EXPERIMENTATION AND ANALYSIS OF CONTOUR CRAFTING (CC) PROCESS USING UNCURED CERAMIC MATERIALS

by

Hongkyu Kwon

A Dissertation Presented to the
FACULTY OF THE GRADUATE SCHOOL
UNIVERSITY OF SOUTHERN CALIFORNIA
In Partial Fulfillment of the
Requirements for the Degree
DOCTOR OF PHILOSOPHY
(INDUSTRIAL AND SYSTEMS ENGINEERING)

August 2002

ACKNOWLEDGEMENTS

My sincere thanks goes to my research advisor and dissertation committee chairman, Dr. Behrokh Khoshnevis, for providing me with the opportunity to work on the CC project. Also, I thank him for his inventive spirit, support, encouragements and guidance throughout my doctoral work.

I also want to thank my member of research committee, Dr. Satish T. S. Bukkapatnam, for his constant encouragement and general guidance. Without his support, this thesis could not have taken on its present form. I am also thankful to my other dissertation committee members, Dr. Kurt D. Palmer, for his useful suggestions and critical commends and Dr. Yan Xiao of the department of Civil Engineering for his useful guidance. I also want to thank my qualifying committee member, Dr. Mansour Rahimi, for his general assistance, and useful suggestions. I also would like to express my heartfelt thanks to all my friends, Jaison Saito, Dooil Hwang, Jihoon Park, and Bahram Asianbanpour, for their support, and help.

I am extremely thankful to my wife, Chansoon Park, my daughter, Soyoung Kwon, and my son, Soonsung Kwon, for the sacrifices they have made in these many years. I am also extremely thankful to my parents, parent in-law, and my sister for invaluable supports, sacrifices, and encouragements. Finally, I would like to express my deepest gratitude to my late brother, and his family for their sacrifices, and encouragement. I dedicate this dissertation to the memory of my brother add to his family.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Contour Crafting (CC) is a new patented additive fabrication technology developed in the University of Southern California, which uses computer control to exploit the superior surface-forming capability of *troweling* to create smooth and accurate planar and free-form surfaces. To produce exceptionally smooth and accurate planar and free-form surfaces, the process utilizes trowels that function as solid planar surfaces. Using fewer different troweling tools than in traditional plaster handwork and sculpting, the process is the ability to rapidly produce parts with superior surface finishes, and enables the creation of various surface shapes. Components as large as boats with complex geometries and smooth surfaces can be made accurately at relatively high speeds with a variety of materials.

This dissertation presents the details of the construction and operation of the fabrication machine as well as procedures and results of experimental investigations of CC in fabrication of ceramic parts. Various geometrical shapes were investigated with carefully chosen uncured ceramic materials to validate the feasibility of CC in rapid prototyping of mechanical parts as well as the potential of the process in automated construction industry. The potential of CC became evident from the prudent investigations and experiments with various materials and geometries.

Using ceramic materials (e.g. clay) as the fabrication material, the experimentation and modeling efforts were conducted to study the material flow patterns in the extrusion and deposition stages of the CC process. Using the FEA simulations, certain basic understandings of the effect of extrusion orifice geometry on the performance of CC were derived. A square orifice was found to be aptly

suited, both in terms of delivering excellent fusion between layers as well as creating the desired external surface profile. The experimental observations support these results. To understand the effect of the flow pattern with respect to the different angles of the movable side trowel, the FEA simulations also were conducted on the performance of CC, and its results were compared with those of experimental observations.

The research also resulted in the identifications of various procedures to create smooth part surfaces and various geometrical features.

CHAPTER 1

INTRODUCTION

Quick and inexpensive introduction of manufactured products is the key to success in a competitive global economy. In order to realize this, time to market must be substantially shrunk; Rapid Prototyping (RP) technologies aid this process. RP involves automatic fabrication of a prototype part directly from a computer file based on a 3D CAD model of the object. The main idea of these RP technologies is the decomposition of 3D models into 2D thin cross-sectional layers, and then physically adding the layers and stacking them up in a layered fashion.

Fabrication processes fall into two primary categories: subtractive, and additive. Rapid Prototyping, faster and cost-effective means of building prototypes, is an additive process as opposed to conventional methods (subtractive process) such as CNC milling, turning, and grinding. Other terminologies applied to rapid additive prototyping technology are also referred to in the literature as ‘solid freeform fabrication,’ ‘desktop manufacturing,’ ‘automated fabrication,’ ‘layer fabrication,’ etc. The new technology is referred to as "Rapid Prototyping (RP)" in this proposal.

Less than two decades ago, the first commercial RP process was presented at the AUTOFACT show in Detroit (US) by 3D Systems, Inc. based in Southern California. At that time the process was not very accurate, and had few choices of materials. Since then, RP technologies have made rapid strides. Nowadays there are over 30 RP processes, some of which are under development in research laboratories (such as USC's Contour Crafting process) while others have already been commercialized. The current RP processes have improved accuracy significantly, and the choice of materials is also relatively wide.

1.1 RP impact on industry

The key benefits of the RP are mainly derived from its capability to rapidly fabricate physical models regardless of shape complexity. Using these technologies, the manufacturing cycle time for a typical rapid prototype part of virtually any complexity can be measured in hours instead of days, weeks, or months depending on the method used. By decreasing development cycle times and increasing product complexity, RP's are valuable in a competitive global market.

According to consultant Terry Wohlers (president of Wohlers Associates, Inc.), RP industry grew up to $421 million in 1996, an increase of over a thousand percent compared to $39 million in 1992 [Rapid Prototyping Report, May 1997]. 1320 RP systems were world widely sold out in 2000, compared to 1178 in the previous year according to Terry Wohlers [Wohlers Report, 2001]. The report also releases that more than 45% of all RP machines were installed in North America at the end of 2000. Among other regions of the world, in the Asia/pacific region 28.6% of the total worldwide installed base of machines was in operation, compared to 24.6% in Europe [Wohlers Report, 2001].

In Europe and Japan, educational infrastructure and computational environment have been conceded as main factors for broadening the use of RP in industry. In 1996, Japan began a research and development program called CALS (Commerce at Light Speed) with funding exceeding $300 million in order to significantly improve the design and manufacturing infrastructure along a broad range of dimensions with particular emphasis on computational tools in design and manufacturing [Prinz 1997].

The larger issue concerns the generation of casting mold for complex parts that make it impossible to use milling in its fabrication. RP processes can be used to create a solid model out of a thermoplastic material for investment casting. The advantage of this approach is the rapid pace using CAD/CAM technology and its support of the freeform design. Using this approach the total turn around time can be reduced to 3 to 4 weeks compared to the conventional tool building process that can take from 8 to 20 weeks depending on part complexity [Wang 1999, and Aubin 1997].

RP use is growing in several fields related to health care and medicine. The most common medical applications of RP are currently using rapid prototyping biomodels to explain surgeries to patients for consent and education, to plan and simulate difficult surgical procedures, and to design and customize surgical implants. Using the information from a non-invasive scan such as computed tomography (CT) and magnetic resonance imaging (MRI), RP processes can fabricate three-dimensional models of anatomical features such as jaws, skulls, and knees that otherwise would only be accessible through surgery [Zhang 1998].

By allowing medical professionals to see the underlying physiology without having to perform exploratory surgeries, RP models provide a medium for practice efforts, and enhance visualization of anatomy and trajectory planning to the surgeon. It also enhances patient understanding. Furthermore, in complex reconstructions, models of the desired results are used to provide feedback for the surgeon to gauge how close the actual surgical results approach the planned results [Ashley 1993, Rapid Prototyping report September and December 1998, and Lightman 1997].

Today, it is expected that RP technologies are to be used for small batch production runs, and capable of fabricating real products instead of only concept models or prototypes. A project conducted by NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, demonstrated that some of RP applications might already have achieved fabrication of real parts used directly in spacecraft production with the SLS process [NASA, and Rapid Prototyping Report November 1999].

1.2 Limitations of current RP technologies

There are several limitations to the current rapid prototyping methods. Most of the current commercially available RP processes suffer from slow build speeds, and are unable to fabricate large objects. Many of them also suffer from bad surface quality, a limited number of possible fabrication materials, and low structural integrity of the built part. All of these limitations are a direct result of the way RP processes produce components [Brown 1997].

Each of the commercially available RP processes fabricates parts directly from the output of CAD files, and creates it one layer at a time. The 3-dimensional CAD file is sliced into 2-dimensional thin cross sections (typically on the order of 0.01 to 0.7 mm thick). These layered cross sections of the solid object are then used to drive the RP processes in fabricating the desired part [Weiss 1997].

The cross-sectioned layer thickness in a built object depends on the technology's limitation; for example, the distance light can penetrate into the liquid photopolymer resin sets limitations on selective photocuring. The thickness of the cross-sectioned layers has implications relating to the fabricating speed and to the surface quality of the desired object. Generally from a fabrication speed standpoint, the build time of a part is directly proportional to the number of its layers. Its build speed is also directly related to the possible size of the object to be fabricated.

The cross-sectioned layer thickness also has a direct effect on the surface quality of the created object. Generally in RP processes, better surface quality is achieved with smaller layers the process has to use. A common difficulty is the fabrication of the vertically curved surfaces such as during the fabrication of a 'vase'. For a vertically curved surface, the layer thickness with each step must be minimized relative to the curve angle to avoid the poor surface finish of the fabricated object taking on a staircase appearance instead of a continuous smooth surface. The desire for a smooth surface finish, and a faster build speed are typically in direct competition with one another with regard to the thickness of the fabrication layer [Dolenc 1997].

RP users would like to be able to create parts that will be made out of material that is inexpensive, and used during regular production. Using the production materials may allow the prototype parts to undergo functional testing. All of the RP technologies are currently limited with regard to build materials. The Stereolithrapy, Masked Lamp Curing, and Laminated Object Modeler are at most constrained with regard to fabrication materials. Selective laser sintering is probably the most versatile with respect to material choice; however, even it is limited to only a few materials. Most of the current technologies lack the ability to build parts out of metals without any secondary operations [Fussell 1997, Beaman 1997, and Lightman 1997].

Because parts are created layer by layer, their structural integrity is not as strong as a part made by traditional manufacturing techniques. The part is only as strong as its weakest link. The inter-layer adhesion between fabrication layers is typically weaker than the material within the layers. This inter-layer adhesion, therefore, dictates the overall strength of the fabricated parts.

The limitations associated with current commercially available RP processes create a desire for new fabrication technologies. The Contour Crafting technique under development at USC is a promising technology that addresses many of the limitations associated with current technologies [Khoshnevis 1998].

1.3 Introduction to Contour Crafting

Contour Crafting (CC) is a patented additive fabrication process that uses computer control to exploit the superior surface-forming capability of a trowel to create smooth, accurate planar and free form surfaces.

Originally in this process, two trowels are utilized as schematically shown in Figure 1-1, which function as solid planar surfaces on the object being fabricated. The large-scale part is fabricated quickly layer by layer with enhanced strength relative to other prototyping methods. Complex surface shapes can also be created with the manipulation of various trowel tools. The overall process is a combination of an extrusion process for forming the part surfaces and a filling process (pouring or injection) to build the object core.

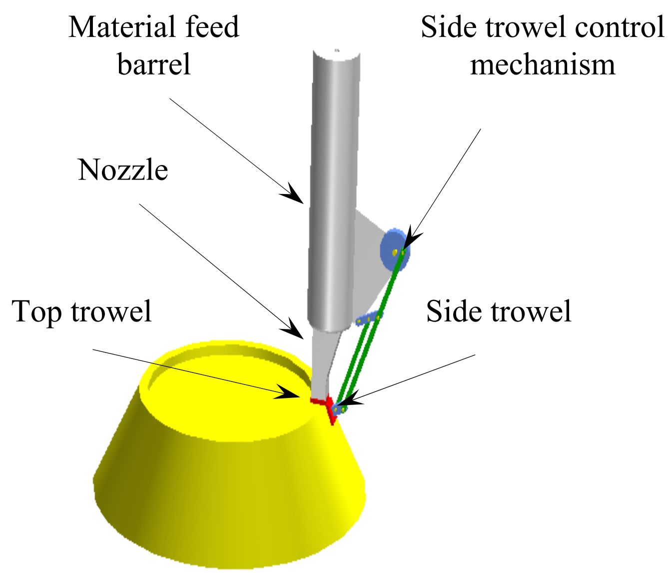


Figure 1-1. Schematic view of extrusion assembly of a contour crafting machine

The recent advances include design and construction of two fabrication machines. One machine for the CC process is customized for thermoplastic materials such as thermoplastic fed in filament form that is melted and extruded through a nozzle between two flat metal surfaces (trowels). The flow of molten thermoplastic is constrained in the vertical and horizontal direction by two trowels [Russell II 1999]. The other CC machine shown in Figure 1-2 utilizes uncured ceramics such as plaster/clay materials. Our current version consists of only a pivoting side trowel, whose function is to shape and smooth-out ceramic material forming the outer surface of the object. As with any other rapid prototyping process, a part is fabricated layer-wise.

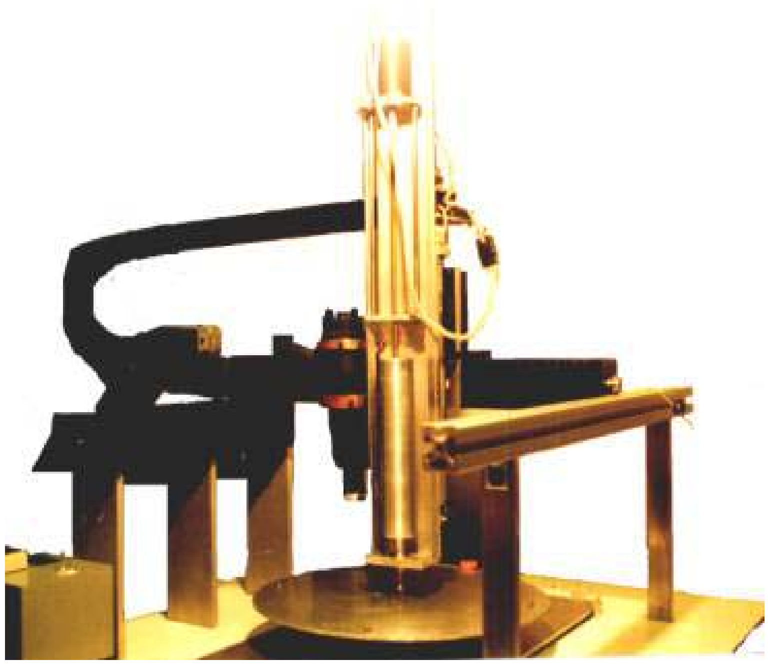


Figure 1-2. Side view of CC machine used for the production of cylindrical parts with clay/plaster

The distinguishing advantages of the CC process over existing RP process are the ability to rapidly produce large-scale parts with superior surface finishes through the automated use of trowels. Components as large as boats with complex geometry and smooth surfaces can be made accurately at relatively rapid speeds with a variety of materials.

Despite its inherent simplicity and versatility, however, there are several major challenges to the CC technology. These include the coordination of design parameters, the development of the machine, the selection of appropriate trowel materials and designs, the selection of appropriate prototyping materials and the control of their viscosity, and the processing of novel materials.

1.4 Research Summary and Results

1.4.1 *Research summary*

With utilizing ceramic slurries as the fabricating material using a fixed and pivoting side trowel that may overlap previous layers, the CC process create complex geometrical shapes using a combination of several primitive shapes with a smooth surface finish. Throught diverse experimental investigations it has been estabilished that the CC process is feasible and has significant potential in rapid construction of large objects. In addition to the use in rapid fabrication of large components, the process has its niche in rapidly fabricating certain components for aerospace and automotive industries, where minimization of green maching is warranted. Following are the research objectives: (a) improve the CC mechanism design; (b) create each primitive individually at first, and then classify primitives with similar attributes into categories; (c) develop a feasible method for construction of overhang parts and for fabricating solid 3D geometrical shapes; and (d) develop the process model to understand the flow characteristics of the extrudate.

1.4.2 *Specific research focus*

The goal of this research is to advance the CC technology to produce 2.5D, and 3D geometrical shapes with heights of up to 5 inches and a surface finish of less than 5 μm. Ceramic slurries have been utilized as the fabrication material using a fixed side trowel that may overlap previous layers. Five main objectives have been established for this research.

1. Optimize the mechanism design of CC for the fabrication of 2.5D and 3D geometrical shapes using ceramic slurries. Studies include the size and shape of nozzle orifice and side trowel, etc.
2. Create complex geometrical shapes using a combination of several primitive shapes. The goal has been the creation of each primitive individually at first, before moving on to more complex shapes. There have been several challenges involved. One challenge in particular is due to the side trowel which when making inner curves, due to its overlapping with previous layer, has a minimum of two points which are always in contact with the lower layer, thereby restricting its turning radius. The approach used to classify most primitives with similar attributes into categories and develop their respective fabrication algorithms.
3. Develop a feasible method for construction of overhang features such as roofs, and conduct other extensive experimentations such as creation of hollow cavities, reinforcements and impregnations, sandwich structures, etc.

Through these experimentations, the feasibilities of the CC process for construction automation are shown.

4. Develop an understanding of the flow characteristics of the extrudate using a computational fluid dynamic (CFD) simulation to assess how different flow patterns may affect the surface finish, and the eventual structural properties of the parts fabricated. The shape of the nozzle orifice and the process parameters influences the flow pattern of the extrudate.
5. Develop a feasible method for fabricating solid 3D geometrical shapes such as cones, pyramids, and domes, using the pivoting side trowel.

   It is hoped that the above objectives will contribute to further development of CC and its establishment as a strong contender in the rapid prototyping industry.

1.4.3 *Research results*

The research results can be classified into two general categories: the primary results that are the original contributions to the scientific body of knowledge, and secondary results that will have to be addressed in the course of refining the CC process.

- Primary results

1. Fabrication of 2.5D parts: To fabricate complex 2.5D geometrical shapes, the CC process has to combine several primitive geometries such as straight line, convex and concave curves, and sharp corner. Several primitive geometries

were investigated to reach this objective. Simultaneously, those shapes were used for analyzing the effects of side trowel to improve the capability of the CC process.

2. Extensive experimental investigation of deposition with hollow cavities, reinforcements and impregnation, and sandwich structure. Through these experimental studies, the potential of the CC process was demonstrated in construction automation. Experiments with some ceramic materials showed the versatility of the process relative to the use of a variety of fabrication materials.
3. Fabrication of 3D parts: The CC process needs to utilize a support structure to build 3D parts with orthogonal sides such as overhang features. Several support materials and approaches were investigated to accomplish this objective. Additionally, the CC process needs to utilize the pivoting side trowel in order to fabricate 3D parts with slant sides such as cones, pyramids, and domes. Through detail experiments effects of the pivoting side trowel were investigated. These results further demonstrated the feasibility of the CC process in construction of supportless roofs for civil structures such as adobe house.
4. Development of the CFD simulation model to understand the flow patterns during fabrication process, and to characterize the effect of the pressure on the deposition point and the relation of pressure with other process parameters. As a result of this part of research a better orifice geometry was

designed to enhance the capability of the extrusion system for the CC process.

- Secondary results

1. Improvement of the capabilities of the CC machine and process to build 2.5D, and 3D parts with the uncured ceramic material.
2. Development of the user interface of the software to control the CC process.
3. Development of several CNC control programs to fabricate several 2.5D and 3D parts by combining several primitive geometries.

1.5 Organization of this thesis

Following is the list of the thesis chapters and their contents:

- Chapter 1-Introduction: An introduction to rapid prototyping, and highlights of RP's impact on industry and the drawbacks of the current RP processes are included in this chapter. A brief introduction to CC, efforts to advance the CC technology to produce 2.5D and 3D geometrical shapes with a smooth surface finish, and how it addresses some of the drawbacks associated with other RP processes in use today processes are also presented in this chapter.
- Chapter 2-Background: In this chapter, there are three main sections. A basic common process and brief description of current RP processes, and their applications and CC's applications are depicted. Additionally, a general description of ceramic material is explained. Finally, a review of analytical modeling (finite element analysis) for simulating the flow pattern is provided.

- Chapter 3-Research methodology: An outline for the research activities, and their methodologies are described in this chapter.
- Chapter 4-Machine development of the CC process: The design of CC process using ceramic material is described and documented. Hardware issues such machine structure, its components, etc., and software issues to control the CC process are described in this chapter.
- Chapter 5-Process characterization: Summary of process characterization, and the related experimental investigations such as a selection of the process parameters, material issues, etc. are presented in this chapter.
- Chapter 6-Experimental optimization to fabricate 2.5D and 3D geometrical shapes: This chapter is the core part of this research, which is broken into two main sections. First, a summary of experimental observations for fabricating 2.5D shapes is presented. Other extensive experimental investigations are also presented, which include the depositions with hollow cavities, reinforcements and impregnation, and sandwich structures. Second, a summary of experimental observations for 3D shapes is presented. The detail effects of several support materials are described, and the procedures for development of 3D parts are presented. Detail experiments and effects of the pivoting side trowel are described.
- Chapter 7-Simulation of material flow: The experimentation and modeling efforts to study the material flow patterns in the extrusion and deposition stages are presented. Using the FEA simulations, the basic understandings of

the effect of extrusion orifice geometry on the performance of CC are presented in this chapter. Also, the effects of the pivoting side trowel with respect to different angles are presented.

- Chapter 8-Conclusion and recommendations for future research: A summary of knowledge obtained from the experiments and analyses in this research, and recommendations regarding the future research activities are presented in this chapter.

CHAPTER 2

BACKGROUND

The CC process is a unique RP process with regard to extruding the uncured ceramic material (e.g. clay). Also, the process somewhat resembles the combination of extrusion and injection molding. First, a general literature review and discussions are conducted regarding RP processes. Section 2.1 and 2.2 discuss the essential process steps that most RP processes use, and the current commercial RP technologies. Applications of RP processes, and the CC process are discussed in Section 2.3 and 2.4, respectively. Second, the general descriptions of ceramic material are detailed in Section 2.5. Finally, a general literature review of analytical and computer modeling is presented in Section 2.6, as they relate to the modeling and understanding of material flow in the CC process.

2.1 Basic procedure of RP

Although several different RP processes exist, all RP processes utilize the same basic five-step procedure as follows [Wozny 1997]:

- Create a CAD model of the design
- Convert the CAD model to STL format
- Slice the STL file into thin cross-sectional layers
- Construct the model one layer atop another
- Clean and finish the model

In the first step, the object to be built is modeled using a Computer-Aided Design (CAD) software package. Because various CAD packages use a number of different algorithms to represent solid objects, the STL format has been accepted as the standard of the rapid prototyping industry to establish consistency. In the second step, the CAD file is converted into STL format. This format characterizes a three-dimensional surface as an assembly of planar triangles, “like the facets of a cut jewel”.

The file has the coordinates of the vertices of a mesh of triangles that covers the surface of the model, and the direction of the outward normal to each triangle. Because STL files use planar elements, they cannot represent curved surfaces precisely. By increasing the number of triangles the approximation can be improved, but it will increase the building cost because of bigger file size. Large, complicated files require more time of a pre-process, and also more time to build the part. Hence, the designer must balance accuracy with manageability to produce a useful STL file.

A pre-processing program prepares the STL file to be built. Most of the programs allow the user to adjust the size, location and orientation of the model. Build orientation is important for several reasons. One of the reasons is that the properties of rapid prototypes vary from one coordinate direction to another because prototypes are usually weaker and less accurate in the z (vertical) direction than in the x-y plane. The other reason is that a part orientation partially determines the amount of time required to build the model because placing the shortest dimension in the z direction reduces the number of layers, thereby shortening build time.

In the third step, the preprocessing software slices the STL model into a number of layers from 0.01 mm to 0.7 mm thick, depending on the RP technique, and the surface quality and accuracy. The program may also generate an auxiliary structure to support the model during fabrication. Supports are useful for fragile features such as overhangs, internal cavities, and thin-walled sections.

In the fourth step, the actual part is built by using one of several RP techniques described in the next section. RP machines physically add the layers and stack them up in a layerwise-fashion from polymers, paper, ceramic powder, powdered metal, etc. Most machines are fairly self-sufficient, requiring minimum human intervention.

The final step is post-processing that removes the prototype from the machine and detaches any supports. Some photosensitive materials need to be completely cured before use. Prototypes may also require minor cleaning and surface treatments such as sanding, sealing, and/or painting. This way, the model will improve its appearance and durability.

2.2 Review of current RP technologies

Currently several RP techniques have been developed in companies and laboratories around the world, and some of these are already used in industry. The various RP processes are classified into five categories: selective photocuring, selective sintering, adhesion of cut sheets, robotically guided extrusion (Fused Deposited Method), and droplet deposition on powder [Burns 1993, BIBA 1995, and Grimm 1998]. A brief description of these techniques, component technologies used to implement each system, and advantages and disadvantages are presented in Appendix 1.

There are also numerous other RP processes under development and investigation in companies and laboratories. Many of the new RP processes under development concentrate on fabricating parts directly out of metal. A brief description of the RP processes that are currently under development is presented in Appendix 1.

2.3 Applications of RP processes

RP processes are widely used in the automotive, aerospace, medical, and consumer products industries. Although the possible applications are virtually unlimited, generally most of them fall into one of the following categories: prototyping, rapid tooling, and rapid manufacturing. The detail applications of other commercial RP process are described in Appendix 2.

2.4 Applications of the CC process

CC has its highest potential in applications involving large parts. Many parts in automotive, aerospace, and ship building concerns are large. These include tooling for car body parts, and structural parts such as chassis. Another application in automotive industry is building of clay models of concept cars [Khoshnevis 1999]. Current rapid prototyping techniques cannot be used for fabrication of such objects. CC can be effectively utilized for this purpose.

Construction of tooling for aerospace manufacturing and shipbuilding is another application area. CC can be also instrumental in building of models for large casting molds. A wax, plastic, or composite model of a ship propeller to be used in sand casting is a representative example. A qualitative comparison of the capabilities of CC relative to other RP processes is provided in Figure 2-1.

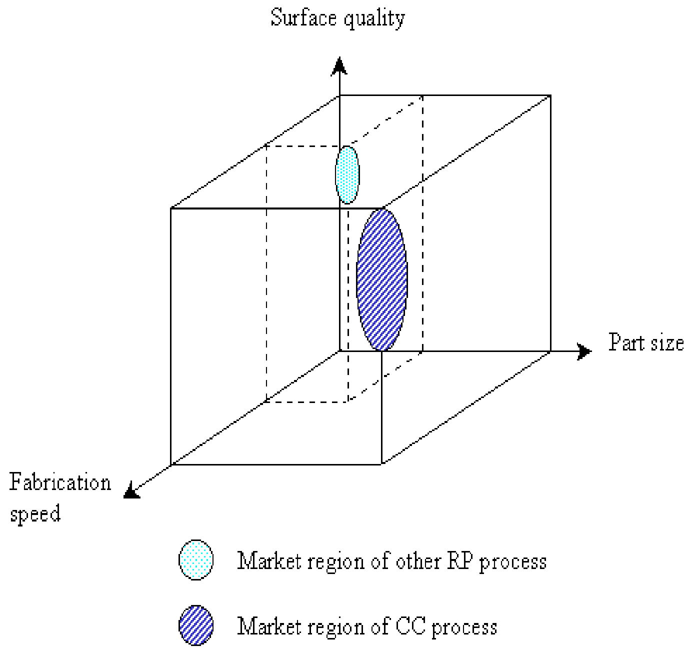


Figure 2-1. Comparison of the CC process against the current RP pro

Layered manufacturing has an excellent potential in construction of civil structures. Reduction in labor cost, better quality, and possibility of using various materials such as

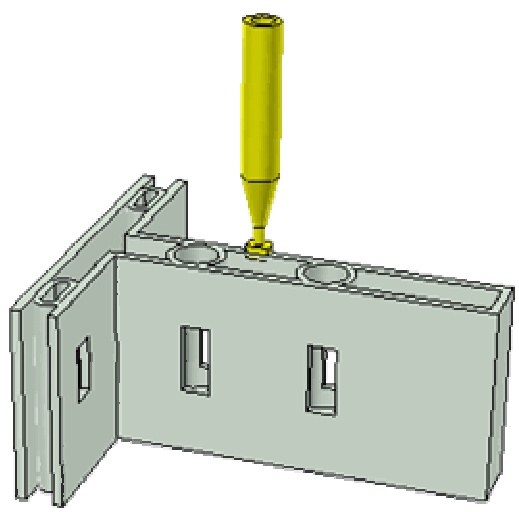


Figure 2-2. Schematic view for imbedding electrical and plumbing conduits [Source: Khoshnevis-Japan paper]

smart concretes are some of the few advantages that construction automation offers. Because of its scalability and its ability to produce smooth surfaces, Contour Crafting is an ideal candidate layered fabrication process for construction automation as shown in Figure 2-2, and 2-3. The potential applications of the CC process are descried in Appendix 3.

