2.1 RAPID PROTOTYPING TRENDS AND DEVELOPMENTS

Rapid prototyping technology has the potential to ensure that quality assured prototypes or parts are developed quickly for the following two reasons, there are almost no restrictions on geometrical shapes and the layered manufacturing allows a direct simple interface with CAD to Computer Aided Manufacturing (CAM) which almost eliminates the need for process planning, a complex procedure for Computer Numerical Control (CNC) machining. Rapid prototyping refers to a group of commercially available processes which are used to create solid 3D parts from CAD, also known as Layered Manufacturing Techniques (LMT). Rapid Manufacturing uses LMTs for the direct manufacture of solid 3D products to be used by the end user either as parts of assemblies or as stand-alone products (Neil Hopkinson and Phil Dickens 2001).

Because of the competition in today’s global economy, enterprises in the capital-goods industry are increasingly compelled to manufacture their product innovations as quickly as possible, in other words, minimize the lead time. An important requirement with respect to the reduction of product development time is the rapid availability of models and test parts in each development phase, in short ‘rapid prototyping’. Along with the reduction of
part build time, RP promotes simultaneous engineering. The minimal time and cost demands of prototype production via RP leads to improved product quality because more time is available for design iteration. Furthermore, errors in part design can be caught early and require little effort to correct. RP should not be viewed as a lone-standing technology, but rather as a link in the process chain to produce parts with various properties and lot size requirements. Reverse engineering further expands CAD/CAM to achieve a complete process chain, beginning with a physical part and ending with a prototype. Depending on the desired application, point clouds representing physical parts that have been measured by optical or tactile methods can be converted into a CAD format or used directly in a RP production process (Wiedemann and Jantzen 1999).

Small parts with high geometric complexity to be made in relatively small volumes are the most suitable candidates for rapid manufacturing. One ultimate aim in RP processes is to fabricate 3D fully functional parts directly from metals and ceramic materials without the use of any intermediate binders or any other materials, including additional processing steps before or after the RP operation (Agarwala et al 1995).

Gibson et al (1993) investigated the contributions of Virtual Reality (VR) and RP towards a more efficient product development in ergonomic, aesthetic and functional aspects of design. They suggested the use of virtual reality as a complementary technology to RP with an interface accommodated through a CAD system.

Improvement of part surface quality in RP has been a major concern. Accuracy and part surface quality have become the focus of RP community
with the increased requirement of prototyped functional parts, enhanced material properties for strength and dimensional tolerance comparable to conventionally producible parts. This has led to a variety of research (Pandey et al 2003). Diane et al (1997) measured Ra values of SL parts and concluded that layer thickness and part orientation are important parameters. They conducted experiments with hatch space, part orientation, layer thickness and over cure depth and confirmed their influence on stereolithography parts quality is significant.

Rapid Prototyping is the most powerful and flexible tool for sculptors that have ever been invented (Michael Rees 1999). The rapid prototyping process, in its simplest form, involves breaking up of a 3D CAD model into 2D slices. The slice data are then translated into a physical model. All of the current RP processes, though adapting completely different techniques, have one common underlying theme: a layered approach to building parts. The productivity of layered manufacturing processes can be significantly improved by upgrading the slicing software and it was demonstrated by Kamesh Tata et al (1998). Layer thickness has been varied according to the surface complexity in order to maintain a predefined criterion within the user defined value. The adaptive slicing algorithm was implemented and validated on a SLA-250 and on a three-axis vertical CNC milling machine.

The method of manufacturing objects as a series of horizontal layers poses a unique set of problems, irrespective of the techniques involved in the fabrication of each layer. Some of the more significant problems are the staircase effect, layer thickness selection, deviation from the CAD geometry, part orientation, shrinkage of the model, distortion of the part and the use of
support structures. Dimensional accuracy has become a prerequisite for successful application especially in tooling and rapid manufacturing (Onuh 2001).

Of the three commercially available materials for FDM process, ABS copolymer, investment casting wax and a nylon copolymer, ABS has the highest tensile modulus and strength. Therefore, there is an interest in developing materials that can be used to fabricate prototypes by FDM with higher mechanical properties which gives the parts greater functionality (Robert W. Gray et al 1998). Today, researchers are addressing strength, accuracy and surface finish issue of RP parts to enhance process capabilities. Reduction in build time and increase of part surface quality are two factors which contradict each other as decreasing build time detracts part quality because of staircase effect. There have been a number of attempts to tackle this problem and adaptive slicing procedures are proposed. Adaptive slicing method generates a variable layer thickness based on the local surface geometry and a pre-specified smoothness requirement. Dolenc and Makela (1994) discussed slicing issues for producing an accurate part surface with consideration of both tolerance and important peak features. The angle of the surface normal is used to predict a possible layer thickness. Sabourin et al (1996) proposed another method by first subdividing the model space into uniform slabs. The thickness of each slab equals the maximum acceptable layer thickness of a particular RP process. Each of these slabs is then subdivided into uniform thinner layers such that the produced cusp height is within a given tolerance.

Kulkarni and Dutta (1996) developed an algorithm for direct and adaptive slicing of a parametric surface model. Normal curvature in the vertical
direction was used to determine the maximum allowable layer thickness at each layer based on a pre-specified cusp height. Pandey et al (2003) proposed an adaptive slicing procedure for fused deposition modeling based on real time edge profile of deposited layers. In comparison to earlier approaches of adaptive slicing based on cusp height and area deviation using the rectangular build edge profiles, the proposed methodology could reduce the number of slices and hence build time. The major advantage of this methodology was that the part quality has been expressed in terms of standard Ra value which would be used in design and manufacturing.

