properties of the clad [W. Lee, 2006] have also been investigated. Most of the theoretical investigations in this area involved a large number of assumptions to simplify the modeling procedures. All these research programs have the same goal, which is to gain insight into the process in order to increase the quality of the clad. In practice, it is difficult or impossible to produce a clad which meets all desired mechanical and geometrical requirements, and an optimized set of requirements should be used. The properties of the deposited layers using the LSFF process can be classified in the following four groups: geometrical, mechanical, metallurgical and qualitative properties.
shows the parameters which contribute to these four groups. Some of these may be inter-related; for instance, the wear resistance can be affected by the hardness, the microstructure, the number of cracks and their depth and direction, and the bonding between base material and substrate

**Geometrical Mechanical Metallurgical Qualitative**

- Clad dimensions, Dilution, Roughness, Hardness
- Distribution, Residual stress, Wear resistance
- Tensile strength, Microstructure, Dilution
- Grain size, Homogeneity, Corrosion
- Resistance, Porosity, Cracking