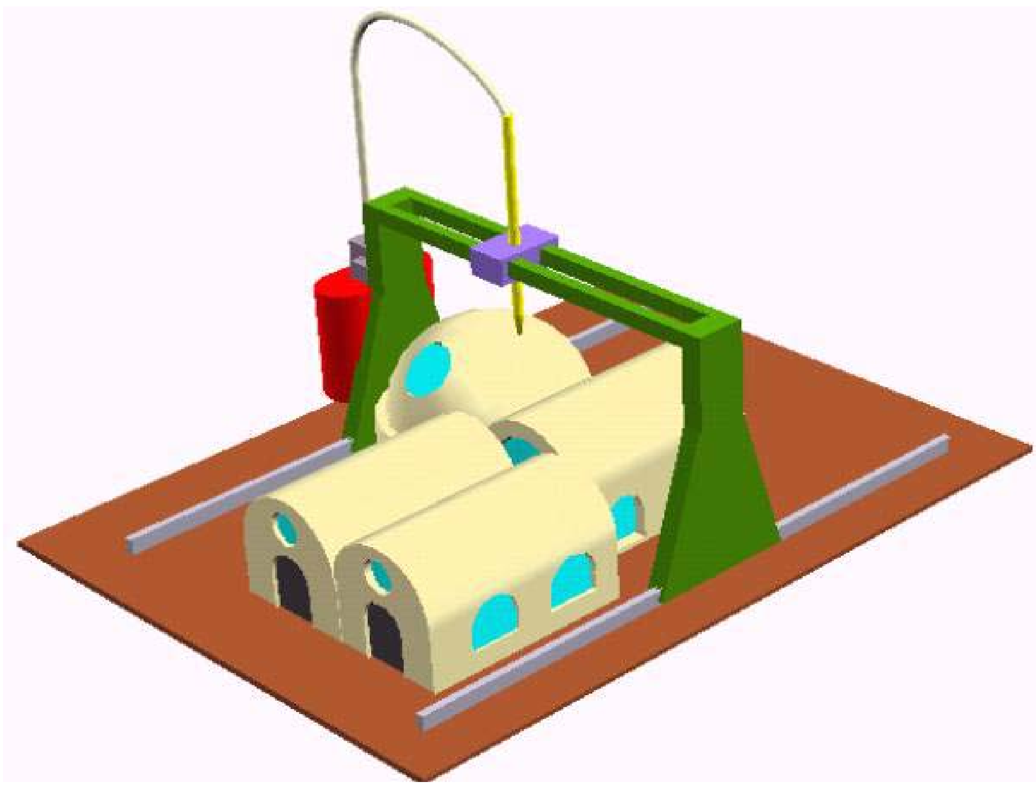


Figure 2-3. Schematic view for the automatic construction of a residential building [Source: Khoshnevis-NSF progress report]

2.5 Ceramic material

2.5.1 *General properties of ceramic materials*

The engineering properties of clay as the special type of green ceramic paste are influenced primarily by its mineral and structural composition, and the amount of contained water referred to as water content. It consists of its particles with voids between them. These voids are generally filled with air and water. The water content w of clay is

$$w = \frac{W_w}{W_s} * 100 \ (\%) \quad \ldots\ldots (2.1)$$

where W_w is the weight of water removed from the clay by oven drying at 105^0 to 110^0C and W_s is the weight of the dried clay. When its mass does not change further by oven drying, the clay is considered to be dry.

A clay particle consists of clay minerals and has plate-like shapes smaller than 2 μm. Four common clay minerals and typical values of their specific surfaces are listed in Table 2-1. Montmorillonite, one of the smallest clay minerals, has a thickness of only a few nanometers while kaolinite, the largest clay mineral, has a thickness or edge dimension of about 1 μm [Craig 1997].

Table 2-I Average values of relative sizes, thickness, and surface of four common clay minerals (Source: Yong, 1975)

Clay mineral	Typical thickness (μm)	Typical diameter (μm)	Specific surface (m^2/g)
Montmorillonite	0.003	0.1 - 1	800
Illite and Chlorite	0.03	10	80
Kaolinite	0.05 - 2	0.3 - 4	15

Layers of water molecules are held around clay mineral particles in several complex ways by hydrogen bounding and by attraction to the negatively charged surfaces. Three main categories of water around a clay particle are shown in Figure 2-4.

- A layer of adsorbed water surrounds the particle surface by powerful electrical forces and virtually in a solid state, and cannot be removed by oven drying up to 110^0C. It is considered to be part of the clay particles.
- The double layer is chemically combined water, which is in the form of water of hydration within the crystal structure. Its thickness depends on clay minerals, type, and concentration of ions in the water, and other factors [Yeung 1992].
- Interstitial water is not so tightly bound as chemically combined and adsorbed waters. Hence, it can be removed by drainage, air-drying, or oven drying.

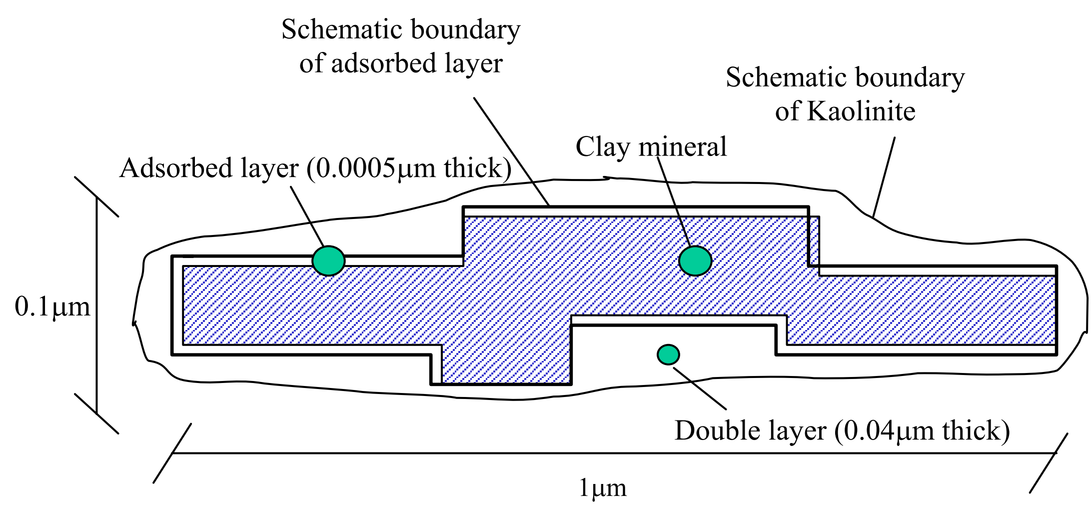


Figure 2-4. Schematic side view of the typical clay particle of Kaolinite

Depending on the water content, the mechanical properties of clay may line in one of the four states as shown in Figure 2-5. With sufficient water, the clay softens, and forms slurry that behaves as a viscous liquid known as the liquid state.

When the water content is gradually reduced by drying it slowly, the clay holds together, and offers some resistance to deformation that is known as the plastic state. The clay shrinks and its stiffness increases until it becomes brittle with the further loss of water, which is known as the semisolid state. By drying continuously, the clay reaches a constant minimum volume that is referred to as the solid state.

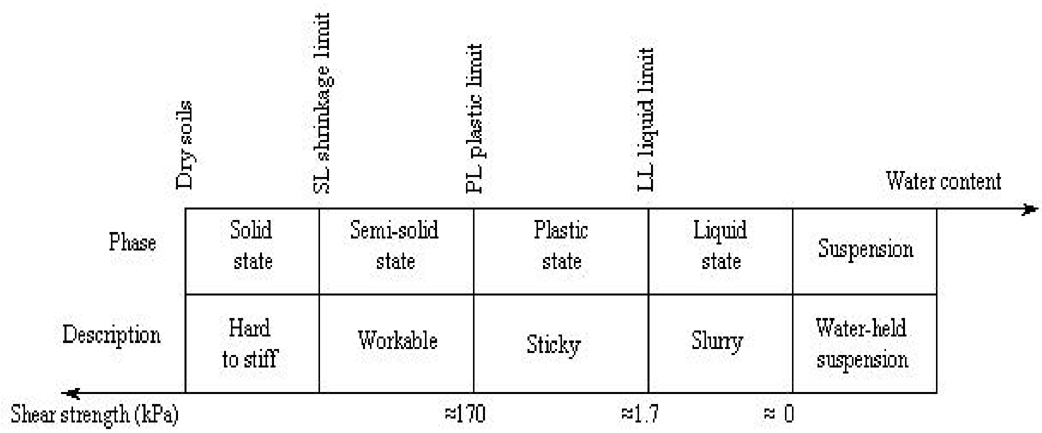


Figure 2-5. Variation of consistency of the clay with water content

Through several experimental investigations, the clay in the semisolid state is the best state for the CC process because of the following reasons:

1. From the structural point of view, the fabricated parts cannot be sagged and collapsed inward or outward during the building process because the clay, in the semisolid state, has enough shear strength to hold the pressure on the deposition point.
2. During pre-process to prepare the workable clay used in the process, the amount of air pockets absorbed into the clay can be minimized because the clay is less sticky in the semisolid state comparing to that in the plastic state.

Hence, the uniformity of the clay is improved. The surface quality of the fabricated part is improved eventually.

3. Through experimental examination of the clay on the semisolid state, it was revealed that the clay did not swell upon exiting the orifice. This is probably due to its readiness to shear and virtual absence of an elastic phase. This super-plastic behavior is demonstrated as shown in Figure 2-6.

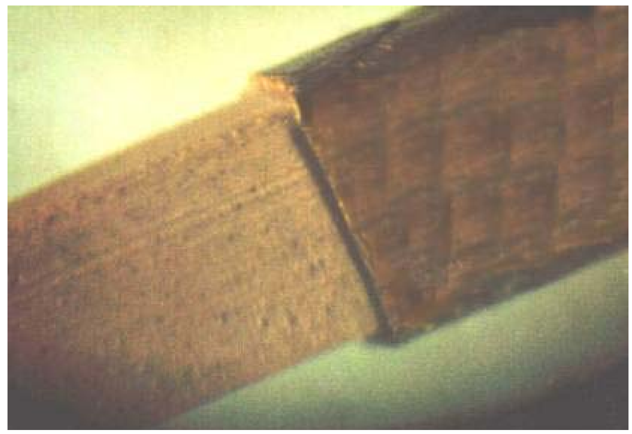


Figure 2-6. Extrudate exhibiting no orifice swell

2.5.2 ***Ceramic material applied in CC***

The clay used in our experiments was procured from America Ware Company, in Los Angeles. Its state is empirically classified into the semisolid state. The composition of the material is shown in Tables 2-2, and 2-3. In Appendix 4, the detail descriptions for the composition of clay used in the CC process are explained.

Table 2-II Composition of clay

Pioneer Talc	3402 gm
Taylor Ball clay	2268gm
Barium carbonate	7gm
Soda Ash	7.5gm
Sodium silicate	0.3oz (Deflocculant)
Water	>0.8[Gallons]

Table 2-III Composition of Taylor Ball clay

SiO_2	62.90%	CaO	0.09%
Al_2O_3	23.70%	Na_2O	0.09%
Fe_2O_3	1.07%	K_2O	0.35%
TiO_2	1.58%	LOI	9.58%

2.6 Analytical modeling of other related processes

A literature search has been performed to determine analytical and computational modeling techniques that might be beneficial for quantifying the CC process characteristics during the fabrication process. The challenges to determine the effects of the pressure on the deposition point can be approached by utilizing several methods such as a finite element method, and finite difference method, etc.

To the best of our knowledge on the RP processes, however, there has not been any work in literature on determining the effects of the pressure on the deposition point using the uncured ceramic materials. As shown in Figure 2-7, the CC process is a hybrid process of FDM since ceramic material used in the CC process is being packed under pressure resulting from the contact with the semi-solid base layers and the trowels.

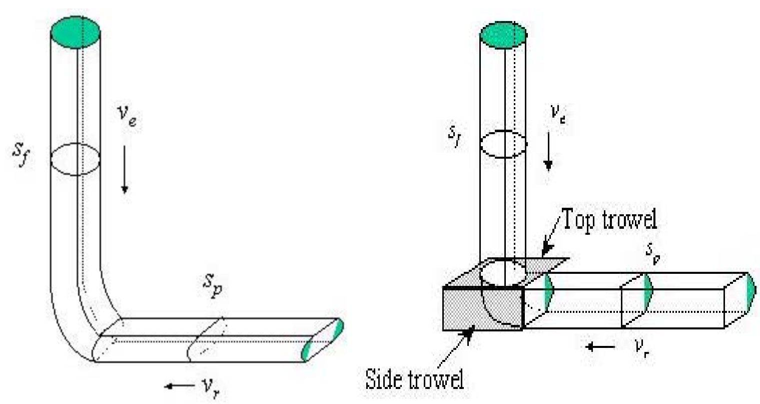


Figure 2-7. Schematic of steady deposition state of (a) FDM, and (b) CC

Alexandrou, and Ahmed [Alexandrou 1993] show the effects of die size, polymer injection pressure at the gate, and the viscosity exponent on the flow field in the injection mold. In this paper, they also discussed that the viscosity of the molten polymer is a function of the rate at which it is being deformed. The rate of deformation is increased as the viscosity becomes lower.

Garcia-Rejon, Diraddo, and Ryan [Garcia-Rejon 1995] used a commercial finite element software package (POLYFLOW) to study the effect of die inclination angle, die opening, and die contraction ratio on the annular swelling characteristics of a high density polyethylene melt extruded from industrial blow molding dies. As shown in Figure 2-6 on the CC process, however, the extruded clay did not swell upon exiting the orifice due to its readiness to shear and virtual absence of an elastic phase.

Kulkarini, and Dutta [Kulkarni 1999] show the effect of different paths on the deposition based on FDM process. In this research, they demonstrated their procedure by comparing existing methods (a zigzag path and a contour path) with alternative methods (a spiral path and a modified zigzag path). A real time coordination controller and a tool path were also studied by Han, and Jafari [Han 2000] to build high quality parts based on FDM process while improving deposition accuracy.

Bugeda, Cervera, Lombera, and Onate [Bugeda 1995] used a finite element method for studying the curl distortion effect owing to the shrinkage of the resin during the SLA process. In this paper, they concluded that dependence of the curl distortion with respect to the magnitude of the volumetric shrinkage is linear only for short parts (less then 6mm), but it becomes non-linear for longer part. They also described that the magnitude of the curl distortion decreases when the layer thickness increases. Zak, Sela, Park, and Benhabib [Zak 1999] present the effect of short-fiber reinforcement based on the SLA process. In this research, the reinforcing fibers such as short glass fibers are introduced into a liquid photosensitive resin in a discontinuous form instead of a continuous form.

Kandis, and Bergman [Kandis 2000] used a numerical simulation of an existing numerical model to predict the shape evolution, microstructure, and effective properties (porosity and thermal conductivity) of an object formed by SLS process. Tseng, and Tanaka [Tseng 2001] show the effects of two deposition techniques for solid freeform fabrication. The first technique is one that can deposit variable sizes of filaments, and the second one consists of an adjustable planar nozzle to form layers. In this paper, they also discussed that analytical solution to study the effects of changing major control parameters on the deposition of filament or layer in the techniques.

CHAPTER 3

RESEARCH METHODOLOGY

Over the past three years there has been considerable effort and progress on the development of the CC process using uncured ceramic materials. It is difficult to separate out developments to date into well-defined categories because of the intimate interplay between the hardware, software, process parameters, fabrication material, etc. Efforts on the CC project, however, will be divided into two main categories (experimental research activities, and analytical research activities) as depicted in Figure 3-1.

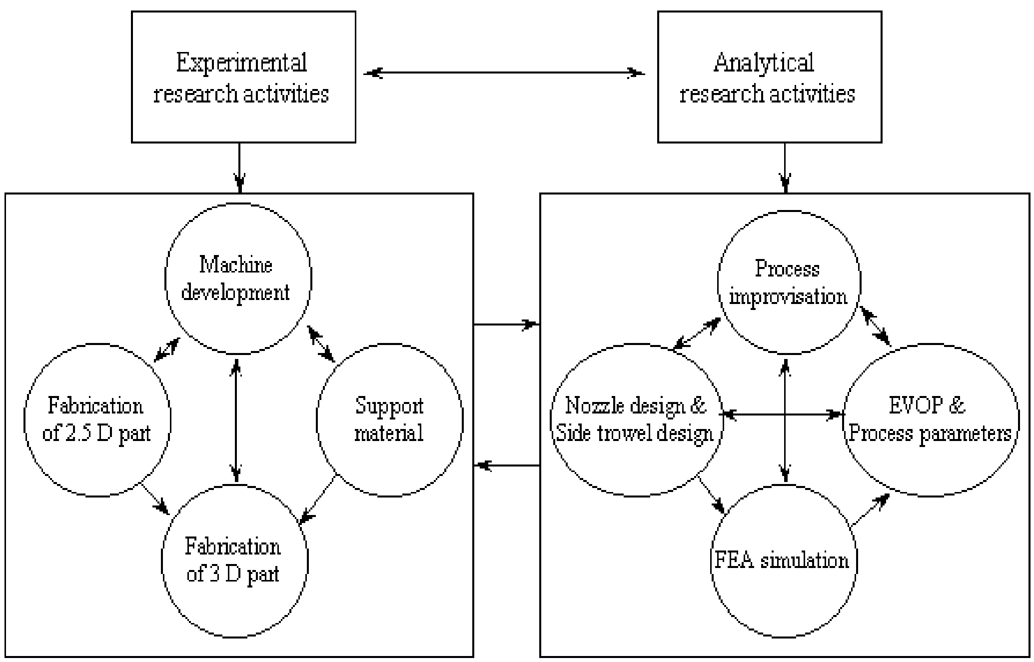


Figure 3-1 Schematic view for interrelation of the CC process development activities

In this section, the detailed aspects of the experimental research methodology are:

- Machine development
- Fabrication of geometrical parts.

The detailed aspects of the analytical methodology are:

- Process modeling
- Process characterization and Improvisations.

3.1 <u>Machine development</u>

The first part of the experimental research methodology involved the developments of the CC machine. These efforts are briefly classified into two categories: hardware issues that include the designs of the machine, and its components; and software issues such as the machine's control interface, CNC motion control program.

3.1.1 *Hardware issues*

Several hardware issues were involved in the machine configurations for the CC process that are following:

- Machine structure

The equipment in Figure 1-2 had been developed to fabricate cylindrical part, which consists of a rotary table, an extrusion system, and a gantry capable of radial and axial position control. The current mechanism had to be modified in order to fabricate other complicated 2.5D or 3D geometrical parts such as convex, concave, and sharp corners. The detail designs of the CC machine and its components are performed by Prof. Khoshnevis and presented in Chapter 4 and Appendix 5.

- Trowel geometry

The trowel geometry of the CC process is one of the main critical factors. It directly affects the outer surface of the fabricated part, and profoundly influences the surface roughness. The four most important issues relating to the trowel geometry are: a) height of the side trowel; b) possibility of creating a locking mechanism between layers; c) side trowel shape for making sharp concave corners; and d) required to pivot the side trowel for making complex 3D shapes. The detailed designs of the trowel are present in Chapter 4, and its effect during the building process in Chapter 6.

- Nozzle shape

The exit geometry is one of the critical factors because it profoundly affects the cross-section of the fabricated part. The trowel and nozzle shape together determine the cross-section of the extrudate during deposition and extrusion. The nozzle is part of the exit geometry. Its shape greatly affects the material flow and also the pressure on the deposited point. The detailed designs of the nozzle shape are presented in Chapter 4, and its effects on the CC process in Chapter 7.

3.1.2 *Software issues*

Unlike all existing layering techniques that assume uniform layer thickness and vertical sides for each layer, the CC process must consider the actual slopes of layer sides because the process has a variable-orientation trowel, which can also be shaped for better fit to the surface. The software issues are basically broken into the two parts that are following:

- Development of the machine's control interface

To operate and conduct the experimentations of the CC process, User Interface (GUI) has to be developed. Since Ptalk that is an ActiveX component has a capability to link Visual Basic with PMAC, A Visual Basic was utilized to develop GUI. It provided a user-friendly environment, easy access to the input parameters, and faster execution as compared to command-line execution. The detail functions of GUI are presented in Chapter 4.

- Development of CNC motion control program

To robotically control and guide the CC machine, CNC motion control program should be written, and also communicated with GUI in order to fast execute the experimentations. The software should have the following functions: a) the control of the material flow rate, b) the control of the robotically guided trowel's velocity, c) layer completion at the start of creation of a new layer, d) the rotation and retraction of the side trowel during cornering, and e) the control of the side trowel angle.

3.2 Fabrication of geometrical parts

The fabrication of geometrical parts is the core part of the experimental research methodology. It includes various issues that are following: a) process algorithms; b) several primitive geometries such as cylindrical, convex and concave, and sharp corner; c) several complex 2.5D geometries that combine the primitive geometries; and d) side trowel effects, which results enhance the capabilities of the CC process.

Fabrication of 3D geometrical parts is another kernel of this research that also include various following issues: a) support material to fabricate vertical 3D shapes with orthogonal sides; b) other experimental studies such as depositions with hollow cavities, and the sandwich structures; c) experimental study of the pivoting side trowel, and its effects; and d) process algorithm for fabricating 3D shapes with slant sides. These investigation results validate that the CC process is feasible and has significant potential in construction automation. The detail results are presented in Chapter 6.

3.3 Process characterizations and improvisations

The first part of the analytical research methodology is briefly classified into two categories: process characterizations that include the process parameters, and their effects; and process improvisation related into the porous material.

3.3.1 *Process parameters*

The process characterization is to understand the behavior of the process parameters, as well as to calibrate the interrelation between the process parameters. In order to conduct this research activity, the data for the surface roughness of the fabricated parts are measured, and then collected. Due to the non-availability of a stylus profile device for measuring the surface roughness, the numerical data for the performance response (surface roughness) of the CC process was not determined directly but inspected visually. With this visual inspection, EVOP technique was utilized to find the near optimal condition.

Some objection to the use of EVOP on the grounds is in violation of some of the principles of statistical process control (SPC). As long as the process is in statistical control, SPC encourages machine operator to leave it alone. This is directly opposed to the EVOP procedure that brings in changes in some process factors almost continuously. EVOP is a useful technique applied to the optimization field which process drifts over time. However, SPC is applied to the detection and elimination of isolatable, external upsets in the process that may increase process variability or shift off-target. The following example describes the procedure of the EVOP technique used in the CC process.

- Case for investigating the near optimal condition on the CC process

As shown in Figure 3-2, several experimental investigations were conducted to find the near optimal line, and the relationship between the extrusion rate and the layer thickness while achieving the same surface roughness virtually with the square nozzle shape. EVOP technique was also employed intuitively to find the near optimal condition with this visual inspection.

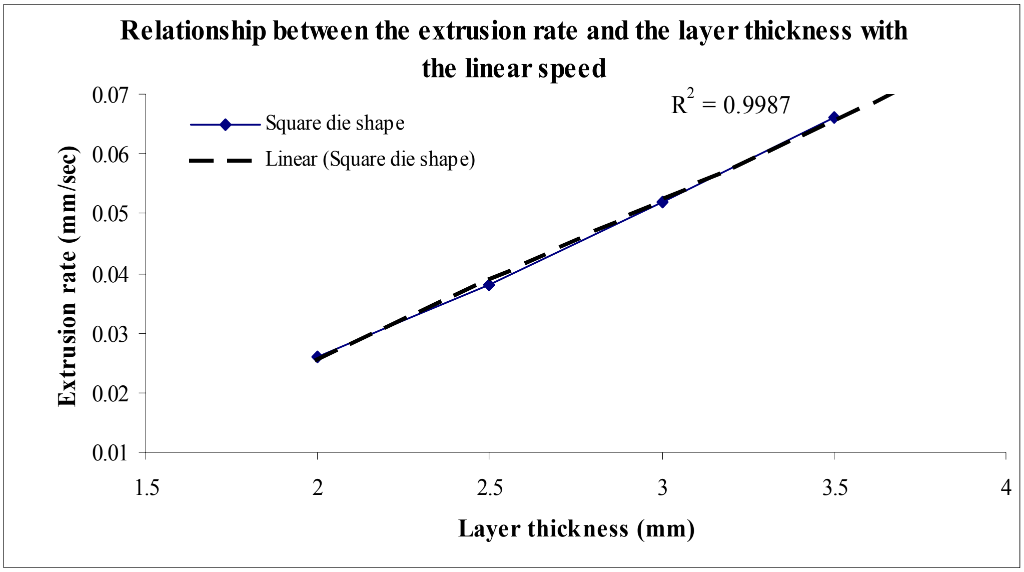


Figure 3-2. The relationship of the layer thickness and the extrusion rate

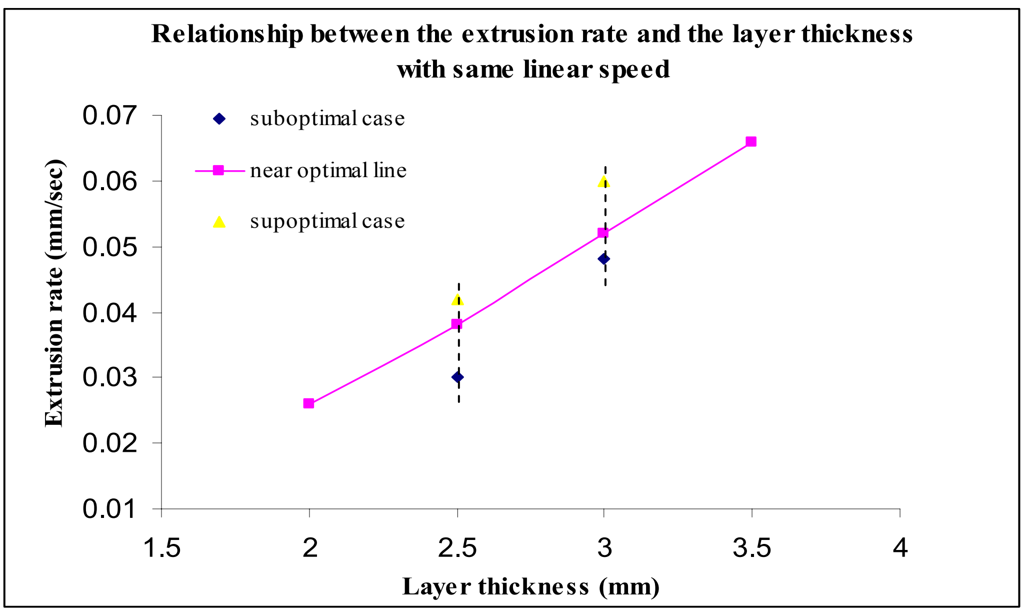


Figure 3-3. Showing the experimental point to achieve the near point

Several experiments were performed along the vertical lines as shown in Figure 3-3 before achieving the near optimal point, which are below and above the near optimal line. After the several parts were fabricated at one of points on the vertical line, the surface quality of the parts was inspected virtually.