As a part of a manufacturing system, rapid prototyping should be integrated with other manufacturing technologies (Ian Gibson and Dongping Shi 1997). To ensure that this integration is successful and intelligent, it is necessary to understand and incorporate the influence of process parameters on surface quality. The process parameters influence the quality of a component in the process and in turn affect the surface quality and mechanical properties of the resultant components. To obtain optimum quality output, knowledge of the effects of process parameters and their interactions on surface quality must be needed. Kruth et al (1998) and Wholers (1997) reported that the accuracy and surface finish are major handicaps than the strength of RP parts.

Improvement in the surface finish might possibly be achieved through modifications of the FDM machine software and/or hardware (Jose F. Rodriguez et al 2000). A new metal component fabrication technique, named Fused Deposition of Metals (FDMet) has been developed and investigations were made. Green fabrication of several complex geometrical components has
been demonstrated and the results showed that FDMet has good accuracy and reproducibility (Guohna Wu et al. 2002).

FDM is used primarily for aesthetic, ergonomic and assembly studies or as pattern masters for casting or moulding processes. In order to accelerate the development process, technical and functional prototypes are of great importance. Therefore, it is necessary to develop powerful technologies for a rapid production of prototypes with nearly serial characteristics, for example material or surface quality (Bullinger et al. 2000).

A novel rapid prototyping technology for efficient production of curved layer parts has been developed by Donald A. Klosterman et al. (1999). The new process, based on LOM, incorporated a curved layer building style and ability to accommodate ceramic and fiber reinforced building materials. The process can best be applied by industry as a product development tool for fabricating testable prototypes or for small lot production.

The state of the raw material affects the surface finish, the manufacturing time and cost. It is found that processes employing liquid raw material to build 3D solid part yield better surface finish than processes using solid – state raw material. If the raw material is in a solid state, the shrinkage of a part in the building process is much smaller than the liquid raw material. (Xu et al. 1999).

Rapid Prototyping and Manufacturing (RPM) is still in its infancy. The physical models made by most of these systems cannot be used as working parts, mostly due mostly to material and economic constraints. The major
problems in the current RPM systems include: part accuracy, limited material variety and economical performance (Xue Yan and Gu 1996). A large number of factors limit the ability of rapid prototyping systems to create parts as accurate as the CAD designs on which they are based. The most common sources of error among the RPM systems could be categorized as mathematical, process-related or material-related. Mathematical errors include facet approximation of the part surfaces in the standard input to RPM systems, limited layer resolution along the Z axis, such as stair steps and accuracy of vertical dimensions. Alternate data preparation methods based on Constructive Solid Geometry (CSG) that can input precise part surface to RPM systems are under development.

Process related errors affect the shape of the layer in the X-Y Plane and along the Z axis, the registration between different layers and the overall 3D shape. These errors are mainly dependent on the accuracy of the RPM machines and operator’s experience. Major material-related errors are shrinkage and distortion. The shrinkage is a by-product of solidification – the cooling down of material with rapid prototyping processes. Predictable dimensional shrinkage can be compensated by scaling the CAD model. Sometimes, the shrinkage is not identical along X, Y and Z axes. During the processes of building parts, stresses due to shrinkage may be locked into parts. Eventually, these stresses may cause the part to creep and distort. There may be several ways to minimize the effect of shrinkage: selection of appropriate manufacturing control parameters, development or exploration of materials with relatively small shrinkages or stress free properties and stress relief methods. All these approaches require in-depth research on the materials and understanding of the processes. In Stratasys Inc. conducted experimental
research using various control parameters and materials on FDM systems. Data is presented to help the user to choose the appropriate material for specific applications. The in-depth research on FDM processes results in system refinements in accuracy, speed and surface finish (Xue Yan and Gu 1996).

Three-dimensional Photonic Band Gap (PBG) structures using alumina (Al₂O₃) as the high permittivity material and wax as a supporting material were modeled and then structures were fabricated by Fused Deposition of Multi-Materials (FDMM) technology. A finite element method and a real-time electromagnetic wave propagation software was used to simulate and design the layered PBG structures for applications in the microwave frequency range. FDMM is found to be a promising tool for the fabrication of PBG crystals in the microwave frequency range (Mauricio et al 2002).

The existing layered manufacturing process has the advantages of rapidly manufacturing 3D RP models directly from 3D CAD models, but on the other hand has limitations, such as limited choice of material, small part size and low part accuracy. One solution to these problems that is being introduced is a new rapid prototyping system that combines conventional layered manufacturing and traditional CNC machining processes. Even though hybrid rapid prototyping systems can be developed to overcome these limitations, they will function as desired only when the process plans are generated wisely. When generating the process plans, the build orientation is an important factor to be considered, because the build direction has a major effect on too-accessible features in a single setup and also on the determination of the layers of the part. Zhu Hu et al (2002) developed an algorithm to determine the build direction to maximize the build efficiency that is suitable for both layered
Yang et al (2001) presented a method to determine the optimal build orientation for robot-based layered manufacturing by considering part accuracy, tool accessibility and number of supports as optimization factors, but the build time was ignored. Tseng and Tanaka (2001) presented two newly invented deposition techniques for the freeform fabrication of metal and ceramic parts. The first deposition technique studied can deposit variable sizes of filaments in a controlled manner. The second technique uses an adjustable planar nozzle to form layers directly. Laboratory scale apparatus has been built to study the behaviour of filament and layer formation of these two techniques. Experiments are conducted in typical operation ranges. Analytical predictions agree very well with the experimental observation.

Diane et al (1997) conducted an experiment on a SLS machine whose results conclude that layer thickness and part orientation are important and they also state that thicker layers would provide better surface finish with a vertical orientation. Since the resulting surface finish due to layer thickness and orientation is a direct effect of layered manufacturing technique, this result will hold good for other layered manufacturing processes. Gautham Kattethota and Mark Henderson (1998) conducted experiments to obtain surface roughness values as a function of orientation and layer thickness and developed decision support software which allows dynamic colour-coded visualization of surface quality with respect to the two build parameters.
Anitha et al (2001) analyzed the effect of process variables such as layer thickness, road width and speed of deposition on the surface roughness of the components produced by the FDM process using Taguchi technique. They found that layer thickness is the most significant factor and other factors road width and speed of deposition also contribute to surface roughness. The part-build optimization has also been considered in regard to layer thickness. Thicker layers require less build time, but sacrifice the surface finish by virtue of the stair-stepping error that occurs on non-vertical surfaces. Adaptive slicing refers to a situation where the layer thickness varies in different regions of the part, allowing thicker layers where surface accuracy is not important and thinner layers where it is crucial to minimize the stair-step effect. This offers a trade-off between surface finish and build time which allows a part to be built as quickly as possible while retaining the accuracy of functionally crucial part features (Kulkarni and Dutta 1996).

The development of layered manufacturing technologies over this past decade has revolutionized the design process by enabling rapid prototyping of physical parts. Designers now have access to physical models of their designs earlier in the design process. This gives them greater insight into their designs and helps them eliminate more errors earlier in the design process and at a lower overall cost. Sabourin et al (1997) presented an interesting approach for tackling the compromising issue of between smooth surface finish and fast build time. First, the object is uniformly sliced to create slabs with maximum allowable layer thickness of the RP system similar to the approach reported in Sabourin et al (1996). Next, contour offsets are generated to separate the parts within each slab into exterior and interior regions. The exterior regions are further sliced into uniform thinner layers based on the local geometry and
tolerance requirements. The exterior regions of the given part are, therefore, built with fast, thick layers to reduce the overall build time. The slicing procedure is based on STL files. This approach has been implemented and tested with .STL CAD models on a Stratasys FDM 1600 rapid prototyping system, where a 50-80 percent reduction in build time of dense parts has been achieved without reducing surface quality or part integrity.

McClurkin and Rosen (1998) developed a Computer Aided Build Style Selection (CABSS) tool that assists SLA users in making trade-offs between their build goals. They considered three process variables in their work. Dimensional accuracy is extremely important in any product development cycle as it directly affects part functionality. The relative importance of the accuracy of various part features is attainable from designer defined tolerances. Dimensional accuracy is quantified as the average absolute deviation between measured points from the actual part surface and the associated nominal part surfaces as representing within CAD model. Better surface quality yields higher precision of dimensions which in turn facilitates the accuracy of component assembly and functionality. Owing to the nature of layered manufacturing, however, the stair-step effect dominates the surface quality issue. Any part facets which are inclined with respect to the Z-axis will possess some degree of stair-step error. Minimizing this effect generally means trying to expose the least number of inclined and curved features to the Z-axis. In addition, research has shown that decreasing the layer thickness in regions of high surface curvature provides a measurable decrease in the stair-step effect (Lan et al 1997). As the application of the SFF move beyond visualization models and design verification prototypes into fabrication of functional components, SFF will change from rapid prototyping techniques into legitimate manufacturing
technologies. One key to this progress is improvement of the software systems that enable advances in the capabilities of SFF. Richard H. Crawford (1993) discussed the potential opportunities for improvement in SFF software in the areas of geometry processing, process modeling and control and design tools and discussed the interdependencies among them for SLS process.

Layered manufacturing is a fundamental development in manufacturing that will parallel the advent of numerical control machines. Given the variety and importance of engineering materials, LM is uniquely poised to enable the realization of highly efficient products (parts, assemblies, etc.,) that are not possible using conventional manufacturing methods. (Prashant Kulkarni et al 2000).

A generic part orientation system based on volumetric error in fused deposition modeling was proposed by Masood and Rattanawong (2002a). The system has been verified analytically and experimentally for parts built on the FDM rapid prototyping system. The system will enable the RP user to make better decisions in fabricating RP parts with a higher degree of accuracy and surface finish, because of the minimization of overall volumetric error in the part.

Lee et al (1995) investigated the layer position accuracy and suggested appropriate selection of materials and techniques to achieve higher packing density for accuracy improvement. The most important characteristics that determine the application of thermoplastic polymers are glass transition temperature and melting temperature. The glass transition temperature is the temperature where a rapid decrease in elastic modulus occurs. It varies with
different polymers and can be observed in the amorphous state. Melting does not occur until a higher temperature is reached. Below glass transition temperature, polymer is in glass state and the molecular motion along the chain is frozen. When there is an increase of 30 K from the glass transition temperature, the molecular motion increases, causing the modulus to drop (Ian Gibson and Dongping Shi 1997).