If there are stair lines between layers as shown in Figure 3-4 (a), the stair lines indicate that the pressure on the deposit point is below the optimal point. If there are cutting tracks on the surface as shown in Figure 3-4 (c), the cutting tracks indicate that the pressure on the deposit point is over the optimal point. Both conditions required changing the extrusion rate with the same layer thickness in order to achieve the optimal pressure. This near optimal condition usually produced the good surface quality as shown in Figure 3-4 (b). After finding the near optimal point at a layer thickness, the layer thickness was changed in order to find another near optimal point. The same procedures were applied at that condition in order to achieve the near optimal point.

Through several experimental studies, the near optima line was found in

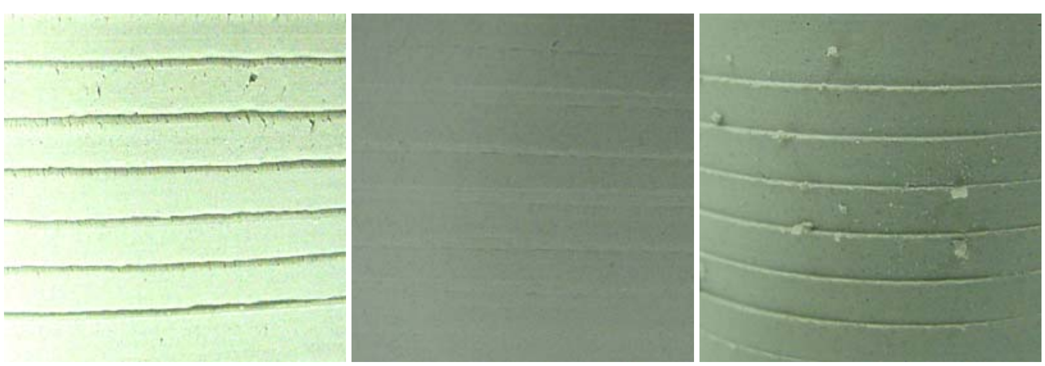


Figure 3-4. Surface quality at the condition under (a) the suboptimal, (b) the near optimal, and (c) the supoptimal case with a square orifice

Figure 3-3 and 3-4, and also the extrusion rate is directly proportional to the layer thickness to achieve the same surface roughness. Thus any change in the extrusion rate affects the velocity of the extrudate, and consequently changes the pressure forming the layer. The detailed results are described in Chapter 5.

3.3.2 *Process improvisations*

In order to select the appropriate type of fabrication material, initial experimentations focused on porous materials such as plaster, wet ceramic, etc. Basically, trial and error experimentation was performed to understand the behaviors of the porous material during extrusion. These porous materials exposed various issues such as air pores, shrinkage, spring-back, etc. The detailed results are presented in Chapter 5.

3.4 Process modeling

To understand the material flow patterns in the extrusion and deposition stages of the CC process, this section presents a methodology of process modeling by utilizing Computational Fluid Dynamic (CFD) simulation software.

3.4.1 *Material flow pattern during deposition on the CC process*

The CC process holds similarities to both extrusion and mold-filling processes. The similarities to normal extrusion processes are obvious, as the extrudated clay is being packed under pressure. The CC process is somewhat similar to a mold-filling operation.

- Extrusion:

Using a direct ram extrusion mechanism, the material in CC is pushed vertically down through an orifice into a space between the top and side trowel and a bottom layer of deposited material. The top trowel is perpendicular to the extrudate flow. The distance between the top trowel and the bottom layer determines the layer's thickness. The side trowel is parallel to the extrusion flow and controls the shape of the outer surface of the layer.

- Deposition:

For a specified material, the initial cross section of the extrudate, ignoring post extrusion swells, is almost the same as the dimensions of the orifice. After exiting the orifice, however, the extrudate is forced into a sharp 90° corner. This creates elastoplastic stresses in the deposited layer, deforming its cross-section. However, if the plastic deformation of the extrudate is ignored, the resulting part's

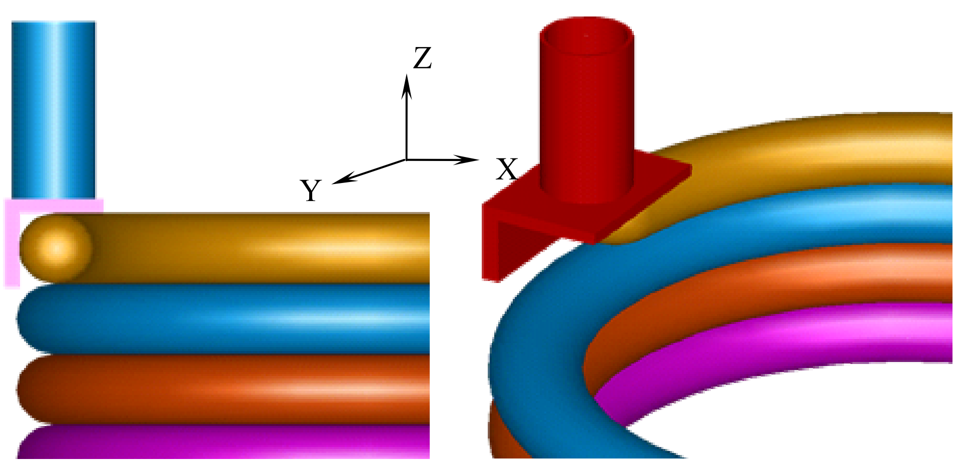


Figure 3-5. Graphical schematic of the CC process where the compression and flow of extrudate to deposition are neglected

surface profile will be totally determined by the orifice shape, as shown in Figure 3-5.

A close examination of parts from CC shows that surface quality critically depends on the flow pattern of the material during extrusion and deposition, which in turn is heavily determined by the geometry of the orifice. A thorough study of the effect of orifice geometry is necessary in order to: (a) understand process flow characteristics comparing the actual process; (b) understand the effect of extrusion orifice geometry on the CC process varying several process parameters such as the extrusion rate, the linear speed, etc.; and (c) find suitable geometries for the orifice and side trowel in the CC process in order to enhance surface quality by minimizing the seam line between layers while comparing several orifice and side trowel geometries.

3.4.2 *Effect of orifice shape on the cross-section of the extrudate*

As mentioned before, the exit geometry of the CC process is an essential factor. The material flow and the resulting part cross-section are strongly affected. Investigating how each factor affects the eventual cross-section of the extrudate and optimizing their effects would lower the fabrication time, and enhance the surface finish. Simple process modeling is undertaken for understanding process flow characteristics. The detail simulation models of the orifice shapes are also descried in Chapter 7.

3.4.3 *Effect of the side trowel angle*

One of the essential factors is the side trowel that consists of exit geometry of the CC process. The material flow and the surface finish are strongly affected. Investigating how the angle of the side trowel affects the eventual material flow would enhance the surface finish of the 3D geometrical part. The detailed simulation models of the trowel angle are also descried in Chapter 7.

CHAPTER 4

DEVELOPMENT OF THE CC MACHINE

In this chapter, the developments of the CC machine and its control system are briefly described. These efforts are classified into two categories: hardware developments that are specifically detailed in Appendix 5, and software developments such as the machine's control interface.

4.1 Machine structure

There are several possible machine configurations for the CC process. As shown in Figure 1-2, this CC machine utilizes uncured ceramic to fabricate cylindrical parts. The machine consists of an extrusion system (a cylinder that holds the raw material, and a piston and a linear ball screw that extrudes the raw material through a nozzle), and the trowel rotation mechanism as shown in Figure 4-1.

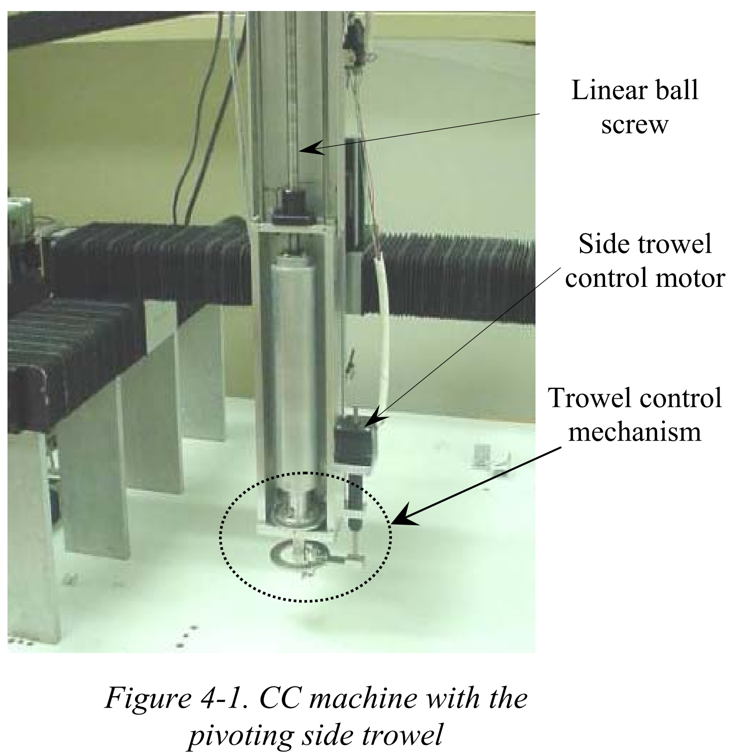


Figure 4-1. CC machine with the pivoting side trowel

The extrusion system and the trowel rotation system were designed by Prof.

Khoshnevis and assembled into the CC machine. The linear ball screw was accommodated to reduce the frictions of the piston shaft while fabricating parts. Accordingly, the CC process became more stable, and more powerful for the material to be extruded. The trowel rotation system consists of a bevel gear, and a connector. The detail design of the CC machine components are described in the Appendix 8.

To further enhance the capability of the CC process, the pivoting side trowel was designed by Prof. Khoshnevis and dimensions were specified by Dooil Hwang, and assembled as shown in Figure 4-1. Eventually, this mechanism improved the capability of the CC process while fabricating other diverse complicated 3D geometrical parts such as cones, pyramids, domes, etc. The detail design, and the trowel mechanism with the pivoting side trowel are described in Appendix 5.

4.2 Software development

For the control of the robotically guided fabricator, a master-slave system structure was designed and implemented as seen in Figure 4-2. The applications (such as process monitoring, data communication, etc) are supported by a PC with Graphic User Interface (GUI). In order to supervise the process and control the motions of each stepper motor, PMAC (a multi-tasking digital signal processing) board is utilized.

4.2.1 *Development of Graphical User Interface*

To operate the CC process, a GUI was developed. To conduct the experimental studies for several primitive and complex geometrical shapes, the corresponding CNC motion control programs for each shape were coded to control each motors. The parameters for these programs were set through the user interface module.

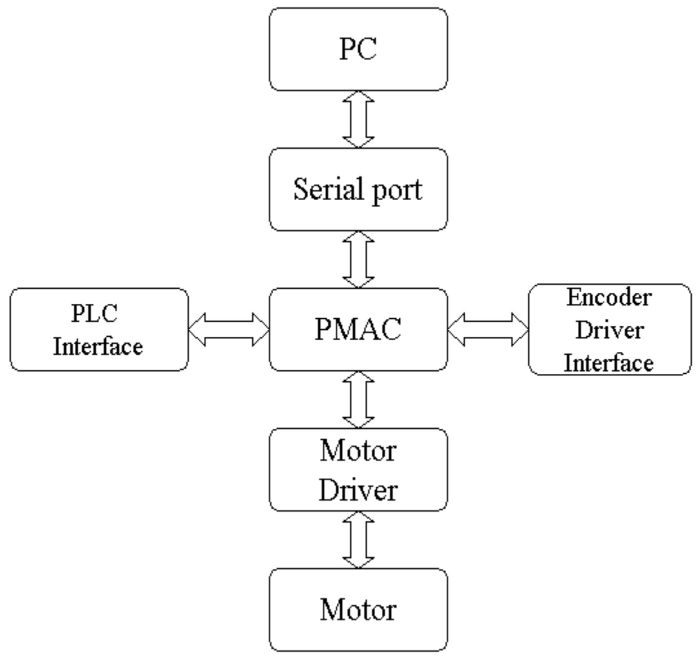


Figure 4-2. System configuration of the CC process

A Visual Basic User Interface was also developed to operate the electronics controller called PMAC, via Ptalk which is an ActiveX component linking Visual Basic with PMAC. This interface provided a user-friendly environment, easy access to the input parameters, and faster execution as compared to command-line execution. As shown in Figure 4-3 and 4-4, the GUI consists of two modules: model making form, and positioning form. The detail program coding of these GUI is described in Appendix 7.

The first module shown in Figure 4-3 has the following features:

- Setting of all of input parameters such as the extrusion rate, linear speeds for the base and the body, layer thickness, etc. (boxes on left).
- Provisions for starting and stopping the program downloaded from PMAC, and possibility of changing the program module to fabricate other geometrical shape (button on right).
- Provisions for monitoring the exact position and the speed of each motor during fabrication on a real-time basis (boxes on bottom).

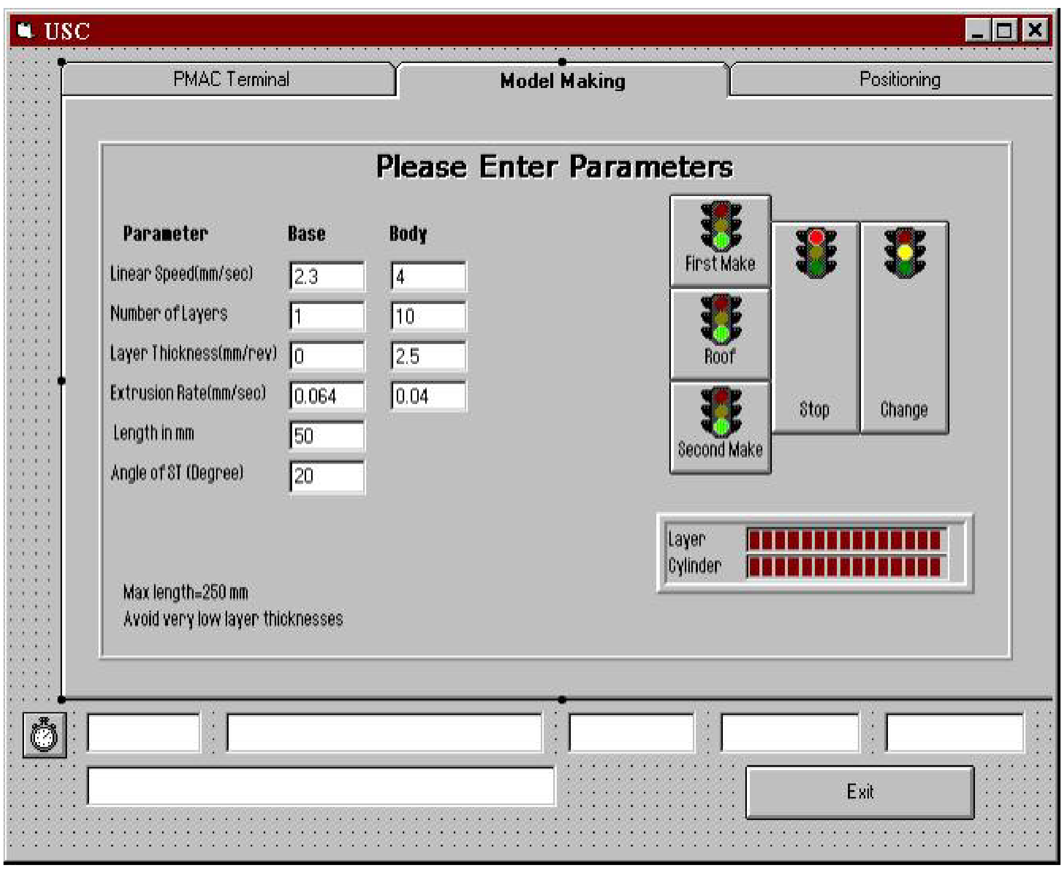


Figure 4-3. Module for entering the input parameters

The second module shown in Figure 4-4 has the following features:

- Provision for monitoring the exact position of each motor during the process of locating the home position.
- Provision for changing the speeds and position of each motor at the click of a button rather than having to provide initialization, assignment and motion-related commands for the motors.
- Provision for setting a new home position before the program starts, and jogging to the home position of each motor after the objects are fabricated.

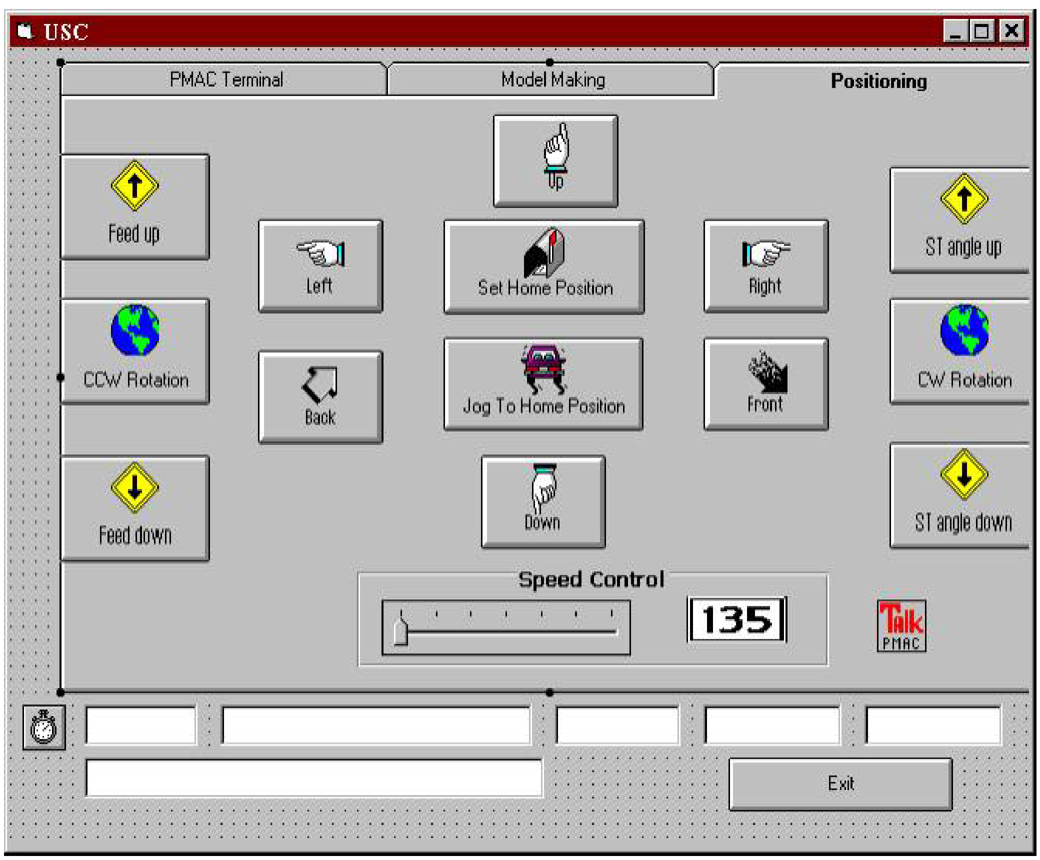


Figure 4-4. Module for controlling the position of each motor

4.2.2 *CNC motion control programs*

CNC motion control programs were developed to conduct several experimental investigations for diverse geometrical shapes. These programs were stored in the PMAC memory before being communicated to GUI via Ptalk. Each program is separated into two sections. The first section is the header of the CNC program. The coordinate system for each motor should be initialized and defined in this section. The movement scale (unit) for each motor also has to be specified with the coordinate system. Various control parameters (such as linear speed, size of the fabricated part, layer thickness, etc.) are incorporated in the header section to allow the main body of the program to communicate with GUI. The second section is the main body of the CNC program. The motion direction and speed of each motor are controlled based on the defined control parameters.

After the pivoting side trowel was developed, CNC motion control programs for 3D geometrical shapes were developed. To fabricate 3D parts with the pivoting side trowel, the slope of each deposited layer should be calculated using the associated geometrical relationships. The detail process algorithms for various shapes are described in Chapter 7. The detail program bodies for other primitive and complex shapes are described in Appendix 8.

CHAPTER 5

PROCESS CHARACTERIZATION AND IMPROVISATION

This chapter is classified into two sections. The first section 5.1 deals with the process parameters. Several material challenges and process improvisations are discussed in Section 5.2. These results are achieved while conducting the experimental investigations to fabricate 2.5D parts using uncured ceramics such as plaster and clay materials.

5.1 **Effects of process parameters**

In addition to the large number of process parameters that exist in a basic extrusion system, additional parameters are involved in the CC process. Because of this complexity, some preliminary experimentation was necessary to determine the process parameters.

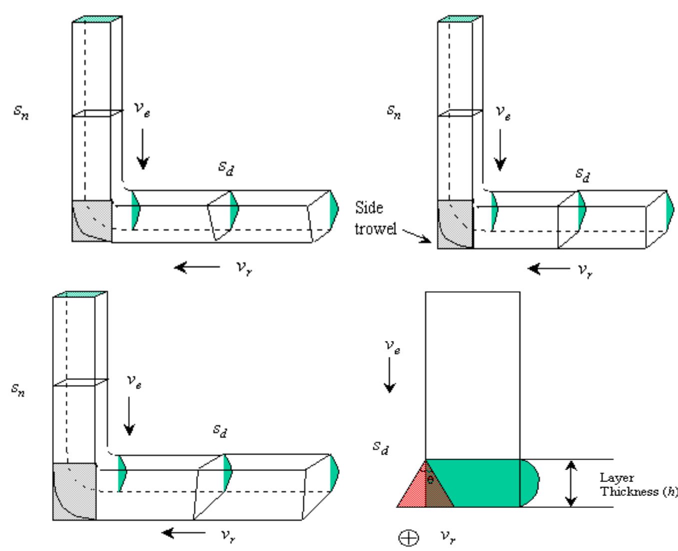


Figure 5-1. Schematic view of steady flow with different side trowel angles

Through several experimental investigations, it is attempted to understand the behavior of the material during extrusion, as well as to calibrate input and output parameters. The input parameters were extrusion rate (V_e) [mm/sec], linear speed (V_r) [mm/sec], thickness of the layer (h) [mm], diameter of the part (D) [mm], and number of layers (n). The output parameters considered were the vertical profile (Δh), and the surface roughness (R_a) which is the main response.

According to mass balance principle, the material input is equal to its output. Thus, the following equation may be written:

$$S_d = C_d \frac{V_e S_n}{V_r} \quad \text{……(5.1)}$$

$$S_d = S_d' + \tfrac{1}{2} * h^2 * \tan(\theta) \quad \text{……(5.2)}$$

where C_d is a constant ratio of material density or the compression factor

V_e (mm/sec) is the extrusion velocity

V_r (mm/sec) is the linear speed of the extrusion head

h (mm) is the height of the deposited layer

θ (degree) is the pivoting angle of the side trowel

S_n (mm^2) is the cross sectional areas of the nozzle

S_d (mm^2) is the cross sectional areas of deposited layer

S_d' (mm^2) is the cross sectional areas of deposited layer when $\theta = 0$

V_e will always increase at the deposition point because the extudated material is partially unbound after the exit of the nozzle. Hence, S_d will increase at the point if other parameters are constant. As shown in Figure 5-1, S_d also relay on an angle of the side trowel and the pressure at the deposition point which mainly affect the surface roughness of fabricated parts. As shown in Figure 5-2 the extrusion rate is directly proportional to the layer thickness for a given surface roughness. Thus any

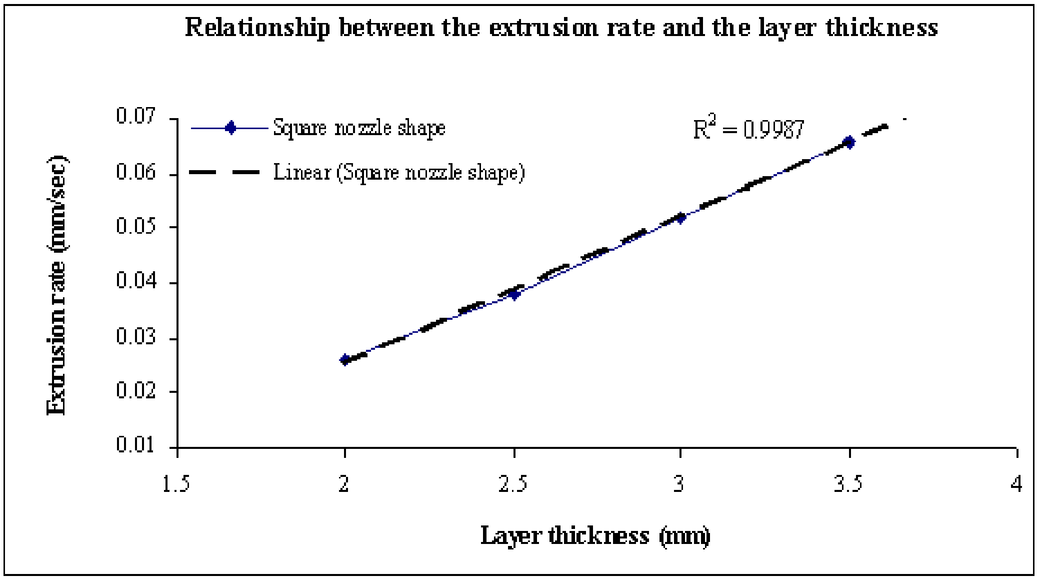


Figure 5-2. The relationship of the layer thickness and the extrusion rate

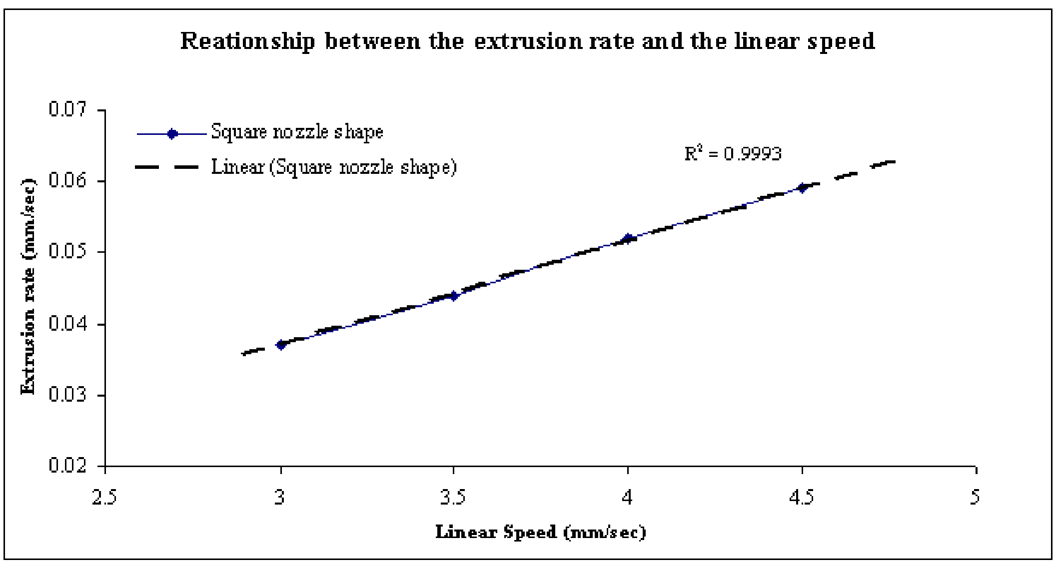


Figure 5-3. The relationship of the linear speed and the extrusion rate

change in the extrusion rate affects the velocity of the extrudate, and consequently changes the pressure forming the layer. To maintain the same surface finish with varying layer thickness, the extrusion rate is directly proportional to the layer thickness. The detail procedures are described in the subsection 3.1.

$$V_e \propto h \quad \text{...(5.3)}$$

The extrusion rate is also directly proportional to the linear speed for a given surface roughness as shown in Figure 5-3. Thus any change in one of control factors (extrusion rate, linear speed, and thickness of the layer) affects the pressure on the deposit point, and hence change the surface roughness of the fabricated parts. Similarly, to maintain the same surface finish, the linear speed can be found to be directly proportional to the extrusion rate.

$$V_r \propto V_e \quad \text{..(5.4)}$$

Combining equations 5-1, 5-3, and 5-4

$$V_e / V_r \propto h \quad \text{..(5.5)}$$

For a given surface roughness the angle of the side trowel is also directly proportional to the extrusion rate as shown in Figure 5-4. Thus any change of the

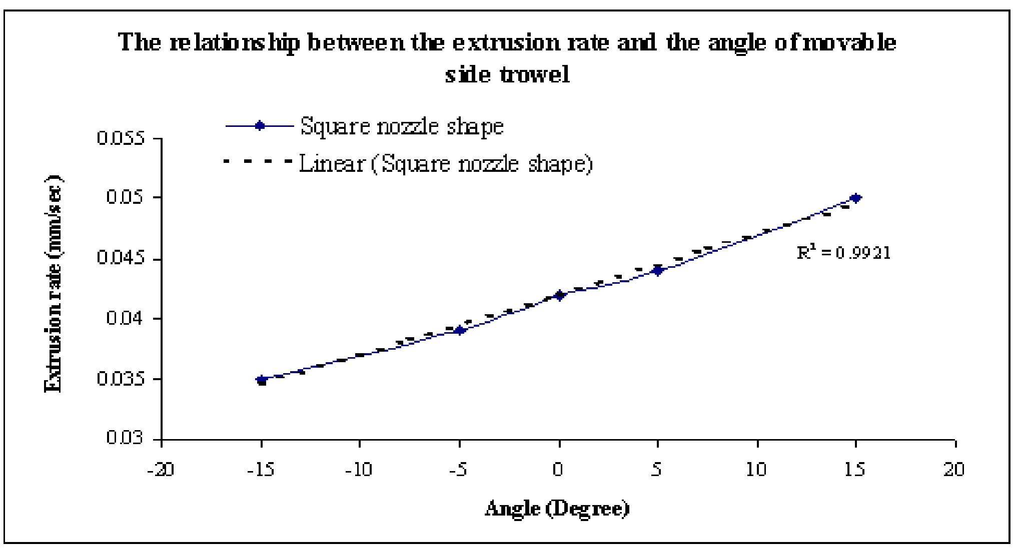


Figure 5-4. The relationship of the extrusion rate and the pivoting angle

pivoting angle of the side trowel affects the pressure on the deposit point. To maintain the same surface finish, hence, any control factor should be changed in order to compensate the difference of the pressure on the deposit point.

$$V_e \propto \theta \quad (5.6)$$

Generally in multivariate response surface methodology, each of the responses does not necessarily have the same optimal process parameter settings. That is, the directions of change in each response toward optimum condition might be different in real applications. However, the best process settings for surface finish in the CC process are as close as optimum conditions for the exterior geometrical profile of fabricated parts in several experimental investigations.