Orthopedics appears to be an attractive market for the manufacturers of rapid prototyping systems. There are number of ways in which RP could have assisted in the development of this surgical tool: reduced cost and time for each iteration reduced part count for the final assembly and increased elegance of design (Jamieson et al 1995). As rapid prototyping technologies improve in accuracy and reliability so the range of applications increases. Integrating industrial robots with rapid prototyping technology in the form of flexible manufacturing or rapid prototyping cells was investigated by Ian Gibson (1996). Handling of parts, removal of parts from machine, handling of parts during post-processing, removal of waste material, removal of recyclable material and surface finishing are the issues identified that require attention if the two technologies, Rapid Prototyping Technology (RPT) and industrial robots are to interact effectively.

Syed H. Masood (1996) presented an intelligent rapid prototyping framework that provided a methodology of improving the efficiency and productivity of a fused deposition modeling system through the application of knowledge based systems and distributed blackboard control technology which is a feature based design technologies. The distributed blackboard framework for rapid prototyping provides an effective platform for the integration, control
and exchange of information concurrently through its four co-operating knowledge sources. With the implementation of intelligent rapid prototyping environment, the necessary and accurate information can thus be made immediately available for fast and economical production of RP prototypes.

Throughout modern industrial development, the integration of two technologies from completely separate applications has been the basis of much advancement. Rapid prototyping itself is an example of this, originally resulting from the integration of 3D CAD and laser scanning. The linking of scanning technology from the field of medicine and rapid prototyping technology from engineering now allows anatomical image data to be viewed in a completely different manner from what was previously possible. The feasibility of producing models of human anatomy by linking MRI and stereolithography was investigated by Swann (1996).

Rapid prototyping techniques were utilized to explore the possibility of developing functional piezoelectric ceramics and ceramic-polymer composites with traditional and novel designs for transducers, sensors and actuators applications. Structures processed via rapid prototyping techniques show superior electro-mechanical properties compared to the same processed via conventional processing. Structures with controlled phase periodicity and various micro and macro features can be manufactured via rapid prototyping techniques that are not possible with various conventional techniques. Moreover, the inherent flexibility of the RP techniques indicates a significant promise to form piezoelectric ceramics and composites for small batch production or design and performance optimization purposes (Bandyopadhay et al 1998).
A shift from prototyping to manufacturing of the final product necessitates broadening of the material choice, improvement of the surface quality, dimensional stability and achieving the necessary mechanical properties to meet the performance criteria. Anna Bellini and Selcuk Guceri (2003) investigated the mechanical characterization of products of ceramic and multi functional components fabricated using fused deposition modeling. Van Weeren et al (1995) studied and classified the various surface and internal defects occurring in Fused Deposition (FD) ceramic parts and suggested process parameter changes to minimize the defects. Robert et al (1998) have developed a new high performance thermoplastic composite for FDM, involving Thermotropic Liquid Crystalline Polymers (TLCP) fibers and have used it in FDM system to fabricate prototype parts. The tensile modulus and strength of this material were approximately four times those of ABS. Therefore, prototypes fabricated with these materials would have greater functionality than those fabricated with ABS.

The unexplored capability of solid freeform fabrication machines for creating whole new classes of materials with tailored mesostructures represents an exiting new development in materials engineering with great potential for optimizing the mechanical performance of functional components. The work presented by Jose F. Rodriguez et al (2001), one of the first efforts of its kind, has elucidated and quantified the nature and range of the mesostructural tailoring capability for unidirectional P400 ABS plastic materials built with the Stratasys FDM1600 machine. Results showed that the void geometry and the extent of bonding between contiguous fibers depended strongly on the fiber gap and extrusion flow rate.
Ceramic parts including lead-zirconate-titanate (PZT) are produced by means of a variation of FDM called ‘Fused Deposition of Ceramics (FDC)’. During FDC, a thermoplastic polymer binder included in the ceramic filament melts inside the liquefier and carries the ceramic particles with it. Hence, selecting suitable binder chemistry is of particular importance in this process. The polymer binder needs to be burnt out subsequently through a post-processing step. A method similar to FDC, called ‘Fused Deposition of Metals’, has recently been developed to enable the fabrication of hard tooling from stainless steel, etc. (Wu et al 2002).

Iwan Zein et al (2002) studied porosity, compressive strength and internal structure of novel scaffold architectures for tissue engineering applications fabricated by FDM process using bioresorbable polymer. Neil Hopkinson and Phil Dickens (2001) discussed the advantages of applying rapid prototyping for direct manufacture in terms of various costs, lead times, freedom in product design and production design. Richard H. Crawford (1993) discussed processing of geometric data, computer based analysis and design for SFF manufacturing. The discussion of geometric processing issues focuses on accuracy and completeness of the input models and the algorithms required to process such models.

In order to reduce lead-time and investment cost for the development of metal forming processes, the technological fusion of Virtual Prototyping and Manufacturing (VPM) and Physical Prototyping and Manufacturing (PPM) with the concept of concurrent engineering is needed. The technology integration of CAD/CAM/CAE and RPM for the development of metal forming process has been investigated by Yang et al (2002). The technology integration
does not necessarily require the fabrication of the conventional trial dies and parts including drawing, machining and final treatments. The technology integration considered the process characteristics such as geometrical complexity, effects of the process parameters, flow pattern of the work piece and deformation induced defects, so that the trial and errors can be reduced in the design stage. The technology integration was examined by some case studies and it has been shown that the technology integration can be effectively applied to various metal forming processes and can reduce remarkably the lead time and cost of the processes.