As the results of the several experimental studies, several process parameters that can influence the surface quality of fabricated parts are listed:

- Extrusion rate
- Linear speed of the extrusion head
- Layer thickness
- Pivoting angle of the side trowel
- Geometric features such as concave, convex, etc.
- Material properties such density, viscosity, water content, etc.
- Rotating angle of the side trowel about Z-axis
- Vibration of the CC machine
- Number of layers of the part

These process parameters are further classified into two categories depending on the extent of impact on the surface roughness of fabricated parts. The control factors strongly affect the pressure at the deposition point, and eventually determine the surface roughness. Secondary factors are those that are uncontrollable or have a relatively low impact on the surface roughness.

Control factors:

- Extrusion rate
- Linear speed of the extrusion head
- Layer thickness
- Pivoting angle of the side trowel

Secondary factors:

- Geometric features such as concave, convex, etc.
- Rotating angle of the side trowel about Z-axis
- Material properties such density, viscosity, water content, etc.
- Vibration of the CC machine
- Number of layers of the part

Since only the four control factors are going to be varied for other experimental studies such as experimental investigations for fabricating diverse geometrical shapes, material flow simulation, etc., all other process parameters might be fixed or assumed to be at the same condition through the experimental studies.

5.2 Process improvisation and material issues

To select the appropriate type of fabrication material, initial work focused on porous materials such as plaster, wet ceramic, etc. To understand the behavior of the porous material during extrusion, trial and error experimentation was performed. During the experimental investigation, these porous materials revealed some common phenomena as well as some specific unique phenomena. In this section, the detail process improvisations and its challenges are described.

5.2.1 *Process improvisation with plaster material*

- Plaster material

A spackling plaster compound adopted in the initial experimentations was procured from Custom Building Products, Inc. This material had several main advantages: a) was commercially available, b) was cheap, c) was light in weight, and d) was quick incurring. The plaster contained acrylic copolymer, amorphous silicate, 3% water per unit volume of material, and small glass bubbles that reduced shrinkage. This material could be extruded at room temperature, which obviates the need for temperature control in the extrusion head. Fabricated parts had a setting time of approximately 3 hours after being made. Novel process strategies had to be adopted because of: a) compressibility of the material, b) low wet-strength, and c) greater then 3% shrinkage after extrusion and setting.

Figure 5-5. Plaster part extruded without heating and wetti

Figure 5-5 shows a plaster part made by simply adjusting the input parameters to improve the quality. However, as can be seen, the part showed a warped external profile, and bad surface finish.

This poor quality may be mainly attributed to the following three causes:

- Low wet strength of the material such that beyond 10 layers (approximately 150 mm) the part started to sag and collapse inward.
- Adhesion of the material to the side trowel which reduced the effective smoothing capability of the side trowel.
- Sticking of the material to its base during drying, causing uneven shrinkage along the parts vertical profile.

Following are the improvisations that were adopted to address these issues.

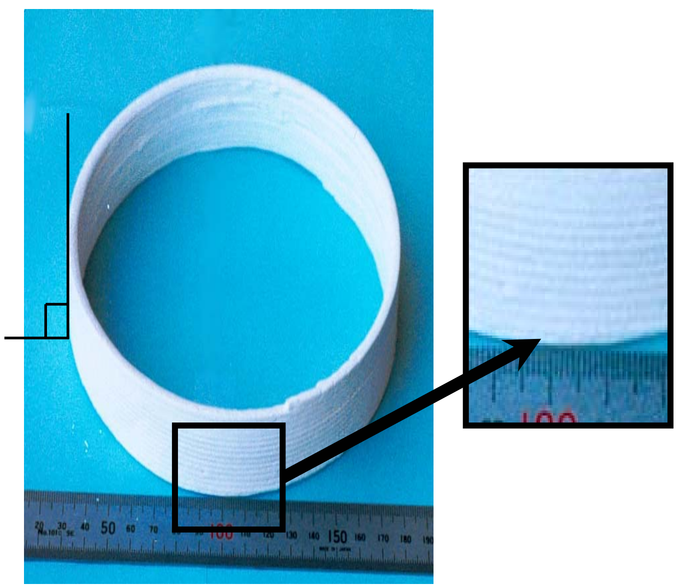


Figure 5-6. Plaster part after extruded while its layers were uniformly dried without wetting

- Drying

In order to improve the straightness of the external profile, structural strength and integrity of the part, we accelerated the drying of each layer by heating the inside of the part being fabricated. A heat gun apparatus (500^{o}C) was attached to the z-axis whereby the internal surface of each layer was uniformly dried upon extrusion. However, this increased the incidence of the plaster sticking to the side trowel and of shrinkage during fabrication as shown in Figure 5-6, thus leading to a poor surface finish. However, The part profile was reasonably good and straight without a conical external profile.

In addition to increasing the structural strength during fabrication, drying at the optimal temperature resolved the following problems: (a) excessive curing, which will damage the profile and cause cracking, (b) over-drying, which may cause sticking of the trowel to the surface causing poor surface finishes, and (c) surface pores, which may be caused by the conduction of heat into the extrusion cylinder. It expands air cavities in the material.

- Wax/ Aluminum Foil Wrap

A uniform (~0.1 mm thick) layer of wax was applied onto aluminum foil that was wrapped around a metal plate. The part was then built on the aluminum foil. The idea was to reduce contact friction between the bottom of the part and the solid base when the part shrunk as the material dried. The reduction of the contact friction facilitated the straightness of the part even after shrinkage and setting. If wax were not used, the parts would assume a conical external profile as shown in Figure 5-5. This was due to the difference in shrinkage at the free top layers and the constrained bottom layer.

- Water-mist

During fabrication, a thin water mist was sprayed periodically onto the external surfaces of the part, 12 times during every revolution of the rotary table. The water mist prevented the adhesion of the plaster to the side trowel. Excessive water, however, caused substantial cracking and significant warping of the outer surface.

After adopting these improvisations, there were marked improvements in each part's surface finish and its vertical profile. Besides, we were able to fabricate parts of larger dimensions than was previously possible. In Figure 5-7 improvement in surface finish (< 10 μm which value was roughly measured by using an image processing technique with Photoshop) and straight profile of a fabricated part can be seen.

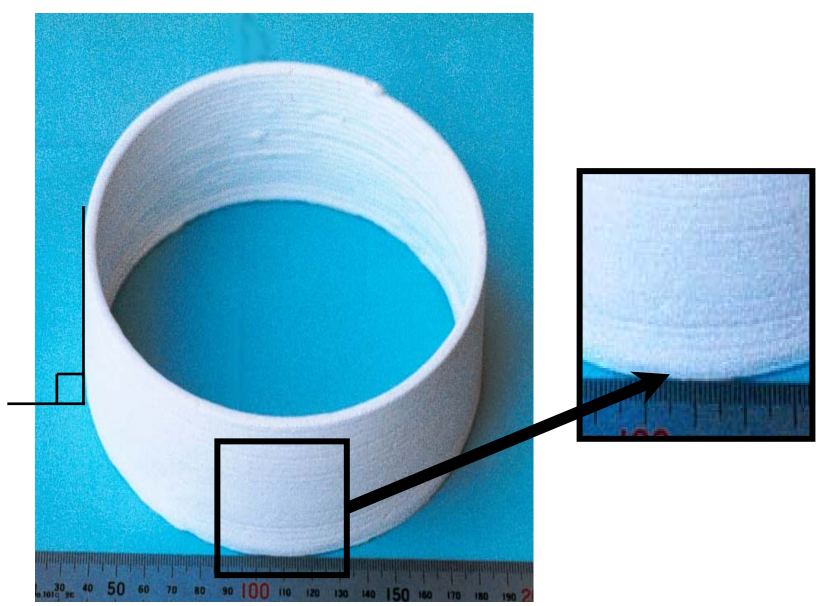


Figure 5-7. Plaster part after extruded using heating and wetting to improve profile and surface finish, respectively

5.2.2 *Clay*

The clay used in our experiments was procured from America Ware Company in Los Angeles. The clay contained: Pioneer Talc 2882, Taylor Ball clay, Barium Carbonate, Soda Ash, Sodium Silicate, and 35% water by mass. The clay parts were fabricated at room temperature and then bisque-fired in a kiln at 1063°C~1066°C for 10 hours. For glazing, a second firing at 1003°C was carried out for 8~9 hours.

Forced drying by heating and the wax-coating procedure were not necessary due to the higher structural wet strength of the clay material. Large parts could be made with the assurance that the clay would not sag or collapse inward as shown in Figure 5-8.

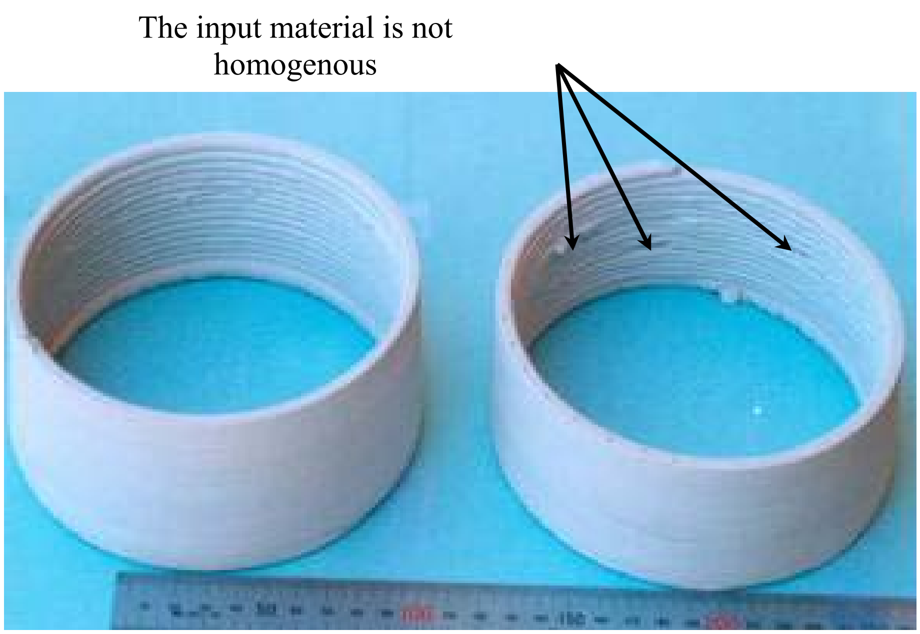


Figure 5-8. Clay parts

- Air pores

One drawback to using clay was that extrudate geometry and properties tend to be highly nonuniform. This is due to the presence of air and water in the extrusion cylinder after filling. This caused certain areas of the extruded layers to have gaps as can be seen in Figure 5-8. However, the gaps (depending on their size) did not affect the surface finish considerably as successive layers filled these gaps with a long side trowel which overlaps previous layers. In Figure 5-9 small air pores can be seen on the surface of the part. These air pores are a result of air present within the material.

Figure 5-9. Effect of the side trowel on smoothing

In order to prevent the occurrence of air gaps in the cylinder, a filling method was devised using a funnel shaped apparatus that enabled the continuous insertion of clay into the cylinder during initial filling. Pre-extrusion processing of the material also seems to significantly affect the void and surface pore formation. As mentioned in Section 3.5, however, these challenges related to the pre-extrusion processing had been removed with changing the state of the used clay from the plastic state to the semisolid state. The clay in the semisolid state is the best state for the CC process because of the following reasons:

1. The fabricated parts cannot be sagged and collapsed inward or outward during the building process because the clay, in the semisolid state, has enough shear strength.
2. The amount of air pockets absorbed into the clay can be minimized because the clay is less sticky in the semisolid state then in the plastic state.

By setting the optimal extrusion rate and angular velocity values, the proper pressure on the deposited point was brought to bear upon the clay, thus filling small air pores in the previous layer.

- Shrinkage

Shrinkage occurred in both materials. There was no vertical shrinkage in the plaster, however, there was a less than 1.5% horizontal shrinkage rate. It remains to be determined whether the shrinkage occurred because of the properties of the material (the plaster, for example, contained 3% water per unit volume) or because of the CC process; however, the results do allow us to quantify the precision capabilities of the process.

In order to prevent the uneven shrinkage of the top and bottom layers during setting, a plastic wrap was used as the cover for the metal base. The idea here is to decrease contact friction.

- Spring-back

Both clay and plaster parts showed improved compressive strength qualities, compared to conventional die cast parts, after compression through the extrusion system. This enabled the lower layers made of these two materials to retain their shape and dimension even as additional material was deposited on them.

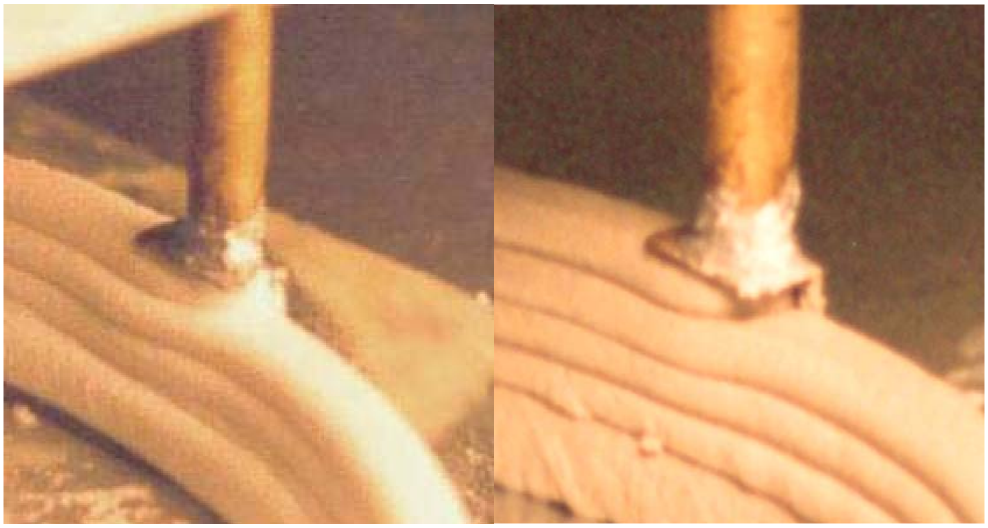


Figure 5-10. Compression and spring-back during fabrication; a) with plaster, and b) with clay

As can be seen in Figure 5-10, the layers directly below the point at which material was being deposited, compressed vertically and expanded horizontally, but returned to their original form (spring-back) once the pressure was released. As can be seen in Figure 5-11, it is an evident fact that if the homogeneity of the material in the cylinder can be maintained, these effects will be consistent through every section of each layer, thus giving the part superior mechanical properties.

Figure 5-11. The cross section profile of a clay part

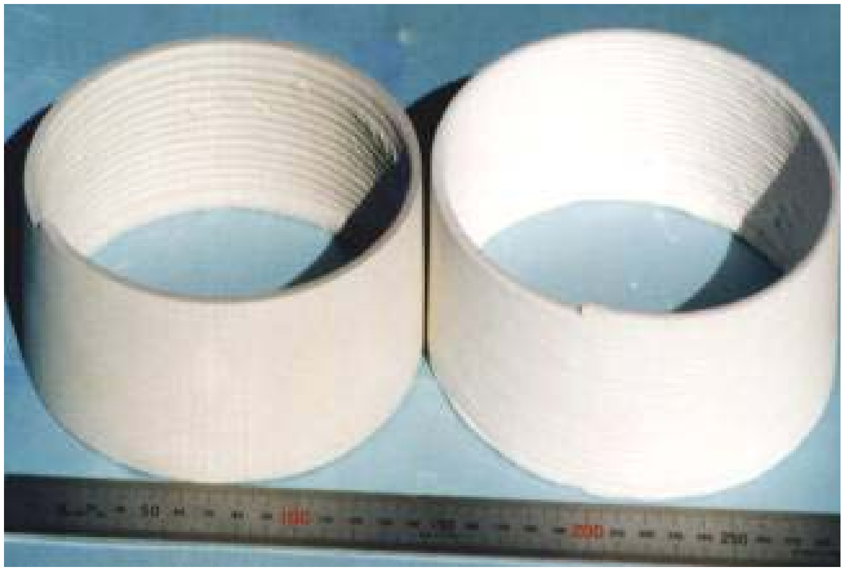


Figure 5-12. The parts showing adequate surface finish with different materials used

As shown in Figure 5-12, cylindrical parts having adequate and consistent surface finish and cylindrical profile could be fabricated with two representative ceramic materials. Representative parts were resulted from our evolutionary operation (EVOP)-based process optimization [Myers 1995]. The detail explanations of EVOP with CC are described in subsection 3.1.

Figure 5-13. The clay parts showing superior surface finishes v thickness

The experimental results reflect the potential of this system to produce parts of superior finish (< 5.0μm), good profile, wide range of part size, and consistent dimension (tolerance). Figure 5-13 shows how the foregoing results were replicated for clay parts of different diameters and heights. Thus, in order to achieve optimum quality the pressure between the trowel and top layer of the part must be constant regardless of the diameter of the cylindrical part. As shown in Figure 5-11, also, the cross section profile of a part fabricated with clay revealed the following three effects:

- The internal layers fused together very firmly.
- The widths of the layers were uniform and consistent except for the top layer, which has not been compressed (sandwiched).
- The smoothing effect of the side trowel on the outer circumference was uniform, hence a straight profile was realized.

CHAPTER 6

EXPERIMENTAL INVESTIGATIONS TO FABRICATE GEOMETRICAL PARTS

This chapter is classified into four main sections. Section 6.1 discusses experimental investigations for 2.5D geometrical parts. Section 6.2 is a discussion with regard to building 3D geometrical parts with orthogonal sides. In Section 6.3, other extensive experimental studies are discussed. In Section 6.4, observations for 3D geometrical parts with slant sides are discussed with using the pivoting side trowel. The specific focus for the experimental optimization of the CC process is to fabricate parts with good surface finish using uncured ceramics such as plaster and clay materials while maintaining minimum processing time and best possible geometric accuracy.

6.1 Experimental investigations to fabricate 2.5D shapes

Various experimentations with the CC process were conducted to investigate the fabrication of complex 2.5D geometrical parts. This section is basically broken into three subsections. The first subsection describes the process algorithm to fabricate 2.5D shapes. The second subsection describes the process algorithm to fabricate sharp convex geometrical 2.5D shapes. The third subsection is a discussion regarding observations of the side trowel effects for achieving a good surface finish for 2.5D parts.

6.1.1 *Process algorithm to fabricate 2.5D shapes*

The fabrication process of the CC generally is divided into 2 stages as shown in Figure 6-1. The first stage of building any part is base layer fabrication which provides a foundation upon which subsequent layers can be built. The base layer height is approximately equal to the length of the side trowel. The second stage comprises body fabrication. The layers comprising the body (circumference) of the 2.5D parts can have any thickness less than or equal to the length of the side trowel. The 2 stages of the fabrication method for the cylindrical part, built on a rotary table with the nozzle moving only in Z-direction, are described as follows:

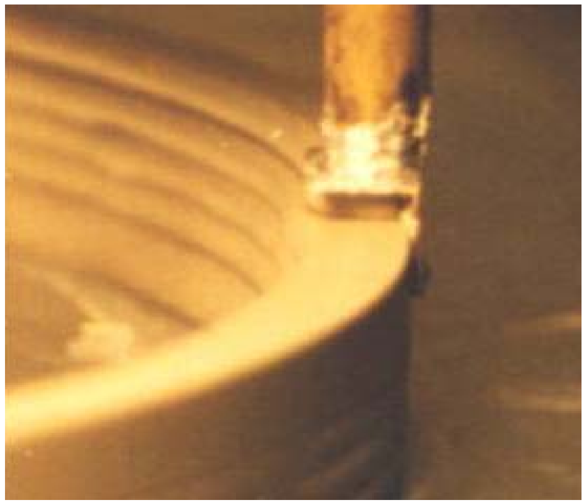


Figure 6-1. The CC process of fabricating the cylindrical part with the rotary table

Stage 1 (base fabrication):

The angular speed of the rotary table required to fabricate the base layer is first calculated as:

$$w_\theta(base) = \frac{V_r(base)}{r_\theta(base)} \quad \text{……(6.1)}$$

where w_θ is the angular speed of the rotary table

r_θ (mm) is the radius of the cylindrical part

V_r (mm/sec) is the linear speed of the extrusion head

w_θ*(base)* is sent to PMAC and the rotary and extrusion motors are started to complete the base layer.

The base layer is finished upon the completion of one revolution of the rotary table, after which, the process is briefly interrupted for the operator to confirm that the base layer has been finished.

Stage 2 (body fabrication)

In the same manner as stage 1, computation of the angular velocity of the rotary table is carried out.

$$w_\theta(body) = \frac{V_r(body)}{r_\theta(body)} \qquad (6.2)$$

However, unlike the base layer, the trowel motion for making body layers assumes a spiral trajectory. The Z-axis with each revolution of the rotary table moves one layer height incrementally.

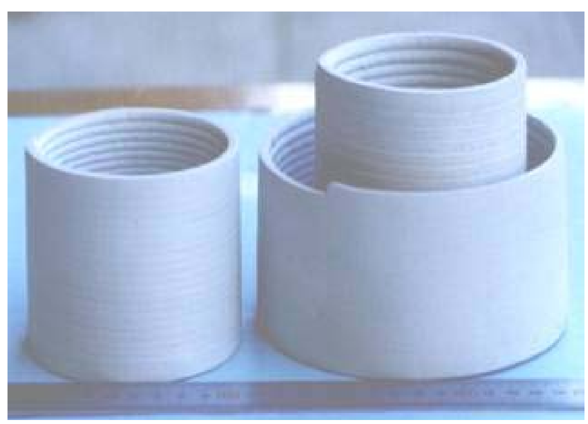


Figure 6-2. The parts with the various input parameters

Step 3 is repeated until the body layers are completed.

The basic differences between fabrication of the base and the body are in the values of process parameters and the movement of the Z-axis motor.

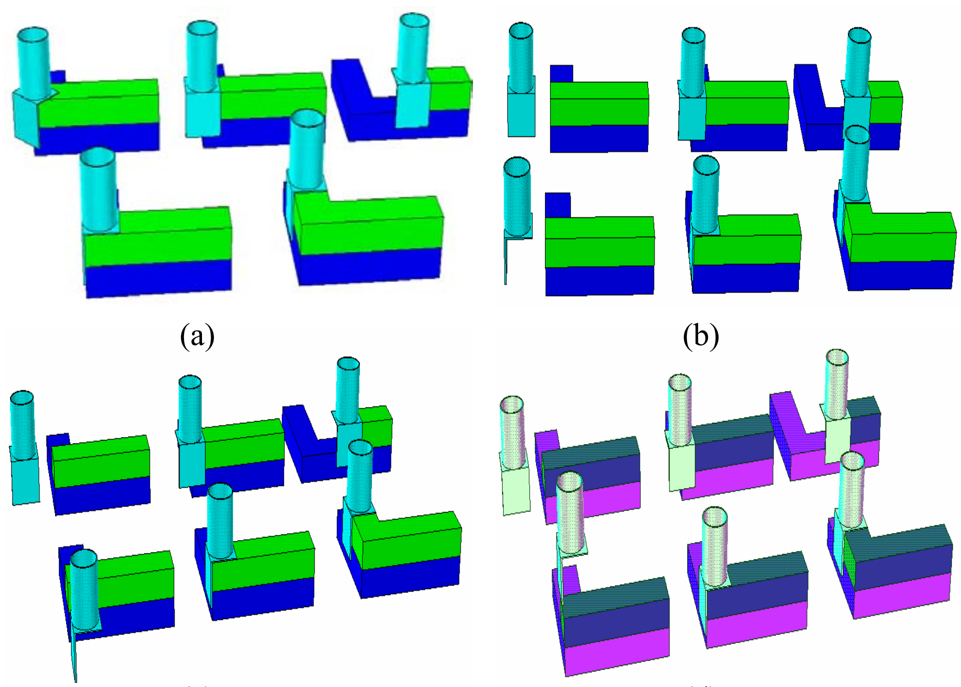
In addition, in order to enhance the process performances (surface roughness and vertical profile) several improvisations described in subsection 5.2 were made to the original process. Owing to the higher structural wet strength of the clay material, various large parts could be made with the assurance that the clay would not sag or collapse inward as shown in Figure 6-2.

6.1.2 *Experimental studies for sharp convex corners*

After the machine in Figure 5-1 was modified to fabricate complex 2.5D geometrical parts, experimental investigations were conducted to fabricate a square shape geometry. This geometry had several challenges:

- Two straight lines are combined to generate at each square corner. Hence, the material flow had to be disrupted at that corner for stopping and starting the straight lines.
- Since the used ceramic material is compressible, certain amount of clay flows through the nozzle exit even after stopping the extrusion motor.
- Since the state of the used ceramic material is semisolid, the edge of the deposited layer was not completely sharp after the extrusion nozzle passed each corner. Hence, tapping the deposited layer was done at each corner.