Economic and industrial communities worldwide will be subject to the increasing impact of competitive pressure resulting from the globalization of markets and supply chains to supply these markets. They will also be subject to great pressure to produce the final product locally to the market while still operating globally. This is an area in which rapid prototyping technology is assisting companies to remain competitive and be on the leading edge of product innovation and development. The initial concept of RP was to use it as a prototype model. But advances in the technology have widened the scope of its applications. Now RP as a technology is racing towards in finishing line with other emerging branches of rapid tooling and Rapid Manufacturing (RM). The emergence of reverse engineering has come as an enabler to the integration of RP into manufacturing processes. Lee and Woo (1998) have done some studies on the use of different hardware or software based equipment (or both) for the integration of RP processes into the traditional or modern manufacturing processes. The use of a laser scanner, robots on the manufacturing and assembly lines, a Co-ordinate Measuring Machine (CMM) to capture the model data and transfer it to CAD software for editing before generation of STL files,
can all be viewed as successful attempts at integrating RP into manufacturing systems.

Brockmeier et al (1999) developed and implemented a low-cost auxiliary system to automatically load and unload FDM 1600 (and FDM 1650 / FDM 2000) rapid prototyping systems. The modifications to the FDM 1600 system are minimal. The door to the FDM 1600 build chamber has been removed, a new build tray has been developed and the Stratasys Machine Language (SML) build files have been slightly modified at both ends to facilitate synchronized operation between the FDM 1600 and the automated loading and unloading systems. Bharath et al (2000) proposed that the best possible surface finish on an FDM part can be obtained by choosing the optimal FDM process parameters.

Shi and Gibson (2000) have done some studies in the use of robots for finishing operations of selective laser sintering parts. Experimental results on different SLS parts using different materials show that surface quality which includes surface roughness, dimensional accuracy can be improved using robotic finishing.

The scope of RP integration is on the increase especially in architecture and construction industries. Pegna (1997) carried out exploratory investigation of RP integration in construction industries. Then it was a radical departure from the perceived use of RP technology. However, the exploratory work is illustrated with sample masonry structures that cannot be obtained by casting. They are manufactured by an incremental deposition of sand and Portland cement akin to Navajo sand painting. A thin layer of sand is deposited,
followed by the deposition of a patterned layer of cement. Steam is then applied to the layer to obtain rapid curing.

From the emergence of the first RP system, Stereo Lithography Apparatus (SLA) in 1998, 2234 RP systems with about 20 kinds of processes were in operation around the world at the end of 1996. At the end of 1997, system manufacturers had sold a total of 3289 systems around the world (Wholers 1997). In the early days of RP, the automotive and aerospace industries dominated the RP application. But this is no longer the case as RP has spread into many other industries. It shows how fast RP technology is developing. Digital design (CAD) and digital manufacturing (RP) have emerged to facilitate and accelerate product creation. Many kinds of technology require two conditions in order to develop quickly. On the one hand, it needs relevant fundamental theories and technologies to support it. On the other hand, it needs improved capabilities and new application fields. RP technology is no exception. Issues including product development tool, direct metal part manufacturing, rapid tooling and RP machine design are discussed by Detlef Kochan et al (1999). RP technology has been introduced successfully in the industries of automotive, aerospace, ship building, computer, toys and consumer products. Micro-electronic-mechanical systems will become the other important field of application with RP. Medical application is another important and promising direction for developing RPM technology. Now human organ models can be produced by means of using RPM technology and medical digital imaging systems. These models are very helpful in diagnosis, preparation of complex surgery and recuperation engineering. The organ-shaped models with biomaterial or bio-compatible material will be applied directly for orthopaedic implant and prostheses. SLS will be used to precisely
control the fabrication of drug delivery devices. It is possible in the future that the RP system with low price and reliability will come into the family as a tool for making arts or adornments with ideas and CAD data from one’s original or from the Internet.

Rapid prototyping technologies are now widely spread and allow the creation of objects having dimensions from a few centimeters to about one meter with a resolution of 100 to 200 micrometers. Miniaturization is a major trend in the manufacturing and commercialization of new industrial products. It allows the integration of many functions in a small volume and stimulates the creativity of designers in order to give birth to new objects which are small enough to hold them in hand or carry them in a pocket. Typical examples are the cellular phone, the CD players or in another field, the new generation of hearing aids. So, miniaturization is to be taken consideration in a growing number of industrial products and rapid prototyping technologies are starting to be confronted in the manufacturing of small, high-resolution objects having tiny holes and openings and on which a manual post processing step cannot be performed.

2.2 PROCESS MODELING

In most of the practical problems there will be two or more process variables that are inherently related and it is necessary to explore the nature of their relationship. A model has to be formed for relating the process parameters with the output response and then the model can be used for prediction, process optimization or control purposes. In many technical fields, there is a
relationship between a response variable $y$ of interest and a set of control variables \{${x_1, x_2 ... x_n}$\} + $\varepsilon$

Where $\varepsilon$ represents the noise or error observed in the response $y$. This type of relationship is called mechanistic model. However in most practical situations, the underlying mechanism is either unknown or difficult to describe completely and the experimenter (scientist or engineer) must approximate the unknown function $g(\cdot)$ with an appropriate empirical model.

$$\hat{y} = f(x_1, x_2 ... x_n) + \varepsilon$$

Usually the function $f(\cdot)$ is a first order or second order polynomial. Multiple variable regression is used to develop the empirical model. This empirical model is called response surface model (Douglas C. Montgomery 1997). After finding the optimal set of model coefficients, the empirical model $f(\cdot)$ is obtained. Then the Analysis of Variance (ANOVA) method is used to evaluate the confidence interval and adequacy of the model $f(\cdot)$ or say, test for significance of regression. Once the models are developed, the adequacy of the model has to be checked using analysis of variance. The developed models will have number of terms related to linear, quadratic and interactive effects. For simplifying the models, less significant effects can be eliminated with the suitable use of significant test. F-ratio is an index to check the adequacy of the model in which calculated value of $F$ should be greater than the F-table value. In order to determine the significance of the individual effects, t-ratio is used. Finally, the values of $R^2$ represent the regression confidence. They should be at least as large as 60%.
Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problem in which a response of interest is influenced by several variables and the objective is to optimize this response. RSM allows for better understanding of relations between the inputs and the response. In the case of FDM process the inputs refer to slice thickness, road width, liquefier temperature and air gap and the responses are porosity, surface roughness, reduction in width and deviation in thickness. The relationship can be written in the form of a polynomial function describing a surface such as in equation (2.1).

\[ Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i<j}^{k} b_{ij} X_i X_j \] (2.1)

This equation has been used in this work to develop a second order response surface mathematical model.

Response surface methodology is a set of statistical techniques for building predictive models that relates design variables (inputs) to system responses (output variables). Typically, low-order polynomial equations are used. A RSM model is a means for expressing the response as a function of several build style variables. A response surface is constructed by running several experiments and fitting polynomial equation, called the response surface, to the resulting surface. Bharath et al (2000) proposed an experimental design technique using a fractional factorial design for determining optimal surface finish of FDM parts. Charity Lynn-Charney and David W. Rosen (2000) developed a mathematical model using RSM to determine the effect of process parameters on process planning and final quality of parts processed by stereolithography.
A mathematical model to describe the principle of layered manufacturing and layer fabrication error was presented by Feng Lin et al (2001). The model is based on the concept of model decomposition and material accumulation into a physical prototype. The presented model can be applied for both planar layered manufacturing process and non-planar layered manufacturing process. The optimal part orientation derived through minimization of layered process error.

Lawrance Flach et al (1998) developed a mathematical model to investigate the effects of process parameters on the temperature profile in a LOM part during a build cycle. The process parameters were independently varied and the LOM process response is simulated. The results were analyzed in order to gain insight into potential strategies for intelligent process control. James W. Comb et al (1994) reviewed the role of several parameters like part geometry, deposition speed, liquefier temperature, material, flow control parameters in FDM process and help user to choose appropriate material to improve FDM process. The integration of material, hardware and software in FDM was discussed. They conducted regression analysis to develop relationship between process parameters and mechanical properties like density, stiffness, flexural strength, tensile strength, tensile ductility, shock resistance and hardness.

Douglas C. Montgomery and Diane A. Schaub (1997) showed that experimental design techniques can be applied to a real industrial product and process development problem. Armillotta et al (1999) conducted an experimental study on the relation between layer thickness, orientation road width, raster angle and surface finish in the fused deposition modeling process.
Chatteijee et al (2003) investigated the effects of sintering parameters: layer thickness and hatching distance on the density, hardness and porosity of the sintered products of selective laser sintering process. Experiments have been conducted according to central composite experimental design approach and response surfaces of the outputs were plotted after regression analysis. It was concluded that the quality of laser sintering is affected by layer thickness and hatching distance.

Sung-Hoon Ahn et al (2002) characterized the properties of ABS parts fabricated by the FDM 1650. Using the design of experiment approach, the process parameters of FDM, such as raster orientation, air gap, bead width, colour and model temperature were examined. Several build rules for designing FDM parts were formulated based on the experimental results. By applying these build rules, the strength and quality of FDM parts can be improved. Thomson and Crawford (1993) chose build-time, surface finish and part strength for manufacturing requirements and developed numerical methods to quantify the requirements with respect to the part orientation for the selective laser sintering process.

Joon Park et al (2000) studied the precision and accuracy of LOM process and the dimensional stability of LOM parts. The process was found to exhibit both constant and random sources of errors in the part dimensions. With the help of design of experiments the process parameters were optimized. Wanlong Wang et al (1996) studied the processing accuracies of slicing solid manufacturing. They introduced an integrated method that combined design of experiments and neural network analysis to determine optimal processing conditions. Pulak M. Pandey et al (2003) developed a semi empirical model for
evaluation of surface roughness of FDM parts. A fractional factorial design of experiments, four process parameters with two levels, is adopted to understand the effect of various process variables. ANOVA is used to find the significance index for process variables and confidence level for the statistical model developed for the surface roughness of hot cutter machined surface. They concluded that the proposed machining method is able to produce surface finish of the order of 0.3 μm with 87% confidence level. This machining process provided a key for development of a hybrid rapid prototyping system which will have features of both layer by layer machining and deposition simultaneously, in order to achieve improved surface finish and functionality of RP parts.

The quadratic model for layer displacement in three dimensional printing was developed from consideration of compressibility and load as two fundamental factors was developed by Lee et al (1995). Suggestion for accuracy improvement is the selection of materials and techniques to achieve higher packing density. Higher packing density would effectively reduce compressibility and thereby minimizing layer displacements. A 1/8 factorial experimental design has been used to characterize the powder layering process in terms of how input parameters affect layered packing density.