To overcome these challenges, several experiments were performed to

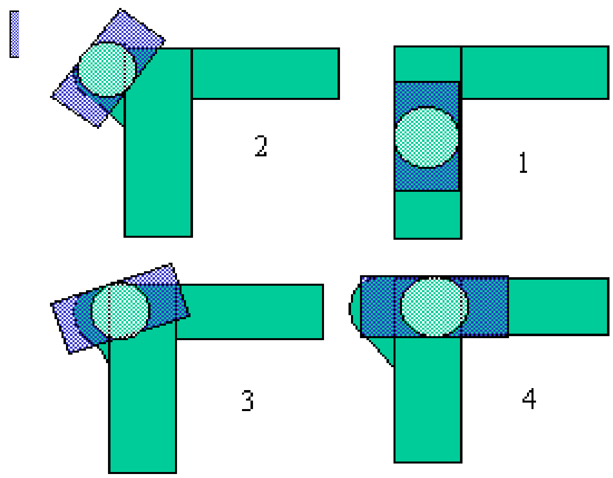


(a) (b)

(c) (d)

Figure 6-3. Schematic view of the alternatives for motion sequences to fabricate sharp convex corners discern the best motion sequence for sharp corners. As shown in Figure 6-3, some alternative motion sequences on the XY plane were considered, which include:

- Stop the nozzle at the corner, rotate the nozzle 90 degrees at that corner, and then move the nozzle into other direction. During the turning of the nozzle, this motion generated the vacuum effect behind the nozzle and pulled the deposited paste back with section of the nozzle that left the corner (see Figure 6-4). Hence, the sharp corner could not be fabricated.



alternative

Figure 6-4. Schematic top view of the vacuum and pulling effe

- Stop the extrusion at the edge of the corner and move the nozzle in the same direction as the straight wall, rotate the nozzle 90 degrees at certain distance, and then move it to the edge of the corner. Since the tapped layer existed at the corner edge, this motion pushed the straight wall during backward move of the nozzle into the edge (see Figure 6-5), and then the straight wall was bent. Hence, the straight wall structure could not be fabricated.

- Stop the extrusion at the edge of the corner and move the nozzle at a little distance with the direction of the straight wall, move the nozzle in other direction while rotating the nozzle 90 degrees, and then move the nozzle in the edge of the corner. Since the tapped layer was existed at the edge corner, the front of the side trowel pushed the tapped layer during forward move of the nozzle into edge (see in Figure 6-6), and then the straight wall was bent. Hence, the straight wall structure could not be fabricated.

- Stop the extrusion at the edge of the corner and move the nozzle at a little distance with the direction of the straight wall (see in Figure 6-7), move the nozzle up in the Z-direction while rotating the nozzle 90 degrees, and then bring it down at the edge of the corner and resume extrusion. This motion sequence generated the best solution among the above

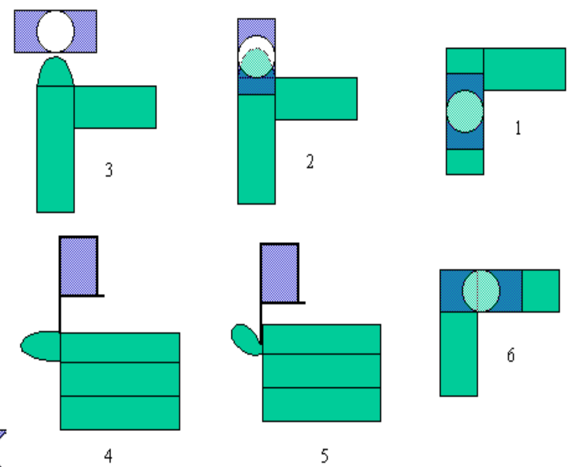
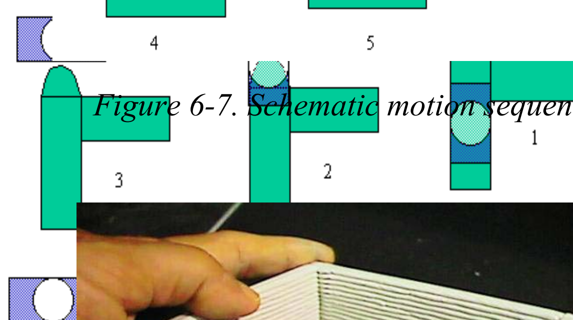


Figure 6-7. Schematic motion sequences of the last altern



Fig

lternative

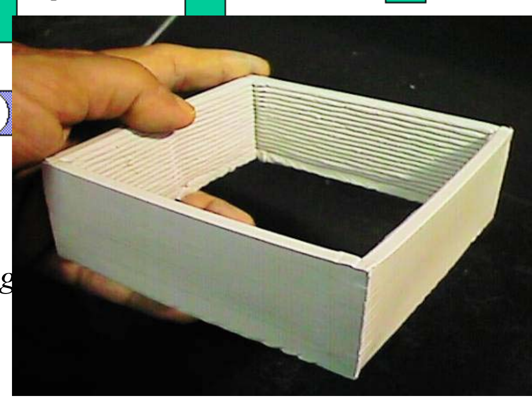


Figure 6-8. Square shape with a sharp corner fabricated from CC

alternatives. In this approach, as the nozzle is lowered in the Z-direction the bottom edge of the side trowel cuts away the end of deposition at the corner edge. In this motion, the side trowel works as a knife. As shown in Figure 6-8, square geometrical shapes with sharp corners have been fabricated using this approach.

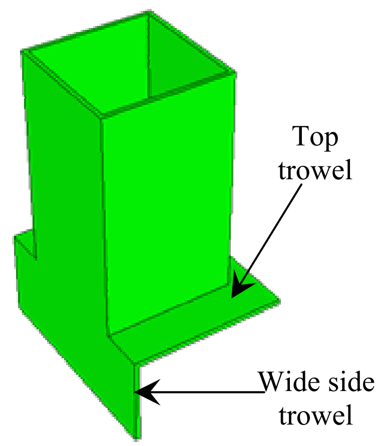


Figure 6-9. Schematic view of two-trowel design

6.1.3 *Experimental studies of the trowel geometry*

Several experiments were conducted with uncured ceramic materials to fabricate diverse geometrical parts with the convex, concave, and sharp corner shapes. When fabricating complex parts, the experiments demonstrated that the original wide side trowel system as shown in Figure 6-9 has several limitations:

- As shown in Figure 6-10, as a wide side trowel is rotated at corners it drags the material and deforms the corner. The magnitude of the dragging effect is magnified when the radius of the corner becomes smaller. Also, the dragging effect is increased when the clay contains more water which makes the clay stickier.
- As shown in Figure 6-11, the wide trowel design is unable to fabricate a concave surface because the backside of the side trowel pushes the wall of the part inward as it fabricate the part. Also, the front of the side trowel cuts the wall surface of the part when the end of the concave corner is being fabricated. The magnitude of these effects is amplified for smaller radius of

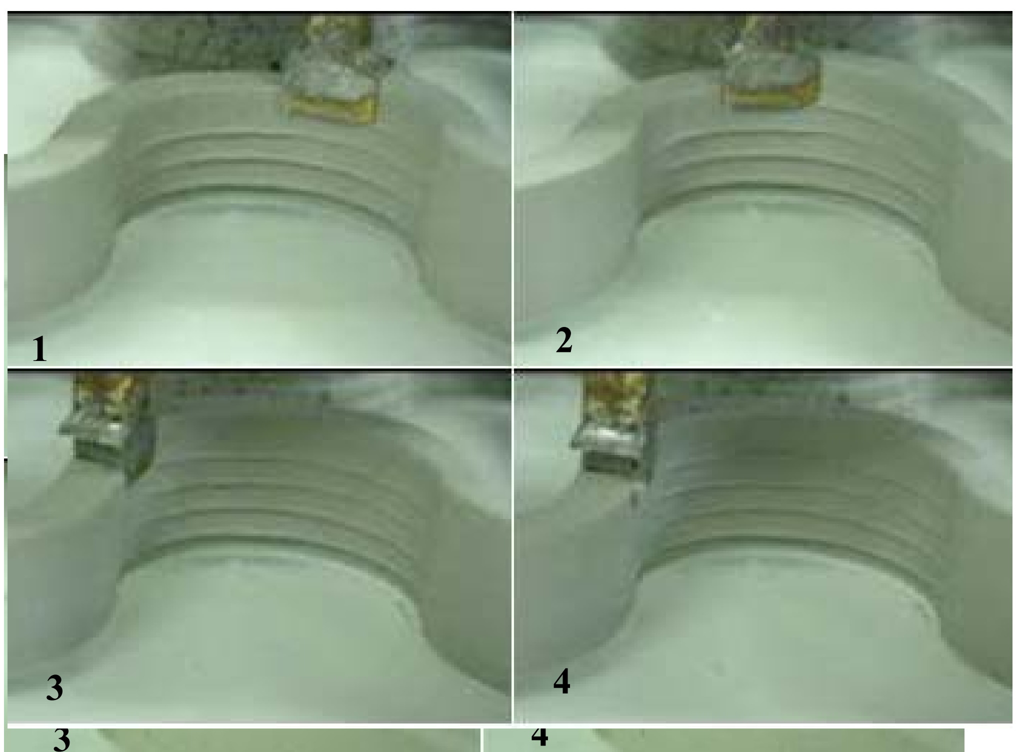


Figure 6-11. Sequence of the process showing the effect of a wide side trowel when fabricating concave corners

Figure 6-10. Sequence of the process showing the dragging effect of a wide side trowel when fabricating sharp square corners the concave corner. When the clay contains more water, also, the part would sags or collapse outward because the clay is transformed into the liquid state and sticks to the side trowel.

To overcome these limits, several other types of trowels in Figure 6-12 were tested with uncured ceramic materials. One of the best side trowels shown in Figure 6-13 has several advantages in addition to being able to fabricate diverse geometrical parts that include convex, concave, and sharp cornered shapes.

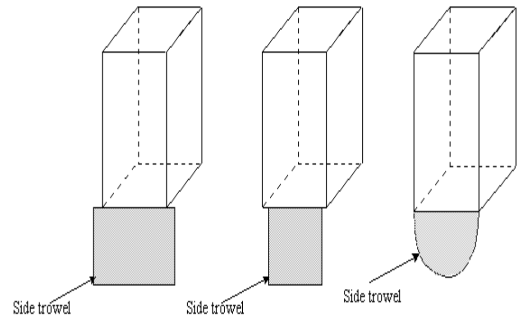


Figure 6-12. Schematic view of other trowel types

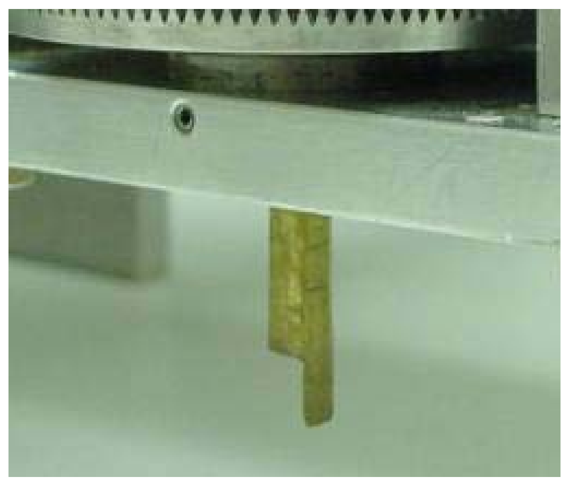


Figure 6-13. A narrow side trowel without the top trowel

As shown in Figure 6-14, the trowel design is able to fabricate smooth surface of parts with sharp corners because the side trowel is narrow. The wall of the part cannot be dragged by the side trowel anymore when the sharp corner is being fabricated. The dragging effect is completely removed even when the radius of the square corner is reduced to 2.5 mm (less than a half of the nozzle size).

As shown in Figure 6-15, a concave surface can be smoothly fabricated with the narrow side trowel. When the concave surface is being fabricated, the wall of the part cannot be pushed inward anymore because the width of the side trowel (5 mm) is the same as that of the nozzle. Also, the surface of the part cannot be cut by the

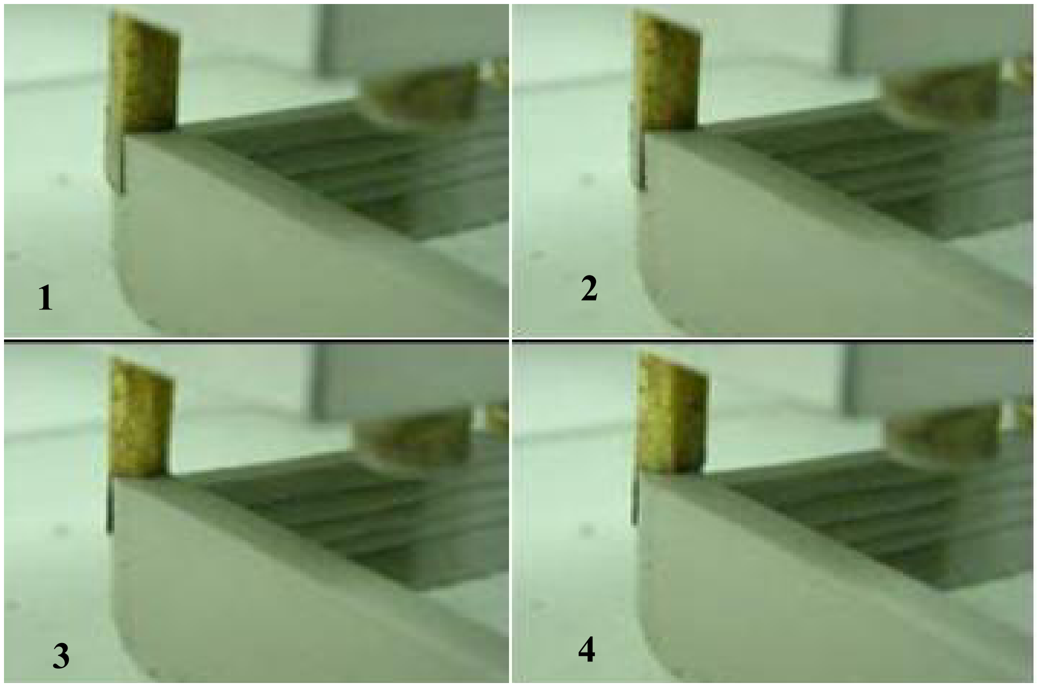


Figure 6-14. Sequence of the process showing the effect of a narrow side trowel when fabricating sharp square corners

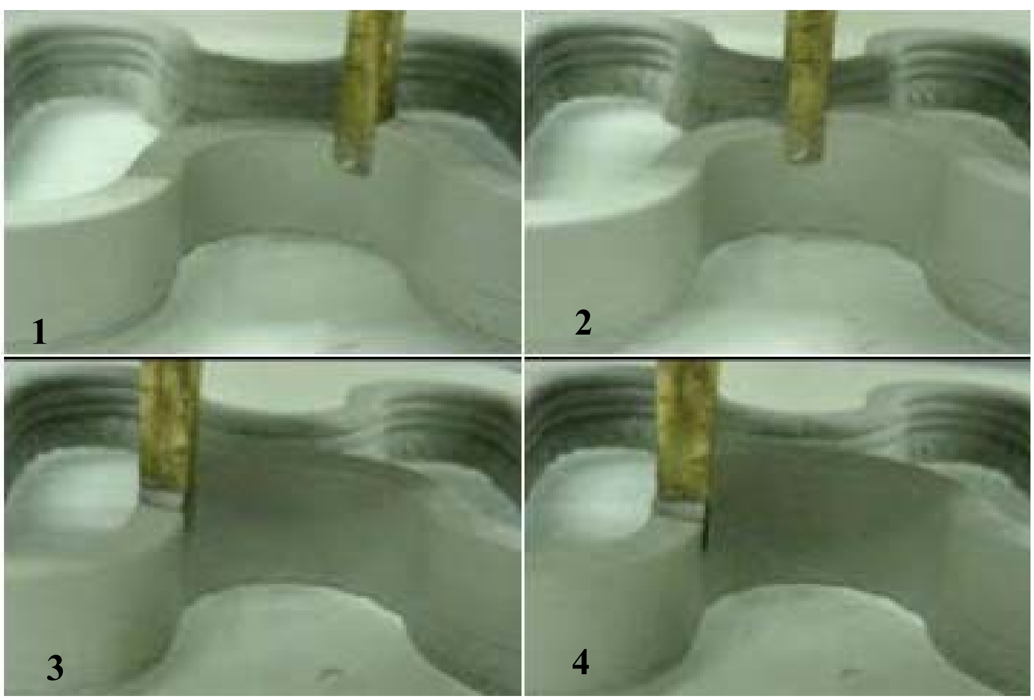


Figure 6-15. Sequence of the process showing the effect of a narrow side trowel when fabricating concave corners

front side of the side trowel when the end of a concave corner is being fabricated. However, these effects might still occur when the radius of the concave corner is smaller than the width of the side trowel (5 mm).

Based on these experimental results, significant progress has been made towards realizing a variety of 2.5D shapes using CC, as shown in Figures 6-16. These complicated profiles were created through the rotation of the nozzle about a vertical axis, while keeping the rotary table stationary. In the following subsection, the process algorithm and the challenges of fabricating 3D parts are detailed.

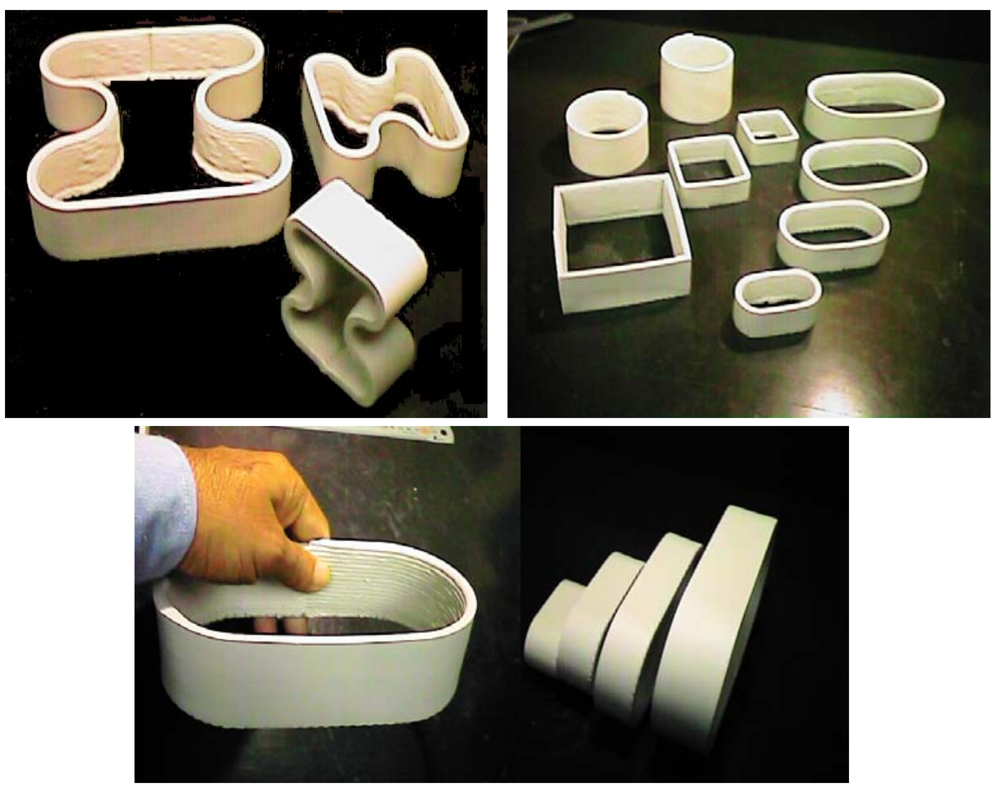


Figure 6-16. Representative 2.5D parts

6.2 <u>Experimental investigations to fabricate 3D shapes with orthogonal sides</u>

To fabricate 3D parts with orthogonal sides, the CC process needs to utilize a support material to build overhanging parts such as roofs. In Section, the detail effects of several support materials, and the procedure and development of 3D parts with orthogonal sides are presented.

Filling solid volumes created by the outside edges may not be always required to fabricate 2.5D parts. When the CC process is required to build the parts with the overhanging features, temporally support materials should be utilized. To be compatible with the uncured ceramic material, several characteristics for the support material are required.

- The ideal support material must have the same shrinkage ratio as the actual build material (uncured ceramic in this case).
- To reduce the overall process time, the curing time of the support material should be faster than that of the clay in order to fabricate other objects on the top of the support structure.
- To fill the exact void volume, it should be possible to control the amount of the support material.
- The support material should have a high strength after curing in order to support the fabricated part and the pressure during the extrusion process.
- The support material should be easily removable from the main object after the part is fabricated.

- From an economic and environmental point of view, it is better if the support material is recyclable.

To find a reasonable support material that satisfies the above constraints, numerous preliminary experiments were conducted with several materials. A brief description of experiments, and advantages and disadvantages of several support materials such as wax, paste, sand, and the combination of sand and wax are presented in Appendix 6.

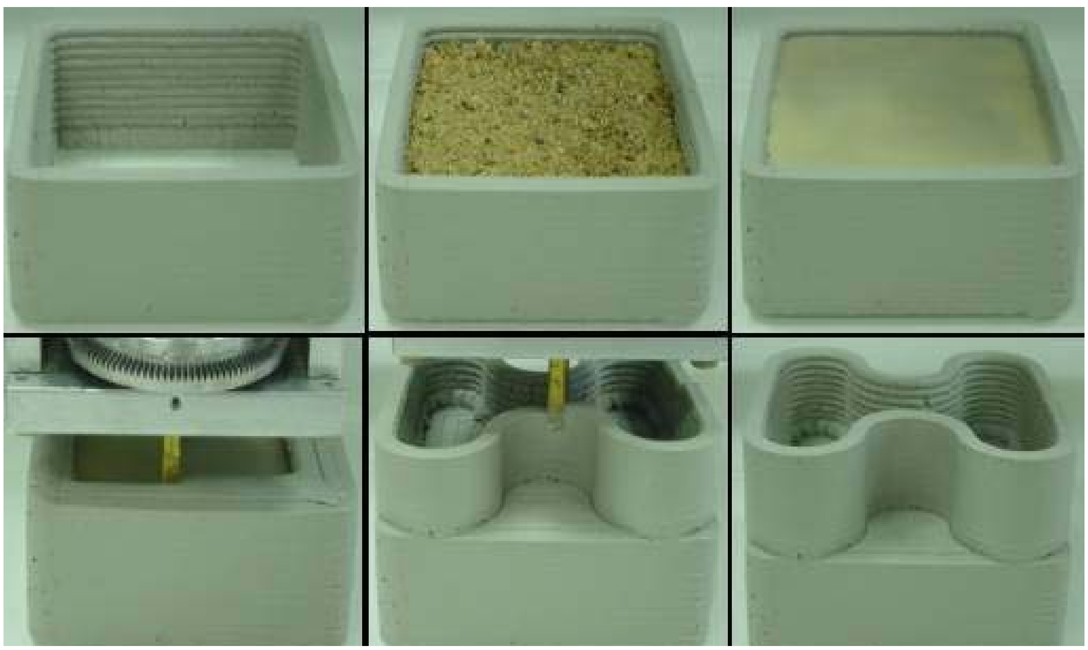


Figure 6-17. Sequence of the process to fabricate 3D part with orthogonal sides

As shown in Figure 6-17, the fabrication process of the 3D part was divided into several stages. At the first stage, the movement of the trowel fabricated a 2.5D geometrical part. After completely building the sand is poured to fill the area inside the 2.5D part. This filling process consists of two sub-processes: the sand is used to fill most of the volume, and then smoothed manually to make a flat top surface.

Molten wax is used to coat the top surface of the sand in order to provide a rigid surface for construction of the overhang feature.

In the third and forth stage, the roof (overhanging feature) is built on the wax surface. After the roof is built on the support material, other 2.5D parts are fabricated on the top surface of the roof. If the roof is not needed, other 2.5D parts are fabricated directly on the wax. In the final stage, the sand can be removed through a hole on the build platform. Wax may be removed by heating the fabricated part.

The sand, because of its compressibility, compensates for shrinkage of the build material and wax fixed the loose sand particles on the top surface of the support structure. By the sand and wax as the support material, a significant progress has been made towards realizing a variety of 3D shapes with orthogonal sides as shown in Figures 6-18.

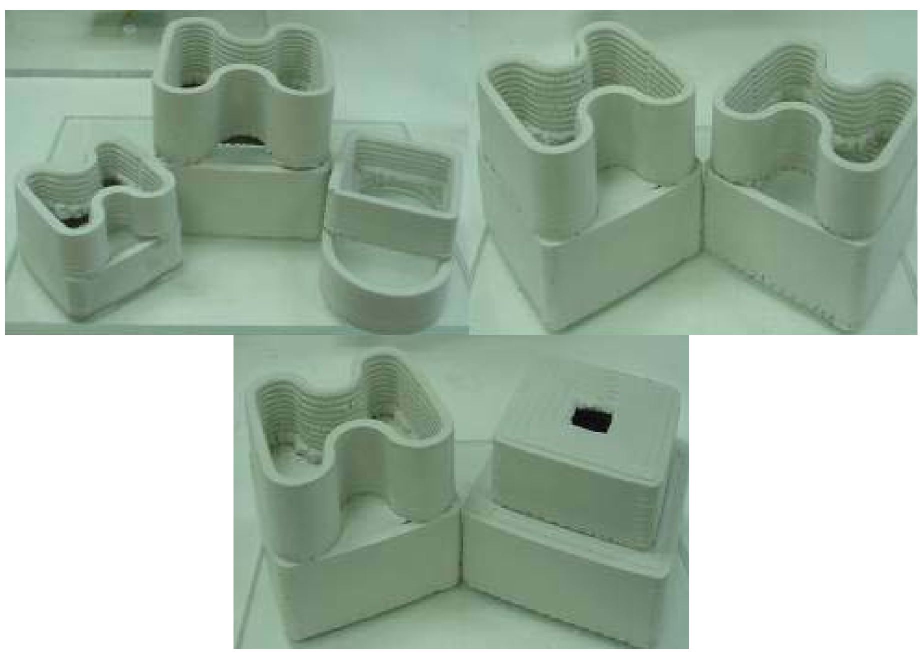


Figure 6-18. Showing diverse geometrical parts with or without the roof

6.3 Other experimental investigations

In order to investigate co-extrusion of multiple materials using a combination of nozzles, extensive experimentation and a series of design enhancements have been made. As shown in Figure 6-19, these features demonstrated the capability to build layers with hollow depositions using CC. Mandrels with various shapes might be installed inside the nozzle for creating hollows of various shapes. These hollow cavities also result in lighter structures.

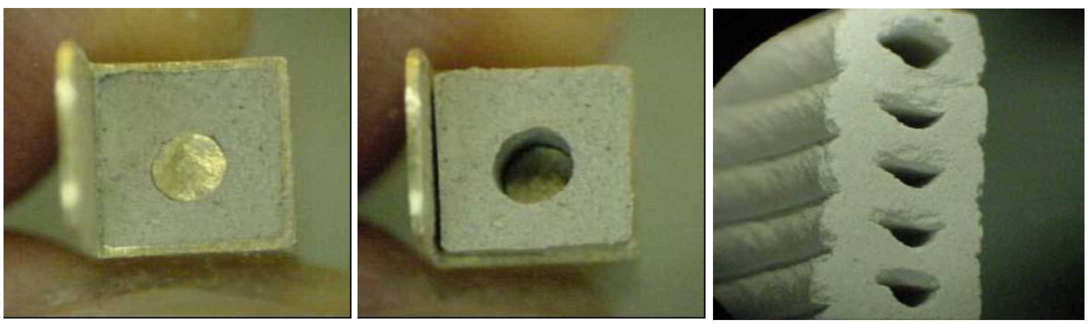


Figure 6-19. Laying hollow sections through CC: (a) the ceramic material in the nozzle before extrusion, (b) hollow circle formed as the extrudate emerges from the orifice, and (c) cross section of the fabricated part revealing the hollow sections

By forcing the material through a nozzle with a central mandrel, two materials may be co-extruded if the mandrel itself is hollow and works as a nozzle to deliver the second material. This feature will provide the capability to lay base material as well as certain reinforcement material simultaneously.

Towards improving the strength of large structures built using CC, a variety of reinforcements and impregnations were investigated. For example, Figure 6-20 shows pictures from our experiments with coil reinforcement. Owing to the high extrusion pressures prevailing in CC compared to other layered free-form fabrication techniques (Zak *et al.,* 1999), the extrudate thoroughly adheres itself around the coils without causing any internal discontinuities. Similar results have been observed from experiments with sand impregnation.