2.3 OPTIMIZATION OF PROCESS PARAMETERS

Simulation can be defined as a technique that imitates the operation of a real-world system as it evolves over time. Simulation optimization can be defined as the process of finding the best input variable values from among all possibilities without explicitly evaluating each possibility. The objective of
Simulation optimization is to minimize the resources spent while maximizing the information obtained in a simulation experiment (Yolanda Carson and Anu Maria 1997). They discussed various types of simulation optimization techniques and their applications.

Physical prototypes are often time and cost intensive and thus need to be reduced to a minimum. By combining CAD technologies, RP, VR and RE prototypes can be produced faster and cheaper as before. Especially, the employment of virtual prototypes in the early phases of product development optimizes the whole development process. The strategic advantage of digital prototyping is the advancement of decisions from the test-phase with physical prototypes to the early phases of product development with digital prototypes. The digital demonstration allows an early modification and optimization of the product. Furthermore, it leads to a cost-saving increase in the variety of prototypes. Pre-requisites for digital prototyping are the following three areas: CAD, Simulation and VR. Simulation and CAD-data produce quantifiable results, whereas the connection with VR-technologies enables a qualitative evaluation of the results. An important component of digital prototyping is the Digital Mock-Up (DMU), a purely digital test model of a technical product. It includes the consistent and current availability of multiple views of product shape, function and technological coherences. This forms the basis on which the modeling and simulation can be performed and communicated for an improved configuration of the design. This primary, digital design model is also called the virtual product. Digital prototyping offers enormous advantages to many different branches, like aircraft construction, ship building or the motor industry (Bullinger et al 2000).
Lawrance et al (1998) developed a mathematical model based on 3-dimensional transient heat conduction in a rectangular geometry LOM part. The parameters roller temperature, roller speed, chamber air temperature, base plate temperature and laser cutting time were independently varied and the LOM process response simulated. The simulation and modeling has revealed that a number of parameter have influence over the thermal environment of the part and suitable for manipulation of the process during online control.

Atif Yardinci and Agarwala (1996) studied the thermal behavior of the FDM processed parts. They developed a simulation model for predicting thermal transport properties and a computationally efficient part building to predict bond quality in the whole part. A genetic algorithm was developed by Wodziak et al (1994) to automatically place multiple parts to reduce build time and to maximize the utilization of space in the build vat of SLA. The parts may be translated or rotated ± 90 degrees about the Z-axis to aid in part packing. The genetic algorithm developed was a successful method for optimizing multiple part layout to reduce build time. The availability of a growing number of rapid prototyping systems with wide ranging capabilities has created a problem of selecting an appropriate RP system for industry as well as educational sector to suit their requirements. Masood and Soo (2002b) developed the intelligent RP system selector as an interactive program to help potential purchaser to select an RP system. The program is a rule based expert system and recommends the RP system along with its full specifications on the basis of interactive question-answer session with the user. The program allows the user to choose any of the four options, namely quick selection, detailed selection, build technology and machine style, to select the RP system.
Cao and Jiang (2000) developed a mixed variable evolutionary programming technique to solve nonlinear optimization problems which contain discrete and continuous variables. Eiben and Schoenauer (2002) have discussed about evolutionary computing and differences between various types, application areas ranging from modeling and simulation to optimization. Ji-Hui Zhang and Xin-He Xu (1999) developed a novel evolutionary program that has a rapid convergence rate but also maintains the diversity of the population so as to escape from local optima. The effect of process parameters such as laser power, laser beam velocity, hatch spacing, laser beam spot size and other dependent process parameters on the SLS process response was studied by John D. Williams and Carl R. Deckard (1998). Physical experiments and implementation of numerical simulation are conducted using Bisphenol – a polycarbonate. They identified that the secondary process parameters, delay period and number of effective exposures have a significant influence on the process response.

Frank and Fadel (1995) developed an expert system tool to select fabrication orientations. The surface finish was a primary parameter in the selection of preferred orientations. Several geometric features, such as hole, plane, overhang and inclined plane, were collected in the part surface analysis. A 2D decision matrix was used to present the selection rules to determine the preferred orientations for each geometric feature. Joel E. McClurkin and David W. Rosen (1998) described a method based on response surface methodology and multiobjective decision support for relating build goals to the build style variables to provide support for making build style decisions. Expected behavior of the build goals with respect to the variables were confirmed and quantified. Thompson and Crawford (1995) developed computational tools for
optimizing the orientation of a part to be built on the basis of part strength, surface “aliasing error”, volumetric supports and build time.

Choi and Samavedam (2002) proposed a virtual reality system for modeling and optimization of rapid prototyping processes. It involved modeling and simulation of RP in a virtual system which facilitates visualization and testing the effects of process parameters on the part quality. A mathematical model has been developed to estimate the build time which incorporates various process parameters and has been integrated with the virtual simulation system to provide a test-bed to optimize process parameters.

Ziemen and Crawn (2001) developed a multi objective decision support system to aid the user in setting FDM process variables in order to best achieve specific build goals and desired part characteristics. The method uses experimentation to quantify the effect of FDM process variables on part quality. Cheng et al (1995) presented a multi-objective approach for determining the optimal part building orientation. Objective functions have been developed based on known sources of errors affecting part accuracy and the requirement of good orientations during building of the model to attain the specified accuracy achievable with the stereolithography process. Developed algorithms are used to derive optimal orientation that can assure better part quality and higher build efficiency.

The functional requirements of a rapid prototyping system are speed and accuracy and they are both functions of vendor defaulted and user selected manufacturing parameters. Accuracy is evaluated by dimensional errors, form errors and surface roughness of manufactured parts. To find the functional
relationships of a SLA parts quality and input manufacturing process parameters, an orthogonal array of experiments has been developed by Jack G. Zhou et al (2000). Two analysis tools, response surface methodology and analysis of variance have been used to evaluate the SLA process and to perform the product optimization and concluded the optimal manufacturing parameters.

Igor Shishkovsky (2001) discussed the prospects of integration of functionally graded materials coating methods and computer modeling methods which developed independently earlier. Functionally graded materials are a new generation of composite materials characterized by a continuously varying property due to permanent change in the microstructure details from one surface of the material to another, such as composition, morphology and crystal structure. Fused Deposition modeling of Ceramics (FDC) technology allows the fabrication of novel piezoelectric ceramic and composites of ceramics and polymers. The properties of ceramic (PZT) and polymer (polyvinylidene fluoride) composites can be tailored by changing the connectivity of the phases, volume fraction of the ceramic in the composite and the spatial distribution of the active piezoelectric phase. This is a practical application that combines computer modeling and layered manufacture and has been demonstrated successfully for porous ceramic – metal filters. ANSYS calculated the stress-strain nature, depending on conditions of particles and then the product was synthesized by the FDC method.

The constant road width in the tool path is the major reason for the defects and voids in an extrusion based SFF process. A system based on a specially developed closed loop CAD system that include modules for solid model design, slicing, single and multi-material tool path generation and virtual
simulation has been reported by Qiu and Langrana (2002). The system can generate void-free tool paths with the help of an intelligent and adaptive algorithm that computes void sizes and their locations. The path is validated with the help of the virtual simulation module.

As RP is moving towards rapid manufacturing, there is an increasing demand on obtaining good surface quality parts (Pulak M. Pandey et al 2003). Surface quality comprises porosity, surface roughness and dimensional accuracy. The dimensional accuracy was affected by two aspects such as expansion and shrinkage of a particular dimension in linear direction. They affect the functionality of the part and critical for cost reduction in terms of reduced post processing of parts and improving surface finish (Gautham Kattethota and Mark Henderson 1998). So the problem should be reduced by careful process parameter control. This needs proper study and analysis of various process parameters and their interactions on surface quality. In this work, porosity, surface roughness and dimensional accuracy in terms of reduction in width and deviation in thickness are the set of variables considered to analyse the integrity of rapid prototypes.

2.4 SCOPE AND OBJECTIVES OF THE PRESENT WORK

From the literature review, it can be understood that the effect of process parameters on the surface quality and structural defects such as porosity, dimensional accuracies in the components produced by RP methods is found to be one of the important areas of research work. However, for rapid manufacturing, FDM is an area still full of open questions. Wealth of data for fabrication of rapid prototypes exists in the published literature. However, there
is complete lack of data on the effect of critical process parameters on product quality and therefore the vendors and users were unable to manipulate the process parameters to obtain good quality products. Hence, there is a need for carrying out studies on several parametric influences on surface quality such as surface finish, porosity and dimensional accuracy. Further it is also necessary to optimize the process parameters in order to improve the surface finish, porosity and dimensional accuracy of the components fabricated in FDM.

The available literature for process parameter optimization for FDM technology is very much limited. Few reported studies have adopted experimental design, genetic algorithm and artificial neural network to optimize the surface quality. In this work, three analysis tools, such as response surface methodology, ANOVA, artificial neural network, have been used to evaluate the FDM process and evolutionary programming is used to perform the product quality optimization.

Based on the above discussion, the objectives of the present research work are listed below:

1. Identification of the key process parameters that will affect the surface quality of the components produced by FDM.

2. Studies on influence of process parameters such as slice thickness, road width, liquefier temperature and air gap on surface finish, porosity, reduction in width and deviation in thickness.

3. Scanning electron microscopic study of the RP components to visualize the parametric influences on structural defects.
4. Development of mathematical models to understand the relationship and their interactions of the process parameters on surface quality and integrity of rapid prototypes and predict the same.

5. Validation of the mathematical models developed and statistical analyses of the experimental results to determine the significant factors and their interactions.

6. Development of models to predict porosity, surface roughness and dimensional accuracy in terms of reduction in component width and deviation in thickness using artificial neural networks.

7. Development of simulation models using mathematical models and artificial neural network models with evolutionary programming to predict the optimal process parameters and to validate the same model.

Methodology adopted for this research work is illustrated in Figure 2.1
Study on Parametric Influence on Integrity of Rapid Prototypes by Fused Deposition Modeling

**Process parameters**
- Slice Thickness, Road Width, Liquefier Temperature and Air gap

**Experimentation**
- Machine: FDM 2000
- Size: 254 x 254 x 254 mm
- Material: ABS

**Monitoring and data collection**

**Output parameters**
- Surface roughness, Ra (μm)
- Porosity (%)
- Reduction in width (%)
- Deviation in thickness (%)

**Parametric influence on surface roughness, porosity and dimensional accuracy**
- Road width
- Slice Thickness
- Liquefier temperature
- Air gap

**Statistical analysis**
- Mathematical modeling
- ANN

**Scanning Electron Microscopic analysis**

**Feature prediction and optimization of process parameters**

Results

Conclusion

Figure 2.1 Methodology of the Research Work