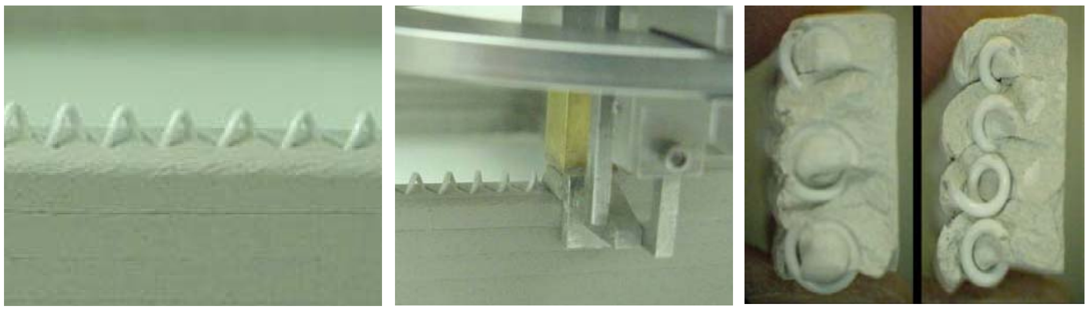


Figure 6-20. Reinforcement process of CC: (a) metal coil placed on a top layer, (b) a fresh layer of extrudate covers the coil, and (c) cross sections of the fabricated part with the reinforcement coil showing a reasonable adhesion between layers

To construct sandwiched structures, filling the intervening space created by the inside and outside wall-structures may be required. The inside and outside structures are constructed simultaneously using the nozzle system. Using a bulk-filling mechanism, the intervening space is filled with a filler material. With the uncured ceramic material, several characteristics for the filler material are required:

- Since the uncured ceramics used in the CC process has 5 to 6 % shrinkage after the first curing, the ideal filler material must have the same shrinkage ratio.
- To reduce overall process time, the curing time of the filler material should be faster than or equal to that of the clay.
- To fill the exact void volume, it should be simple to control the amount of the filler material.

- A high strength material is recommended after curing in order to support the fabricated part.

Through extensive experimental investigations of various filler materials (such as paste, foam, concrete, etc.) rapid concrete seems to be the high potential candidate of the filler material (Figure 6-21). These achievements enhanced the capability of CC process to build the large walled structures and the feasibility of CC process for construction automation.

Figure 6-21. Sandwich structures fabricated by CC: (a) two objects with the different geometries being fabricated respectively, (b) the intervening space is filled with a concrete, (c) various sandwich structures after being solidified with filler material

6.4 Experimental studies with the pivoting side trowel

To fabricate 3D parts with slant sides such as domes, cones, pyramids, etc., experimental investigations were conducted to study the effects of the pivoting side trowel. In the following Subsections, the detail results and some challenges of using the pivoting side trowel are described.

6.4.1 *Process algorithm to fabricate 3D parts with slant sides*

Similar to 2.5D geometrical shapes, the fabrication process of 3D shapes with slant sides was divided into two stages of base and body fabrication. The base layer fabrication provides a foundation upon which subsequent layers can be built. Depending on the slope of the sides of the fabricated part, the base layer thickness is less than or equal to the height of the side trowel. The pivoting side trowel is operated like an oblique plane during fabrication as shown in Figure 6-22.

The second stage comprises body fabrication that has the slope of the subsequent layer, and the layers comprising the body of the part as shown in Figure 6-23. The layer thickness can be less than or equal to the height of the side trowel depending on the slope of the deposited

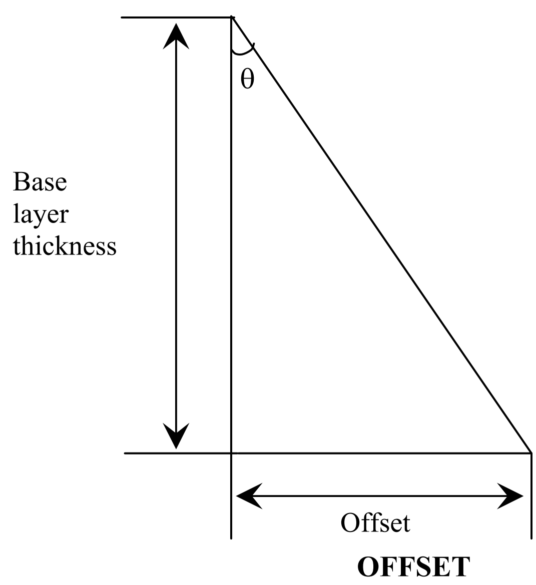


Figure 6-22. Schematic view for calculating the base layer slope

subsequent layer. The two stages of fabrication are described as follows:

Stage 1 (base layer fabrication)

The angle of the pivoting side trowel is first calculated (see Figure 6-17):

$$\theta\,(angle\ \ for\ the\ base) = Tan\left(\frac{\nabla\,(Base)}{h\,(Base)}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.3)$$

where θ is the angle representing the slope of the outer surface of the layer.

∇(mm) is the offset of each layer.

h (mm) is the layer thickness.

The base angle (θ) is then sent to PMAC. Next the side trowel motor is started to control the angle of the side trowel, and then other related motors are started to complete the base layer.

The base layer is completed, after which the process is briefly interrupted for the extrusion system to move up by one layer thickness in the Z-axis. The extrusion system moves by the offset distance in the X-axis.

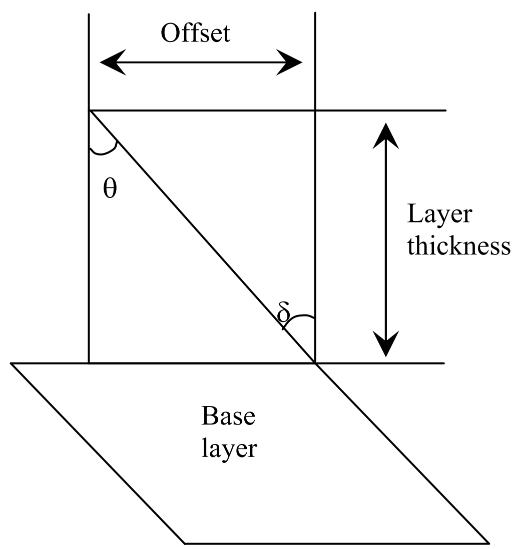


Figure 6-23. Schematic view for calculating the body layer slope

Stage 2 (body fabrication)

In the same manner as in stage 1, computation of the angle of the side trowel is carried out as shown in Figure 6-23:

$$\delta = Tan\left(\frac{\nabla\,(Body\,)}{h\,(Body\,)}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.4)$$

$$\theta(\,angle\;\;for\;the\;body\,) = \delta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.5)$$

Hence,

$$\theta(\,angle\;\;for\;the\;body\,) = Tan\left(\frac{\nabla\,(Body\,)}{h\,(Body\,)}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.6)$$

With the equation (6.6), the body angle (θ) is calculated, and then forwarded to PMAC. The side trowel motor is then started to position the trowel. In the same manner as stage 1, other related motors are started to complete the body layer. The second stage is repeated until the body layers are completed. The basic differences between fabrication of the base and body layers are in the values of process parameters and the angle of the pivoting side trowel.

6.4.2 *Experimental results for the pivoting side trowel*

Adapting the pivoting side trowel control mechanism as shown in Figure 6-24, the existing CC fabrication machine has been modified for fabricating a variety of 2.5D and 3D shapes that constitute the some primitive geometries (e.g. flat floors, straight walls, pyramid, domes, etc.) and hybrid geometries made of these primitives.

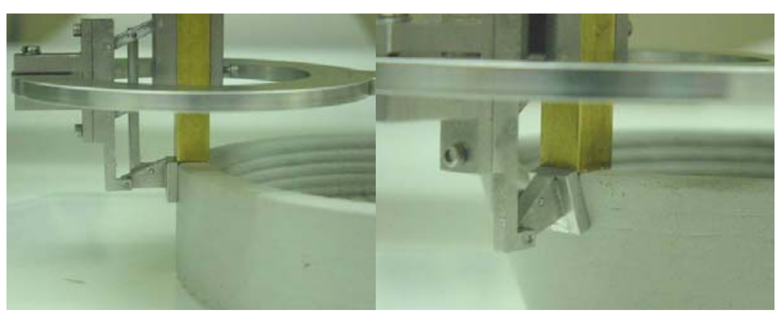


Figure 6-24.On-line process with the pivoting side trowel

The primitives have been carefully chosen so that these form the basic shapes for the scaled models of adobe houses (Khalili, 2000). Typical considered primitives (see Figure 6-25) will represent scaled models of adobe houses such as those adopted by CalEarth (see www.calearth.org) and shown in Figure 6-26.

Figure 6-25. Various primitive geometries fabricated with the pivoting side trowel

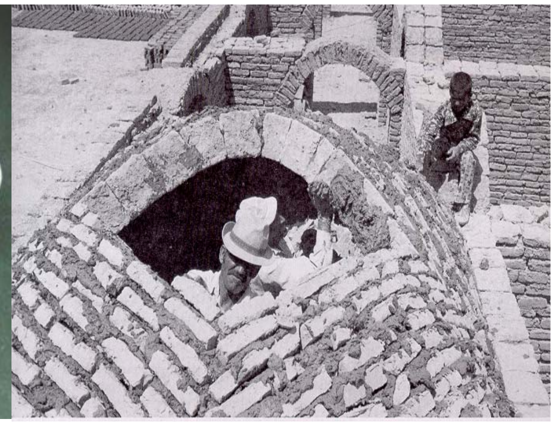


Figure 6-26. Manual construction of adobe form structures using clay bricks (Source: Khalili, 2000)

CHAPTER 7

SIMULATION OF MATERIAL FLOW

In this Chapter, the experimentation and modeling efforts are presented. The specific focus here is to study the material flow patterns in the extrusion and deposition stages of the CC process. For this purpose, a finite element analysis (FEA) was conducted for extrusion and deposition mechanisms of CC with ceramic materials (e.g. clay). Using the FEA simulations, certain basic understandings of the effects of extrusion orifice geometry and the angle of the pivoting side trowel were derived. Section 7.1 discusses basic concepts such as material flow of the CC process, the assumption and boundary condition of FEA modeling, and the governing relationships of the CC process. Section 7.2 is a discussion regarding the process modeling of the orifice shapes. In Section 7.3, the process modeling of the trowel angles are discussed.

7.1 Basic concepts in process modeling

7.1.1 *Material flow pattern of the CC process*

The CC process somewhat resembles a mold-filling operation in that clay is being packed under pressure resulting from the contact with the semi-solid base layers and the trowels. Troweling is the chief surface formation mechanism in CC. The final surface finish will rely on the pressure at the deposition point for the trowel to smooth out the surface, and the flow pattern of the material as a result of that pressure. Besides, the material undergoes a 90^0 rotation immediately after extrusion as shown in Figure 7-1.

7.1.2 *Assumptions in FEA modeling*

As previously mentioned, the trowels and the orifice are part of the exit geometry and play a significant role on affecting the flow of the extrudate clay. The surface quality is also determined by a multitude of parameters like the design of the extrusion system, the material, the fluid properties, and the test parameters (variants of the system).

Figure 7-1. Clay part showing compression and spring-back during fabrication from the front view

Furthermore, we used the material property values consistent with those of Bingham fluid in our analysis. This is because the clay that we used in our studies behaves like a Bingham fluid.

Analysis of any non-Newtonian flow is very complicated. However, the following assumptions were introduced in order to facilitate the finite element modeling and analysis [Ding 1993, and Fox 1985]. The flow in its steady state condition exhibits linear rheological properties as a result of the effect of the deflocculant additives. The compressibility of the clay is neglected, and the flow is assumed to be a single phase, isothermal and laminar. Making use of these assumptions, the linearized governing flow equations can be described by

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)+\frac{\partial}{\partial z}(\rho w)=0 \qquad (7.1)$$

$$\frac{\partial}{\partial z}\left(\eta\frac{\partial u}{\partial z}\right)-\left(\frac{\partial P}{\partial x}\right)=0 \qquad (7.2)$$

$$\frac{\partial}{\partial z}\left(\eta\frac{\partial v}{\partial z}\right)-\left(\frac{\partial P}{\partial y}\right)=0 \qquad (7.3)$$

where η is the viscosity, P is the pressure, ρ is the density, and u, v, w are the velocities in the x, y, and z direction at the boundary condition (u = 0, $v = V_r$, and $w = V_e$). With these assumptions the boundary conditions of FEA model are detailed in the following Subsection, and the governing equations are also described.

7.1.3 *Boundary conditions of FEA modeling*

The solution domain showed in Figure 7-2 is defined by three boundaries: (1) the die land wall, (2) the free surface boundary, and (3) the walls of the trowel. The governing equations of mass, momentum, and energy are combined with the above boundary conditions. For the momentum equations the velocities are specified along the boundary.

Isothermal conditions are also assumed for the energy equation. The prescribed conditions at these boundaries are:

1. The die-land wall:

Under constant flow rate the velocity profile of the material is parabolic with constant magnitude.

2. The free surface boundary:

The free surface boundary conditions are based on the requirement that

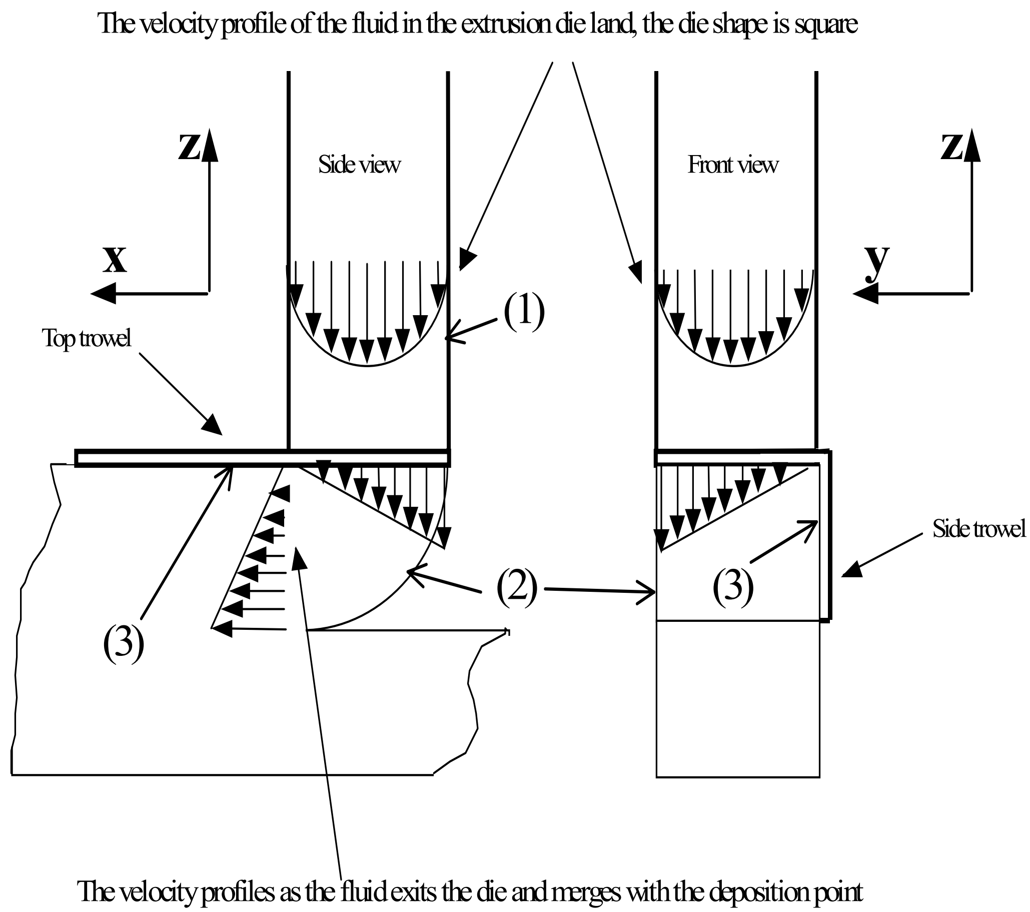


Figure 7-2. Schematic of material flow in CC

no momentum flux may cross the free surface of the fluid. The stress tensor normal and tangent to the free surface are 0.

3. The walls of the trowel:

At the walls of the trowel the no-slip boundary condition is applied. The velocity components, both tangential and normal to the wall, become zero at the walls.

7.1.4 *Governing relationships*

The main process parameters of CC are the extrudate velocity V_e [mm/sec], the linear speed of the extrusion head relative to the deposited extrudate V_r [mm/sec], and the desired layer thickness *h* [mm]. As mentioned in Chapter 6 with Figure 6-2 and 6-3, that the extrudate velocity V_e must be increased in direct proportion to the layer thickness *h* with V_r kept constant in order to achieve consistent surface quality. With *h* kept constant, the extrudate velocity V_e is also directly proportional to the linear speed V_r by achieving the consistent surface quality. Clearly, any changes in one of the main process parameters and the orifice affect the flow profile and the pressure *P* at the deposition point, and thence the surface quality of the fabricated parts.

The following equations provide the gross relationships between the velocity settings, pressures and surface quality. The basic velocity relationship is given by

$$V_e^2 + V_r^2 = V_R^2 \qquad (7.4)$$

where V_θ is the extrudate velocity, V_r is the linear velocity and V_R is the resultant velocity. The extrudate velocity (V_θ) cannot be directly measured. It is a function of the extrusion rate (V_e), and the die shape and extrusion system for a given material.

In our examination of the material flow from a cylindrical barrel into the die land, the overall pressure is a superposition of the following two components:

P_1: a pressure differential needed to cause the clay in the barrel to flow into the die land,

P_2: a pressure differential required to permit the clay to overcome the shear stress at the wall of the die land.

$$P_1 \approx \sigma_0 + \alpha V_\theta \quad (7.5)$$

$$P_2 \approx \tau_0 + \beta V_R \quad (7.6)$$

Where σ_0 is a uniaxial yield stress extrapolated to zero velocity, and α is a factor characterizing the effect of velocity. The parameter τ_0 is the wall shear stress extrapolated to zero velocity, and is termed the initial wall stress, where as β is a factor, which accounts for the velocity dependence of the wall shear stress, and is termed the wall velocity factor. Thus $\sigma_0 + \alpha V_\theta$ can be regarded as the bulk yield stress corrected for shear rate, and τ_0 and β are parameters characterizing the clay.

7.2 Process modeling of the orifice shape

7.2.1 *Pre-process of the orifice shape*

A commercial CFD package is used, which is called Flo++ for our simulations. For our flow problem, the flow domain was subdivided into a number of cells to form a computational grid as can be seen from Figure 7-3. The detail program coding for the flow domain is described on Appendix 9. After the grid

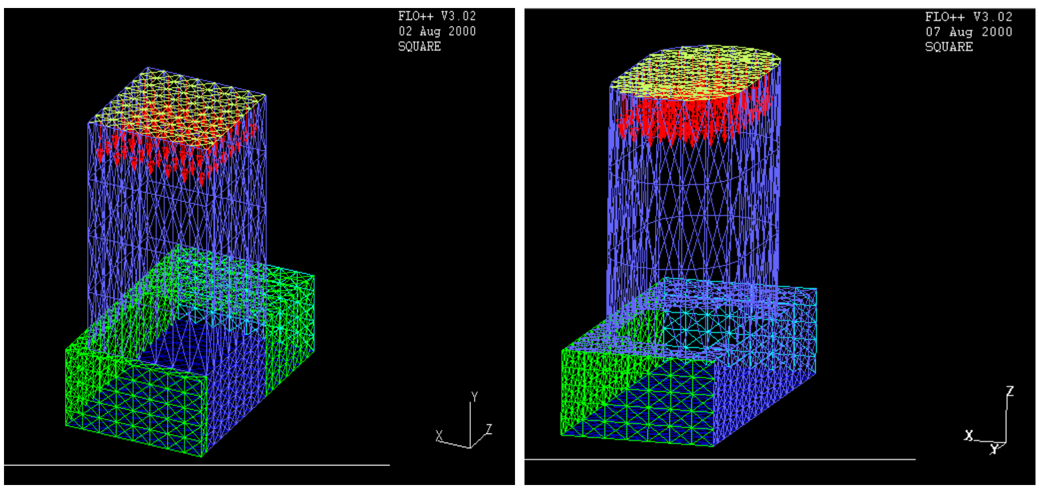


Figure 7-3. Grid structure for (a) a square and (b) an elliptical orifice

generation, six boundary conditions were specified: the trowel walls (blue), the orifice walls (blue), the inlet boundary (yellow with red arrows), the free surface boundaries (green), the moving bottom layer (dark blue), and the outlet boundary (light blue). The viscosity (η) measured in terms of the damping ratio [Lanzo 1999] and density (ρ) were set at 15 %, and 24 kN/m^3 respectively. The flow was considered to be laminar and isothermal.

7.2.2 *Post-processing of the orifice shape*

Figure 7-4 shows the flow profiles of the particulate flow with the square orifice at condition: η is 15%, ρ is 24 kN/m^3, and V_e is 1.962 mm/sec, V_r is 4 mm/sec. As shown in Figure 7-5, the flow profiles of the particulate flow with the elliptical orifice are at conditions: η is 15 %, ρ is 24 kN/m^3, and V_e is 1.697 mm/sec, V_r is 4 mm/sec.

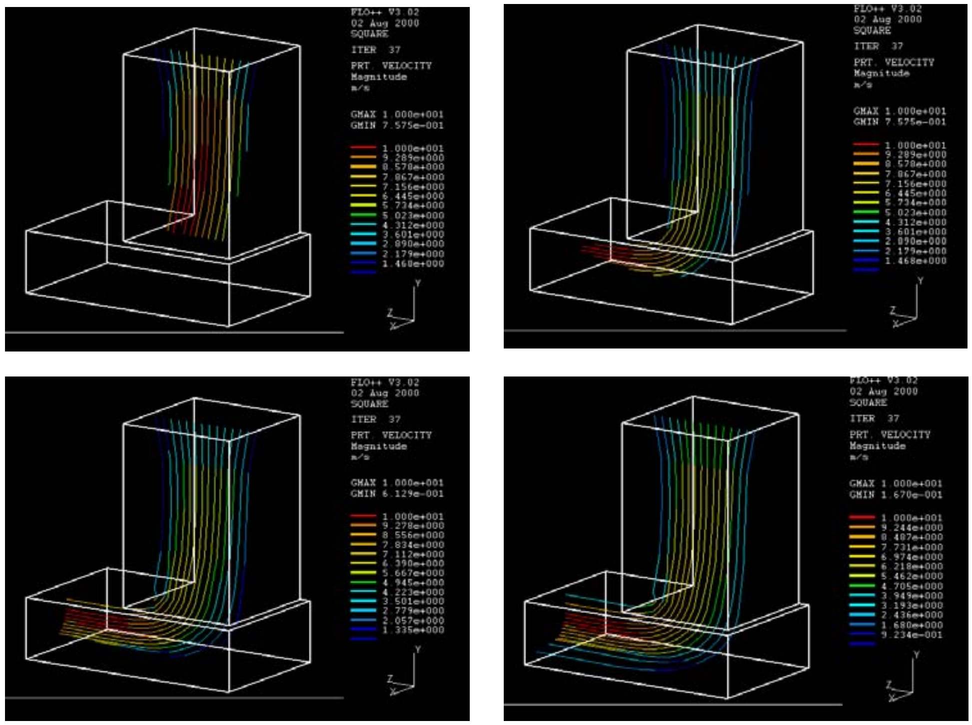


Figure 7-4. Particle flow lines with a square orifice

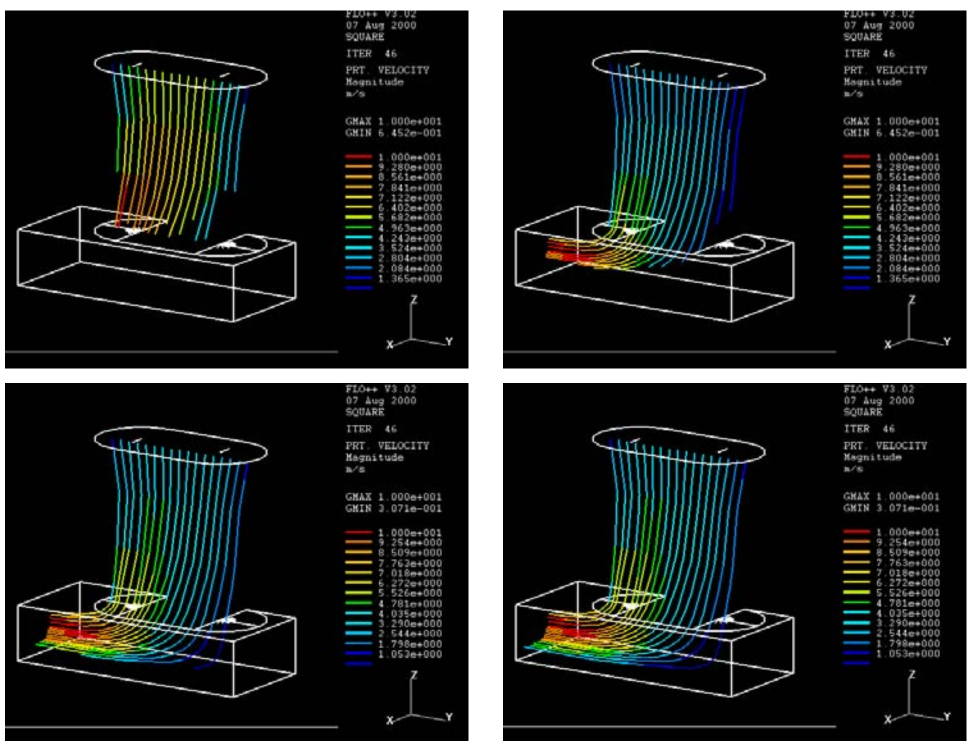


Figure 7-5. Particle flow lines with an elliptical orifice

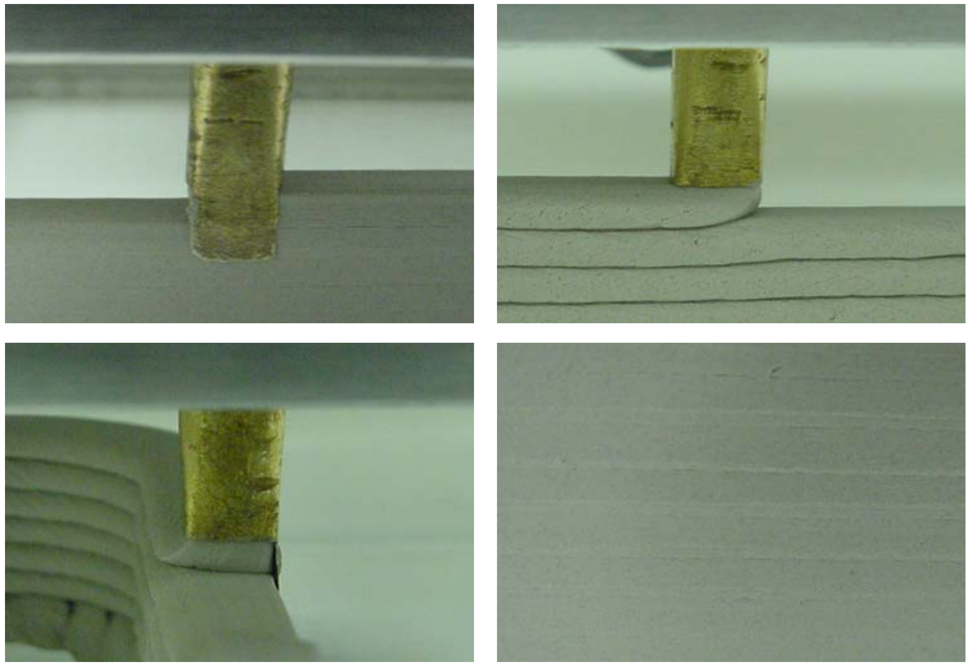


Figure 7-6. Actual material flow under near optimal conditions with a square orifice: (a) outside view, (b) inside view, (c) front view, and (d) surface quality

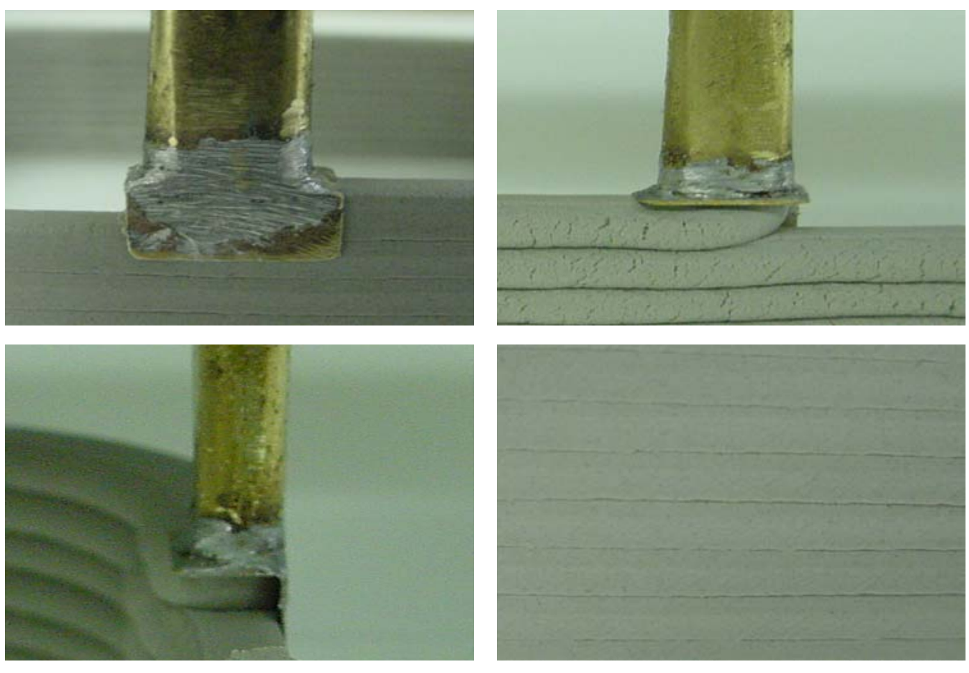


Figure 7-7. Actual material flow under near optimal conditions with an elliptical orifice: (a) outside view, (b) inside view, (c) front view, and (d) surface quality

These simulation results indicate the complex flow conditions occurring in the flow domain. The friction at the boundary, especially the walls and side trowel, retards the flow, which explains why we get the flow profile indicated by different colors. The photographs of CC with a square orifice taken on-line, shown in Figure 7-6, confirm the results obtained by the simulation in Figure 7-4. The photographs taken on the actual CC process with an elliptical orifice, shown in Figure 7-7, confirm the results obtained by the simulation in Figure 7-5.

7.2.3 *Discussion*

Basically, the near optimal conditions (described in subsection 7.2.2) of the process parameters were achieved through the experimental investigations with the CC process. These optimal process parameters were applied to the process model. The flow pattern of the process models was compared visually with the actual process in order to validate the results.

With each of the two chosen orifice geometries, finally, the optimal conditions of the process parameters achieved desirable surface quality and

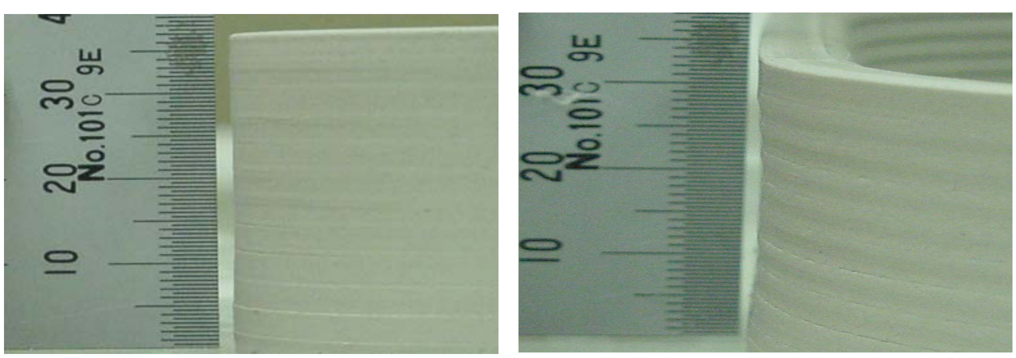


Figure 7-8. (a) A straight profile of the part fabricated with a square orifice, and (b) a curved profile of the part fabricated with an elliptical orifice (under near optimal conditions)

geometric characteristics. For the parts resulting from our experimentation, it is noted from our examinations that the surface quality was nearly the same shown in Figure 7-6 (d) and 7-7 (d). However, it is observed that the geometric profile varied significantly with die shapes in Figure 7-8.

From examination of the inner walls of the above parts, it is found that cross-section of each layer resembles the geometry of the orifice through which it was extruded. Inner walls of parts fabricated using a square orifice tend to be flatter and more uniform compared to those of parts fabricated using an elliptical orifice, whose which tend to have curved profiles with irregularly bloated franks (Figure 7-9).

Figure 7-9. Cross section of the fabricated parts by (a) an elliptical, and (b) a square orifice

Surfaces of parts fabricated with a square orifice were also smooth and devoid of noticeable cracks (Figure 7-10 (a)). But tiny surface cracks were observed on

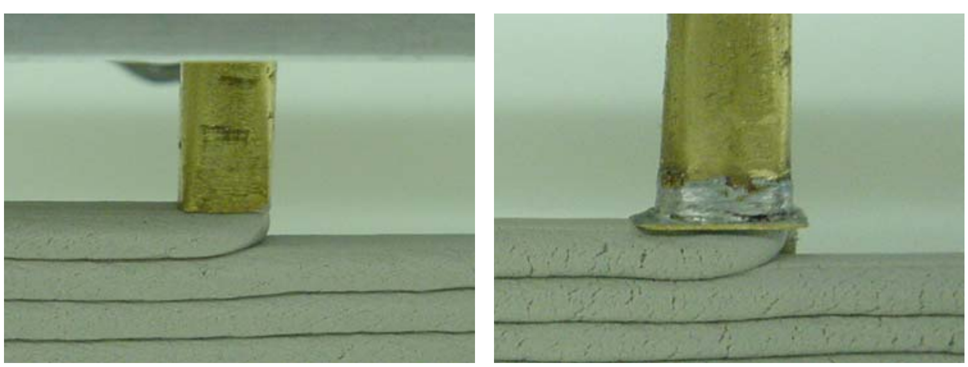


Figure 7-10. Inner walls of the extrudate deposited using (a) a square and (b) an elliptical orifice

parts fabricated with an elliptical orifice (Figure 7-10 (b)). This phenomenon perhaps results because the uniform cross-section of each layer being extruded through a square orifice leads to a lower local shear stress on the extrudate as it exits orifice and negotiates a sharp 90° turn before deposition. The non-uniform cross-section of each layer being extruded through an elliptical orifice contributes to increasing the local pressure and local shear stress at the deposition point, which leads to tiny surface cracks.

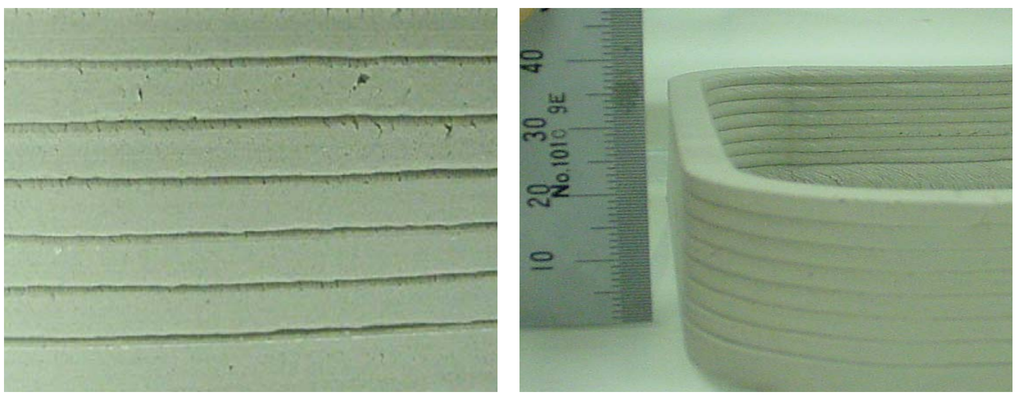


Figure 7-11. (a) Stair lines (gap) between the layers, and (b) a straight profile of a part resulting when fabricated under the suboptimal case with a square orifice

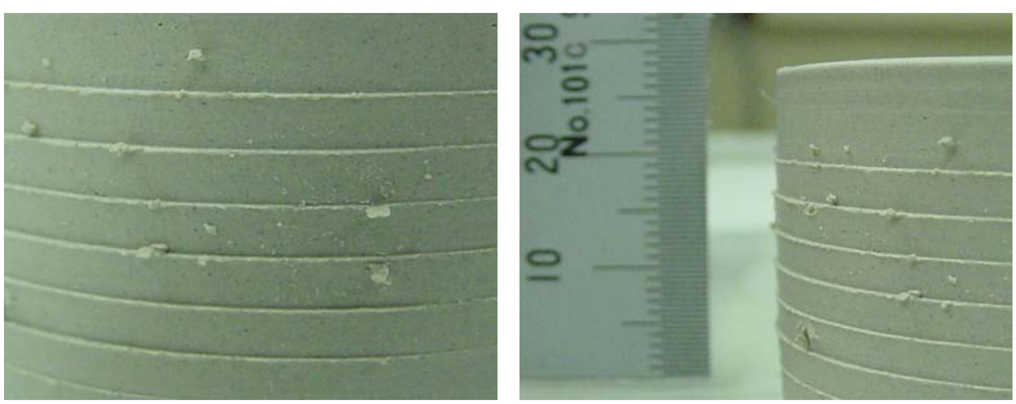


Figure 7-12. (a) Cutting tracks between the layers (due to excess pressure on the extrudate, and (b) a straight profile of a part resulting when fabricated under the supoptimal case with a square orifice

Figures 7-11 to 7-14 illustrate the surface qualities and geometric profiles of parts fabricated using different orifices under process conditions. The elliptical orifice results in parts having interlayer grooves and the layers show a slight outward bulge. This is the due to presence of higher local compression pressures at the deposited point. By far, the square shaped die showed best results in maintaining the geometry and surface profile.

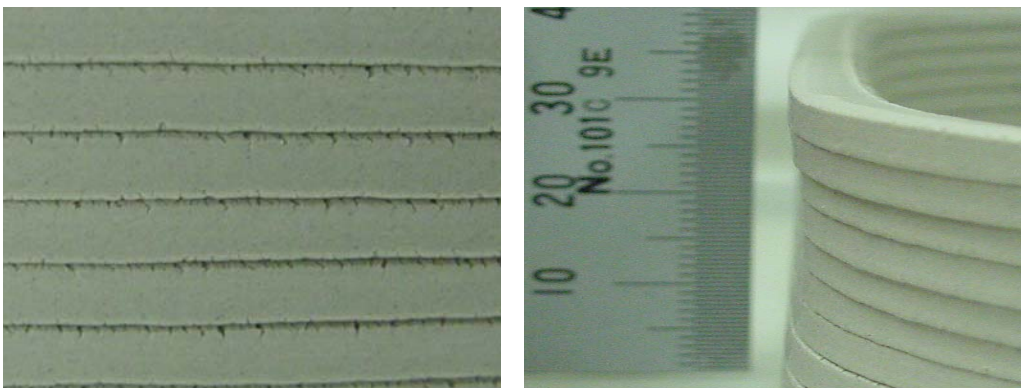


Figure 7-13. (a) Stair lines (gap) between the layers, and (b) a curved profile of a part resulting when fabricated under the suboptimal case with an elliptical orifice

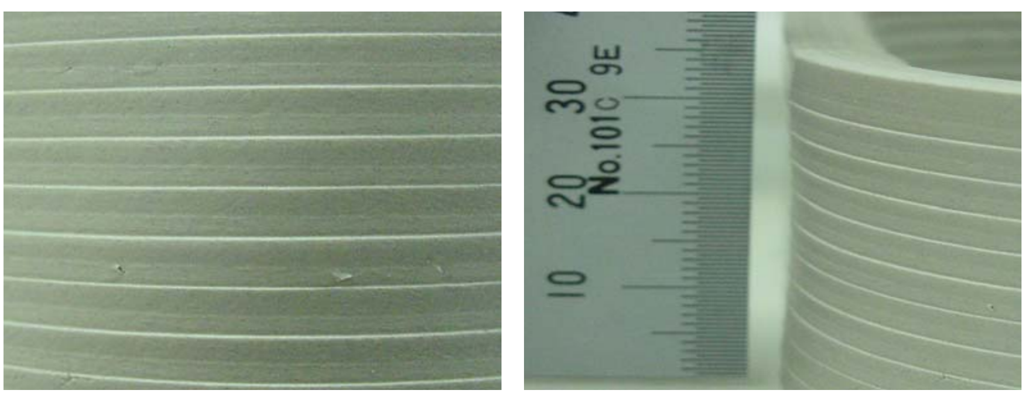


Figure 7-14. (a) Cutting tracks between the layers (due to excess pressure on the extrudate, and (b) a curved profile of a part resulting when fabricated under the supoptimal case with an elliptical orifice

The variation of surface finish (R_a) was computed for the fabricated parts with a square and an elliptical orifice. Various sample lengths were considered on each individual part. On an average, R_a values with the square orifice ranged between 0.01 – 0.04 μm, and those with an elliptical orifice ranged between 0.1 – 0.13 μm, as shown in Figure 7-15 and 7-16.

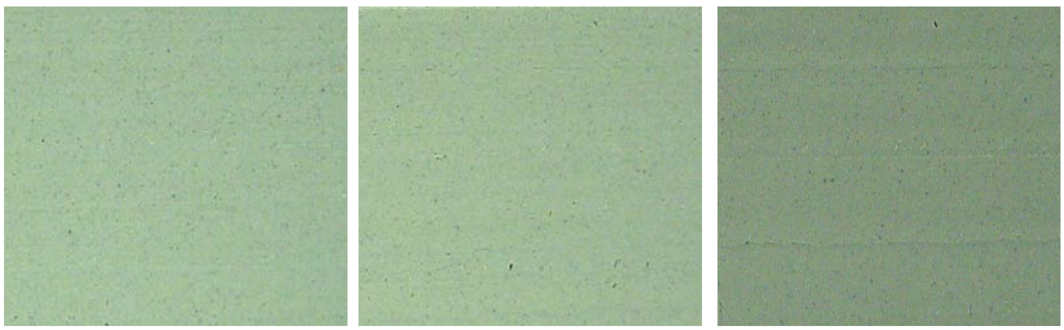


Figure 7-15. Virtually optimal surface quality at the different conditions (a) h *= 2 mm,* V_e *= 0.026 mm/sec, (b)* h *= 2.5 mm,* V_e *= 0.038 mm/sec (c)* h *= 3 mm,* V_e *= 0.052 mm/sec, (with* V_r *= 4 mm/sec and using a square orifice)*

Figure 7-16. Virtually optimal surface quality at the different conditions (a) h *= 2 mm,* V_e *= 0.024 mm/sec, (b)* h *= 2.5 mm,* V_e *= 0.034 mm/sec (c)* h *= 3 mm,* V_e *= 0.045 mm/sec, (with* V_r *= 4 mm/sec and using an elliptical orifice)*

To achieve a near equal surface roughness value with the elliptical orifices, higher velocities were needed to smooth out the presence of unfilled regions between the consecutive layers and tiny cracks in the coming layer that increase the surface roughness. However, if the extrusion pressure on the deposited point to fill up these voids was increased beyond the optimum value, it would cause loss of the desired geometric profile, thus deteriorating the surface quality as shown in Figure 7-14. A close study shows that the experimental results are consistent with the flow characteristics revealed by the FEA model.

7.3 Process modeling of the pivoting side trowel

7.3.1 *Pre-processing of the pivoting side trowel*

A commercial CFD package is also used for simulating the side trowel angle. To form a computational grid as shown Figure 7-17, the flow domain was subdivided into a number of cells. After the grid generation, six boundary conditions were specified: the trowel walls and the orifice walls (blue), the inlet boundary (yellow with red arrows), the free surface boundaries (green), the moving bottom layer (light blue), and the outlet boundary (red). The detail program coding for the flow domain is described on Appendix 9. As the same as the orifice simulation, the

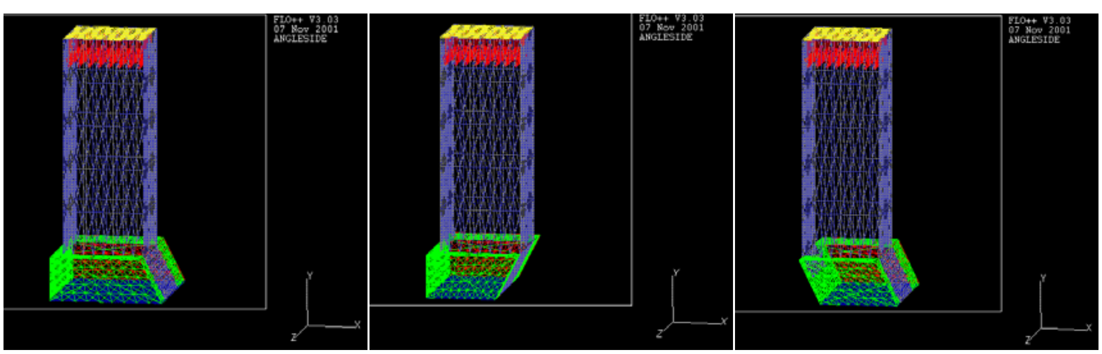


Figure 7-17. Grid structure for (a) an exterior angle, (b) an interior angle, and (c) two side trowels

viscosity (η) measured in terms of the damping ratio [Lanzo 1999] and density (ρ) were set at 15 %, and 24 kN/m^3 respectively. The flow was considered to be laminar and isothermal.

7.3.2 *Post-processing of the pivoting side trowel*

Figure 7-18 shows the flow profiles of the particulate flow with the exterior angle at condition: η is 15%, ρ is 24 kN/m^3, and V_e is 2.112 mm/sec, V_r is 4 mm/sec. As shown in Figure 7-19, the flow profiles of the particulate flow with the interior angle are at conditions: η is 15 %, ρ is 24 kN/m^3, and V_e is 1.471 mm/sec, V_r is 4 mm/sec. The flow profiles of the particulate flow with the two side trowel in Figure 7-20 are at conditions: η is 15 %, ρ is 24 kN/m^3, and V_e is 2.188mm/sec, V_r is 4 mm/sec.

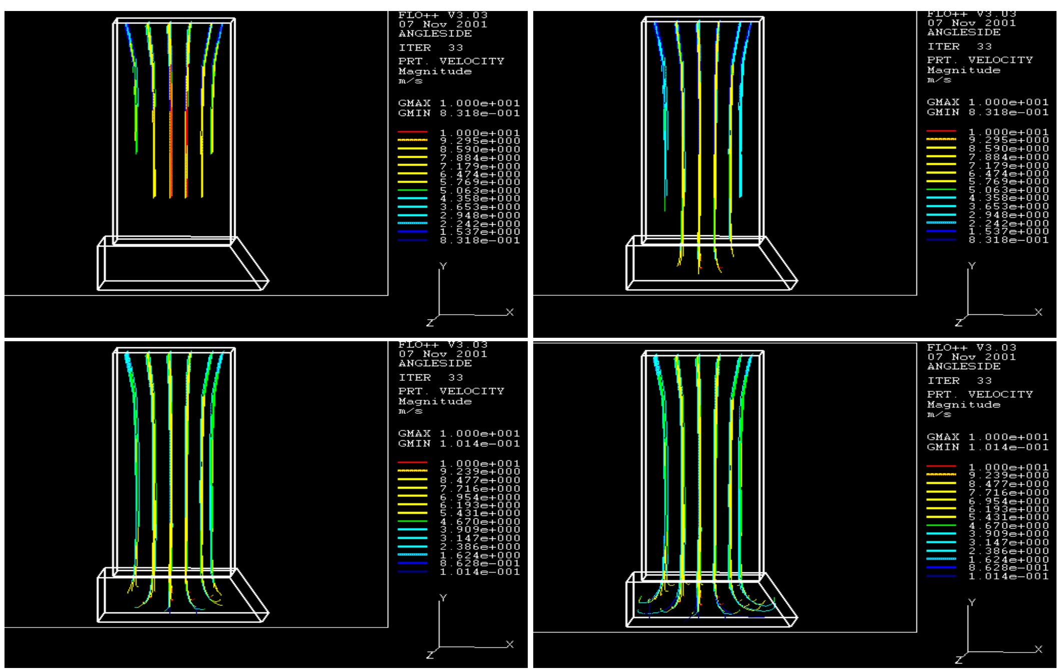


Figure 7-18. Particle flow lines with an exterior angle

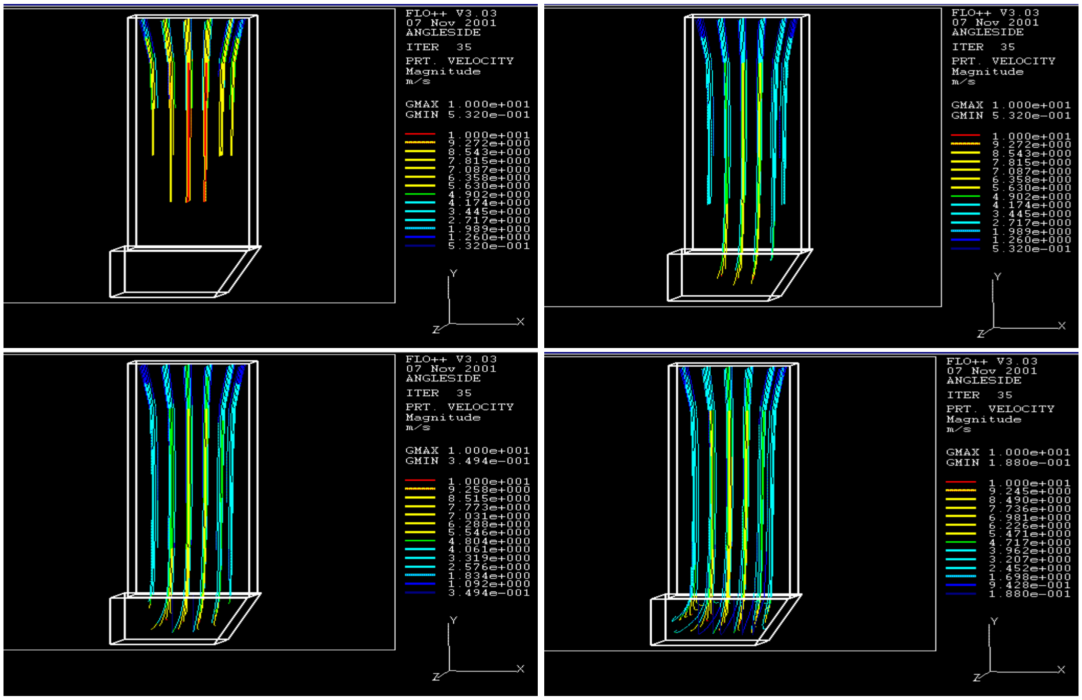


Figure 7-19. Particle flow lines with an interior angle

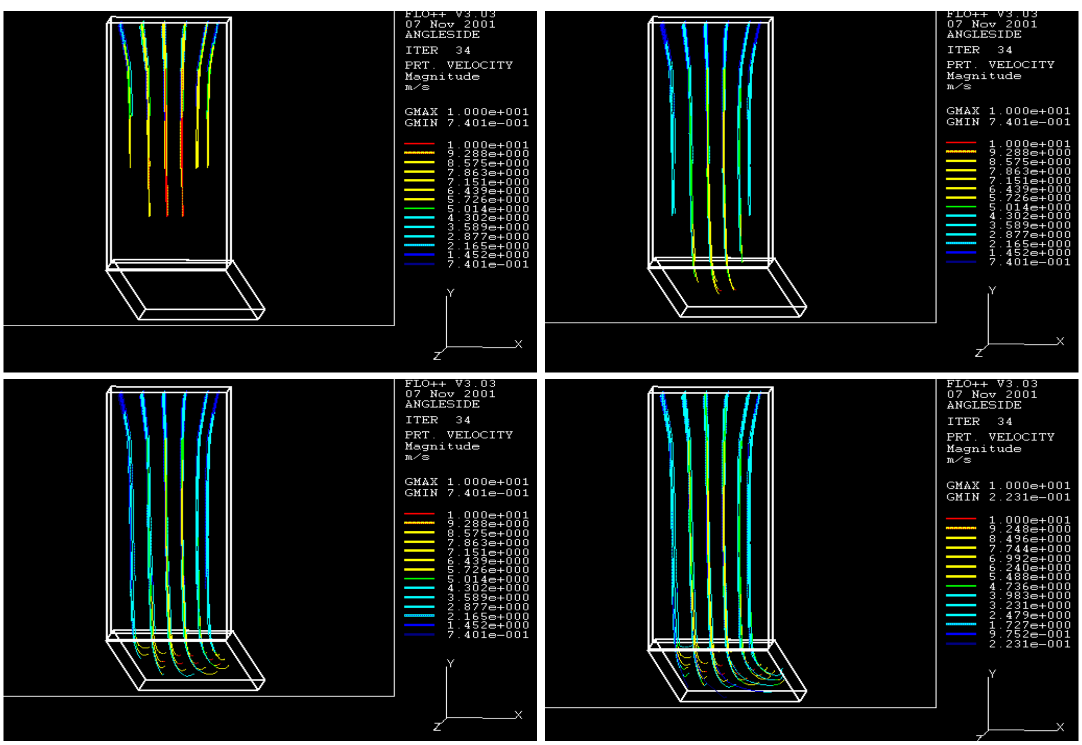


Figure 7-20. Particle flow lines with two side trowels

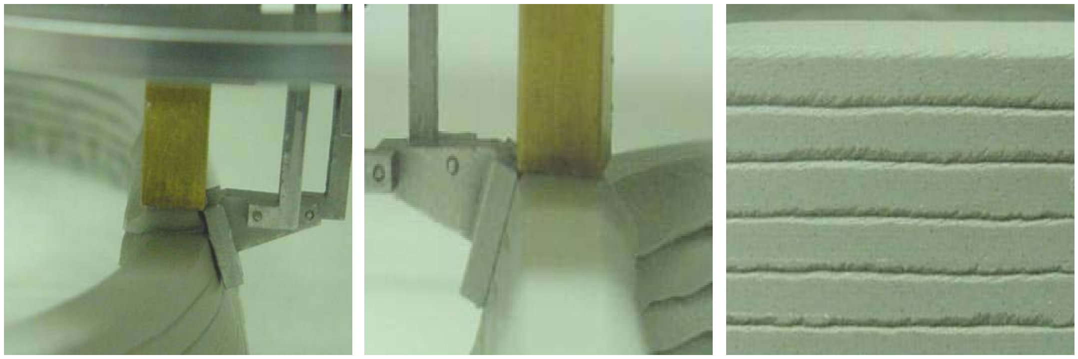


Figure 7-21. On-line process with an exterior angle: (a) font view, (b) back side view, and (c) surface quality

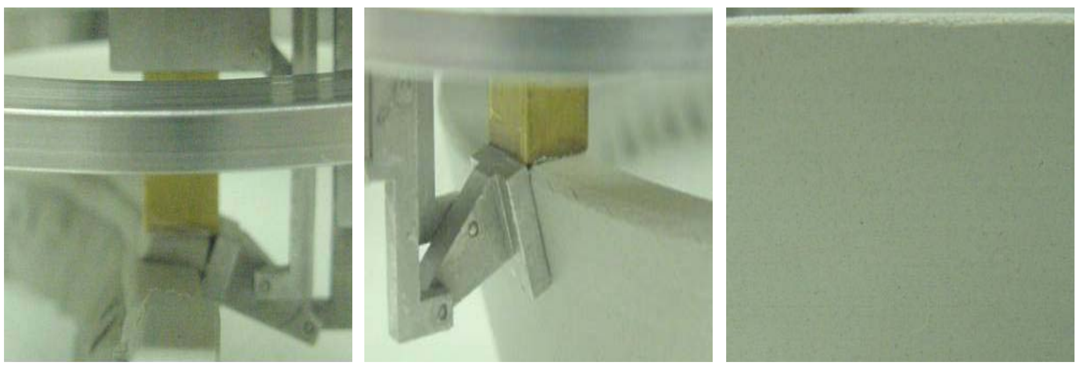


Figure 7-22. On-line process with an interior angle: (a) font view, (b) back side view, and (c) surface quality

Figure 7-23. On-line process with two side trowels: (a) font view, (b) back side view, and (c) surface quality

As shown in these simulation results, the complex flow conditions were occurred in the flow domain. Since the friction at the boundary, especially the walls, retards the flow, the flow in the center of the nozzle is much rapid. Also, the flow patterns are changed on the deposited point relating to the side trowel angle, which explains why we get the flow profile indicated by different colors. The photographs of CC with an exterior angle taken on-line, shown in Figure 7-21, confirm the results obtained by the simulation in Figure 7-18. The photographs with an interior side trowel angle taken on-line, shown in Figure 7-22, confirm the results obtained by the simulation in Figure 7-19. The photographs taken on the actual CC process with the two side trowels, shown in Figure 7-23, confirm the results obtained by the simulation in Figure 7-20.

8.3.3 *Discussion*

To achieve desirable surface quality, the process parameters are optimized under each of the three different conditions. As shown in the Figure 7-24 (a), the material is dispersed symmetrically in and outward on the bottom phase. Hence, it might be difficult to fill the material into the corner. Owing to the inside trowel, the flow pattern is changed in Figure 7-24 (c). The material is intended to flow into outward where the outside trowel is. This design might be better to fill the material into the corner, and to achieve better surface finish of the fabricated part in Figure 7-23 (d). When the angle of the side trowel is interior as shown in Figure 7-24 (b), the outside material is directly deposited on the side trowel, and then sledded inward.

Hence, the corner is going to be filled completely, and then the perfect surface quality is achieved as shown in Figure 7-22 (c).

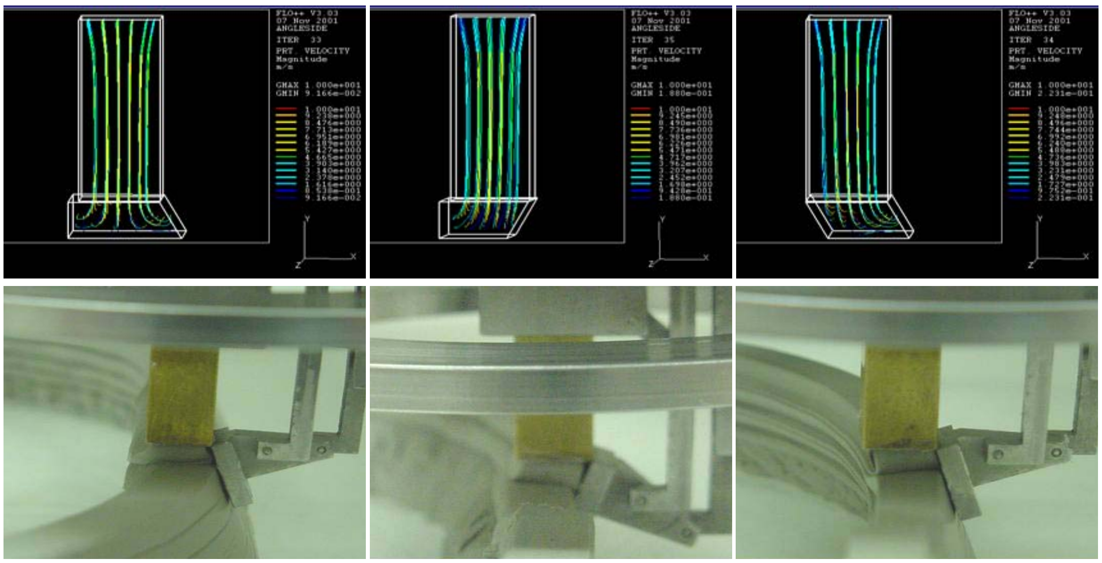


Figure 7-24. Comparison with the partial lines vs. on-line process under near optimal conditions: (a) an exterior, (b) an interior, and (c) two side trowels

By smoothing out the presence of unfilled regions between the consecutive layers at the exterior angle in Figure 7-21 (c), higher velocities were needed in order to achieve a near equal surface roughness value. However, if the extrusion pressure on the deposited point was increased beyond the optimum value to fill up these voids, it would cause loss of the desired geometric profile, thus deteriorating the surface quality as shown in Figure 7-25.

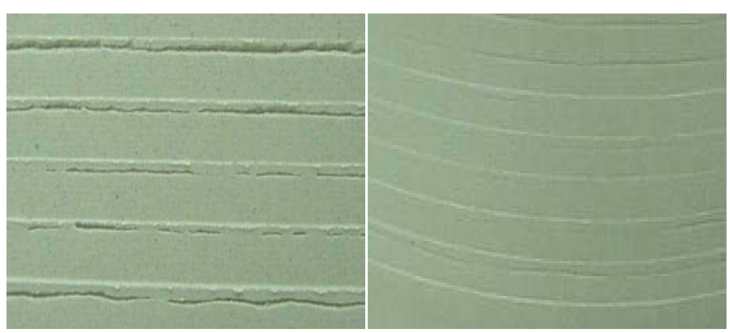


Figure 7-25. Surface finish at the sup-optimal condition: (a) a side trowel with an exterior angle, and (b) two trowels with an exterior angle

CHAPTER 8

CONCLUSION AND RECOMMENDATION FOR FUTURE RESEARCH

8.1 Research summary

Through experimental investigations with ceramic materials, it has been shown that the CC process is feasible and has significant potential in the rapid prototyping industry. In addition to its use in rapid fabrication of large components, the process has its niche in rapidly fabricating certain components for aerospace and automotive industries, where minimization of green machining is warranted. The results of experimental studies also indicate that the process is feasible and has significant potential in construction automation. The potential of CC became evident from the presented experimental investigations. Experiments with ceramic materials show the versatility of the process relative to the use of a variety of fabrication materials. The process with ceramic materials seems especially suited for automated construction of emergency structures as well as large scale construction of houses with exotic features such as adobe houses.

Furthermore, the first simulation study (related to the orifice shapes) played an important role in gaining a better insight into the flow processes in the CC process. It enabled the prediction of the consequences of varying the boundary conditions, different orifice geometries, and other flow parameters related to the process. The experimental results form a basis to conclude that the results obtained with the square orifice are better than other types. The second simulation study also has played an important role in obtaining a better insight into the effects of the pivoting side trowel. The consequences of varying the side trowel angles, and other related process parameters were made possible to predict through the simulation efforts. The results obtained with two side trowels showed better surface quality than that of a single side trowel under a condition of the exterior angle. However, the two-side trowel system is difficult to fabricate certain shapes such as sharp edges and curves. Also, it was learned that the optimal extrusion pressure in all examined cases must be high enough for the layers to fuse with each other with a uniform flow pattern, and low enough to avoid distortion of the part (maintaining the geometric profile).

8.2 Recommendations for future research

There are many issues for the future research to perfect this promising fabrication process. Following are some recommended research directions:

1. *Analysis of the uncured ceramic properties such as viscosity, shrinkage, etc.*
   As mentioned in Chapter 3, the properties of the extrudate material (e.g. clay) depend on the water amount. Measurement of the water weight of the processing material would be beneficial to quantify the clay properties, and to compensate for variations between raw material lots. To reduce the shrinkage rate of the processing material will also be useful to compensate for

variations in the geometrical profile, and to improve the accuracy of the fabricated part.

2. *Side trowel geometry*

The current movable side towel has a rectangular shape. Studying various side trowel geometries such as those shown in Figure 8-1 may improve the capabilities of the CC process by reducing the CC limitation in relation to concave corners. Based on the preliminary results with two side trowels presented in Chapter 7, the two-side trowel nozzle created better surface quality than the one-side trowel nozzle. Further investigations may be conducted to resolve the problems associated with the two-side towel system.

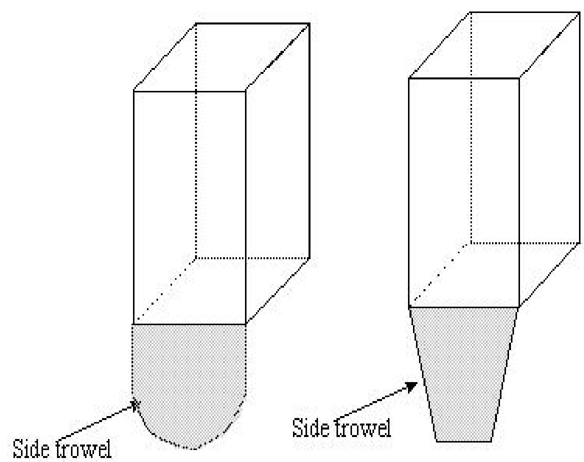


Figure 8-1. Schematic views of alternative side trowels

3. *Develop an empirical model with Response Surface Methodology (RSM).*

The Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques. It is useful for modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response. In addition, RSM allows for

For generalization of the foregoing results, however, one needs to find a means to study the correlations between the pressure and surface roughness under experiments involving different trowel designs and fabrication materials. Also, he/she needs to develop an empirical model and to profoundly conduct a study in relation to the correlations between the surface roughness and the process parameters. For these analytical researches a better measurement system should be develped to accuratly measure the surface roughness.

5. *Locking mechanism to compensate for layer start/stop issues.*

   The material property (fluid inertia) causes problems when starting and stopping each layer fabrication. Experiments could be conducted to determine the best machine control mechanism to minimize these effects. Reversing the direction of the extrusion motor upon completion of a layer may decrease the material flow stop problem, but it could not resolve this issue completely. A valve mechanism at the nozzle exit might aid in stopping the material flow.

6. *Tool path generation.*

   Because the CC process has a variable-orientation trowel being shaped for better fit to the surface, unlike all existing layering techniques the apparatus must consider the actual slopes of layer sides. Hence, one must develop an interface with a solid modeling system that involves approximating the surface adaptively with a series of horizontal slices that are not simply extrusions of a contour. This research is being conducted by John Yeh, who is Ph.D. candidate at USC.

7. *Develop a filling mechanism for the inner solid volumes.*

   A systematic method should be devised to automatically apply the filler material when desired.

8. *Develop the other alternative mechanism for fabricating 3D shapes.*

   To fabricate certain structures, it may be beneficial to pivot the extrusion nozzle with respect to the Z axis. For example, Figure 8-3 shows a vault structure made of clay bricks using a traditional manual procedure. Here the vault is constructed by first laying side squinches, and the dome structure is built layer-by-layer. The corresponding deposition pattern of the CC process could be such as the one schematically illustrated in Figure 8-4.

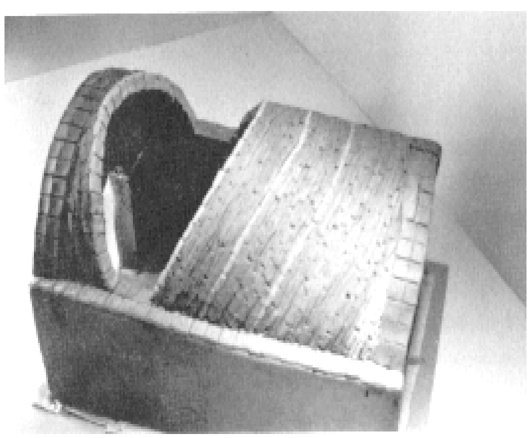


Figure 8-3. A vault structure made of clay bricks [Source: Khalili, 2000]

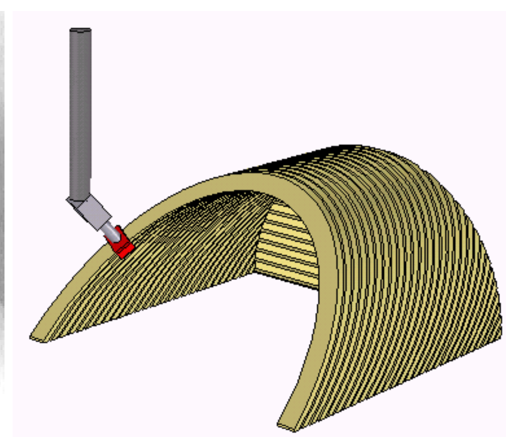


Figure 8-4. Our approach to fabricate supportless structures

9. *Develop new control software.*

   In order to make fabrication structures such as the one shown in Figure 8-4, new computer control software needs to be developed. The new software should pprovide for fabrication of primitive as well as hybrid geometries. Such a software should allow for experimenting with various types of trowel motions and material flow patterns.

BIBLIOGRAPHY

1. Agarwala, M. K., Bandyopadhyay, A., Weeren, R. Van, Langgrana, N. A., Safari, A., and Danforth, S.C. (1996), "Fused Deposition of Ceramics (FDC) for Structural Silicon Nitride Components" *Paper Presented at the Solid Freeform Fabrication Symposium*, Austin, TX, August.

2. Alexandrou, A. N., and Ahmed, A. (1993), "Injection Modeling Using a Generalized Eulerian Langrangian Formulation", *Polymer Engineering and Science*, Vol. 33, pp. 1055-1064, August.

3. Ashley, S. (1995), "Rapid Prototyping is Coming of Age", *Mechanical Engineering*, Vol. 117, No. 7, pp. 62-68, July.

4. Atwood, Clinton L. (1997), "Metal Casting Applications", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

5. Aubin, Richard F. (1997), "Tooling Applications", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

6. Bardet, Jean-Pierre (1997), *Experimental Soil Mechanics,* Prentice-Hall.

7. Beaman, Joseph J. (1997), "Materials -- Metal", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

8. Benbow, John and Bridgwater, John (1993), *Paste Flow and Extrusion*, Oxford.

9. BIBA (1995), "Introduction to Rapid Prototyping Technology", http://www.biba.uni-bremen.de/groups/rp/rp_page.html, March.

10. Brown, Robert L. (1997), "Needs, Goals, and Objectives", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

11. Bugeda, G., Cervera, M., Lombera, G., and Onate, E. (1995), "Numerical analysis of stereolithography processes using the finite element method", *Rapid Prototyping Journal*, Vol. 1, No. 2, pp.13-23.

12. Burns, Marshall (1998), *Automatic Fabrication*, *Prentice Hall*.

13. Bylinsky, Gene (1998), "Industry's Amazing New Instant Prototypes", *Fortune Features*. http://www.pathfinder.com/fortune/1998/980112/imt.html, January.

14. Castle Island Co. (1995), "Introduction to RP Technologies", http://home.att.net/~castleisland/techn.htm, March.

15. Craig, R. F. (1997), *Soil Mechanics,* E & FN Spon.

16. Cooper, A.G., Kang, S., Stampfl, J., and Prinz, F.B. (2000), "Fabrication of ceramic parts for a miniature jet engine application using Mold SDM", *Ceramic Transactions*, Vol. 108, pp.389-398.

17. Delta Tau Data Systems Inc. (2000), "PMAC PC ", http://www.deltatau.com, February.

18. Ding, D., Townsend, P., and Webster, M.F. (1993), "Numerical Solution of Filling Problems Related to Injection Moulding", *IUTAM Symposium on Numerical Simulation of Non-Isothermal Flow of Viscoelastic Liquids*, Kerkrade, Netherlands, November.

19. Dolenc, A. (1997) "An Overview Of Rapid Prototyping Technologies In Manufacturing", http://www.cs.hut.fi/~ado/rp/rp.html, March.

20. Engelund, Walter C., Stanley, Douglas O., Lepsch, Roger A., and McMillian, Mark M. (1992), "Aerodynamic configuration design using response surface methodology analysis", *American Institute of Aeronautics and Astronautics inc.*, pp. 1-11.

21. Fox, Robert W., and McDonald, Alan T. (1985), *Introduction to fluid mechanics,* John Wiley & Sons.

22. Fussell, Paul S. (1997), "Materials -- Overview, Plastics, and Resins", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

23. Garcia-Rejon, A., DiRaddo, R. W., and Ryan, M. E. (1995), "Effect of die geometry and flow characteristics on viscoelastic annular swell", *Journal of Non-newtonian Fluid Mechanics*, Vol. 60, pp. 107-128, November.

24. Griffith, Michelle and Lamancusa, John S. (1998) "Rapid Prototyping Technologies", http://www.me.psu.edu/lamancusa/me415/rpintro2.pdf.

25. Grimm, Todd (1998) "Quantity Before Quality", http://www.acceltechinc.com/articles.html.

26. Han, W., and Jafari, M. A. (1999), "Coordination Control and Deposition Planning for Improving Deposition Accuracy in Layered Manufacturing Process", *technical working paper*.

27. Hardro, Peter J., Wang, Jyh-Hone, and Stucker, Brent E. (1999), "A design of experiment approach to determine the optimal process parameters for rapid prototyping machines", http://www.egr.uri.edu/ime/faculty/jhwang/hardro/hardro.htm.

28. Kandis, M., and Bergman, T. L. (2000), "A Simulation-Based Correlation of the Density and Thermal Conductivity of Objects Produced by Laser Sintering of Polymer Powders", *Journal of Manufacturing Science and Engineering*, ASME, Vol. 122, pp. 439-444, August.

29. Khalili, N. (2000), *Ceramic houses & Earth architecture*, Cal-Earth Press, California.

30. Khoshnevis, B. (1998), "Innovative rapid prototyping process makes large sized, smooth surfaced complex shapes in a wide variety of materials", *Materials Technology*, Vol.13, pp. 52-63.

31. Khoshnevis, B., and Bukkapatnam, Satish (1999), "Contour Crafting – A novel Rapid prototyping Process", *A proposal to Ford Company*.

32. Khoshnevis, B. (2000), "Automated construction using the contour crafting layered fabrication technique", *8th international conference on rapid prototyping*, Tokyo, June.

33. Khoshnevis, B., Russell, R., Kwon, H., and Bukkapatnam, S. (2001), "Contour Crafting – A Layered Fabrication Technique", *IEEE Robotics and Automation Magazine*, Vol. 8, No. 3, pp. 33-42, September.

34. Khoshnevis, B., Bukkapatnam, S., Kwon, H., and Saito, J. (2001), "Experimental Investigation of Contour Crafting using Ceramics Materials", *Rapid Prototyping Journal*, Vol. 7, No.1, pp. 32-41.

35. Kulkarini, P., and Dutta, D. (1999), "Deposition Strategies and Resulting part Stiffnesses in Fused Deposition Modeling", *Journal of Manufacturing Science and Engineering*, ASME, Vol. 121, pp. 93-103, February.

36. Kwon, H., Bukkapatnam, S., Khoshnevis, B., and Saito, J. (2001) "Effect of orifice shape in Contour Crafting of ceramic materials" *Rapid Prototyping Journal,* August (Accepted).

37. Langdon, Ray (1997), "A Decade of Rapid Prototyping", *Automotive Engineer*, pp.44-45, May.

38. Lanzo, Giuseppe, and Vucetic, Mlanden (1999), "Effect of soil plasticity on damping ratio at small cyclic strains", *SOILS AND FOUNDATIONS*, Vol. 39, No. 4, pp.131-141, August.

39. Laboratory for Freeform Fabrication of Advanced Ceramics at Rutgers University (1998), http://www.caip.rutgers.edu/sff.

40. Levy, Sidney and Carley, James F. (1994), *Plastics Extrusion Technology Handbook,* ASME Press.

41. Li, X.C., Stampfl, J., Prinz, F.B. (1999), "Design and fabrication of materials for Laser Shape Deposition Manufacturing", *44th International SAMPE Symposium*, L.J.Cohen et al. (eds), Long Beach, Vol. 44, No. 2, pp.1849-1856, May.

42. Lightman, Allan J. (1997), "Materials -- Ceramics", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

43. Lightman, Allan J. (1997), "Medical application", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

44. Malik, Zahid and Rashid, Kashif (1999), "Comparison of optimisation using Response Surface Methodology with Neurofuzzy methods", http://infoeng.ee.ic.ac.uk/~malikz/papers/ieee_mag_2000/ieee_paper_rev1_final_pretty.html.

45. Malkus, David S., Nohel, John A., and Plohr, Bradley J. (1993), "Oscillations in Piston - Driven Shear Flow of a Non-Newtonian Fluid", *IUTAM Symposium on Numerical Simulation of Non-Isothermal Flow of Viscoelastic Liquids*, Kerkrade, the Netherlands, November.

46. Myers, Raymond H., and Montgomery, D. C. (1995), *Response Surface Methodology*, John Wiley & Sons, New York.

47. Montgomery, D. C. (1997), *Design and Analysis of Experiments*, John Wiley & Sons, New York.

48. Montgomery, D. C. (1992), "The Use of Statistical Process-Control and Design of Experiments in Product and Process", *IIE Transactions*, Vol. 24, pp. 4-17, November.

49. NASA, "Rapid Prototyping research and development", Marshall Space Flight Center in Huntsville, Alabama, http://nasarp.msfc.nasa.gov.

50. Park, Byong-Ho, and Prinz, Fritz B. (2000), "Mesoscopic Assemblies with SDM Processing", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, August.

51. Pegna, Joseph (1997), "Explorary investigation of solid freeform construction", Automation in construction, Vol. 5, No. 5, pp. 427-437.

52. Plasun, Richard (1999), "Optimization of VLSI Semiconductor Devices", http://www.iue.tuwien.ac.at/diss/plasun/diss/diss.html.

53. Prinz, Friedrich B. (1997), "Significance of Rapid Prototyping", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

54. Rapid Prototyping Development Laboratory (2000), "LOM of Ceramics and Fiber Composites", http://www.udri.udayton.edu/rpdl,

55. Rapid prototyping report (1997), "Busyness New", http://www.cadcamnet.com, Vol. 008, No. 2, May.

56. Rapid prototyping report (1999), "Selective laser sintering parts used directly in spacecraft production", http://www.cadcamnet.com, Vol. 008, No. 1, November.

57. Rapid prototyping report (1998), "Medical rapid prototyping", http://www.cadcamnet.com, Vol. 008, No. 1, December.

58. Rapid prototyping report (1998), "Rapid prototyping helps doctors evaluate new device", http://www.cadcamnet.com, Vol. 008, No.1, September.

59. Russell II, Richard J. (1999), "An Experimental Approach to Analyzing Melt flow and Troweling using the Contour Crafting Process", *Ph. D. Dissertation*, USC.

60. Sandia National laboratories (2000), "Rapid Prototyping", http://mfgshop.sandia.gov/1400_ext/1400_ext_RapidPrototype.htm,

61. Tseng, A. A., and Tanaka, M. (2001), "Advanced deposition techniques for freeform fabrication of metal and ceramic parts", *Rapid Prototyping Journal*, Vol. 7, No. 1, pp.6-17.

62. Venkataraman, N., Rangarajan, S., Matthewson, M. T., Harper, B., Safari, A., Danforth, S.C., Wu, G., Langrana, N., Guceri, S., and Yardimici, A. (2000), "Feedstock material property – process relationships in fused deposition of ceramics", *Rapid Prototyping Journal*, Vol. 6, No. 4, pp.244-252.

63. Wang, W. L., Conley, J. G., and Stoll, H .W. (1999), "Rapid Tooling for Sand Casting Using Laminated Object Manufacturing Process", *Rapid Prototyping Journal*, Vol. 5, No. 3, pp.134-140.

64. Walters, Fredrick H., Parker, Lloyd R., Morgan, Stephen L., and Deming, Stanley N. (1991), *Sequential simplex optimization: a technique for improving quality and productivity in research, development, and manufacturing,* CRC Press LLC.

65. Warszawski, A., and Navon, R. (1998), "Implementation of robotics in buildings: current status and future prospects," *Journal of Construction Engineering and Management*, Vol.124, No.1, pp. 31-41.

66. Weiss, Lee E. (1997), "Process overview", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, March.

67. Wozny, Michael J. (1997), "CAD and Interfaces", *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*, http://itri.loyola.edu/rp, Vol. 1, March.

68. Yeung, A. T. (1992), " Diffuse double layer equation in SI units", *Journal of Geotechnical Engineering*, *ASCE*, Vol. 118, No. 12, pp. 2000-2005.

69. Young, R. N., and Warkentin, B. P. (1975), *Soil properties, and Behavior*, Elsevier Scientific Co., New York.

70. Zak, G., Sela, M. N., Park, C. B., and Benhabib, B. (1999), "Layered-Manufacturing of Fiber-Reinforced Composites", *Journal of Manufacturing Science and Engineering*, ASME, Vol. 121, pp. 448-455, August.

71. Zhang, Guangming, and Surana, Rena (1999), "Integration of rapid prototyping and vacuum casting", *International Journal of Advanced Manufacturing Systems*, Vol. 1, Issue 2, pp. 263-272.

Appendix 1: Description of other commercial RP processes.

The various RP processes have been currently developed in companies and laboratories around the world. Some of these are already used in industry. As tabulated on Table I-1, I-2, and I-3, most commercialized RP processes are dominant in the United States, Europe, and Japan. A brief description of these techniques, component technologies used to implement each system, and advantages and disadvantages are presented in this appendix.

Table I-1 Commercialized Rapid Prototyping in United States

Manufacturer	Process Name	Materials	Process type
3D System	Stereolithography Apparatus (SLA)	Acrylate, epoxy	Selective photocuring
Helisys	Laminated object Manufacturing (LOM)	Paper, tape castings	Adhesion of cut sheet
Stratasys	Fused Deposition Modeling (FDM)	ABS, wax, nylon, gel casting	Robotically guided extrusion
DTM	Selective Laser Sintering (SLS)	Nylon, wax, polycarbonate,	Selective sintering
Sander Prototype	Model Maker	Low-melt plastic	Droplet deposition on powder
Soligen	Direct Shell Production Casting (DSPC)	Ceramics	Droplet deposition on powder
BPM	Ballistic Particle Manufacturing (BPM)	Low-melt plastic	Droplet deposition on powder
3D System	Multi-Jet Modeling	Wax	Droplet deposition on powder

Table I-2 Commercialized Rapid Prototyping in Europe

Manufacturer	Process Name	Materials	Process type
EOS (Germany)	STEREOS	Acrylate, epoxy	Selective photocuring
EOS (Germany)	EOSINT	Polyamide, polystyrene, metal alloy, resin-coated sand	Selective sintering
Cubital (Germany/Isra)	Solid Ground Curing (SGC)	Acrylate, wax	Photomasking
Fockele & Schwareze (Germany)	LMS	Acrylate, epoxy	Selective photocuring

Table I-3 Commercialized Rapid Prototyping in Japan

Manufacturer	Process Name	Materials	Process type
CMET (NTT Data Communications)	Solid Object Ultraviolet Plotter (SOUP)	Epoxy	Selective photocuring
D-MEC (JRS/Sony)	Sony's Solid Creation System (SCS)	Urethane acrylate	Selective photocuring
Kira Corp.	Solid Center	Paper	Adhesion of cut sheet
Teijin Seiki	Solid Forming System (Soliform)	Urethane acrylate, glass-filled resin	Selective photocuring
Denken Engineering	Solid Laser Plotter (SLP)	acrylate	Selective photocuring
Meiko Corp.	Meiko	acrylate	Selective photocuring

1.1 <u>Selective photocuring</u>

It consists of the original Stereolithgraphy and its variation in the category of selective photocuring. In these processes, a special type of polymer resin is utilized, which has the property of turning solid when exposed to light, usually in the ultraviolet range. A scanned laser or a masked lamp provides light to solidify the selected portion on a surface of the liquid in the shape of 2-dimensional cross-section of a CAD file corresponding to the desired object being built.

Stereolithgraphy (SLA) is the first commercial RP technique developed and commercialized by 3D System, Inc. shown in Figure I-1. It is the most prolific of RP techniques accounting for at least 50% of RP currently in use with its variations. Initially in this process, the laser beam scans the surface of liquid contained in a vat following the contours of the slice that is based on the cross-section of 3D CAD file. The liquid is a photopolymer that is cured or solidified when exposed to the ultra-violet (UV) laser beam. After the layer is completely traced and hardened, the elevator is moved down the vat a distance equal to the thickness of layer. A new thin layer of liquid

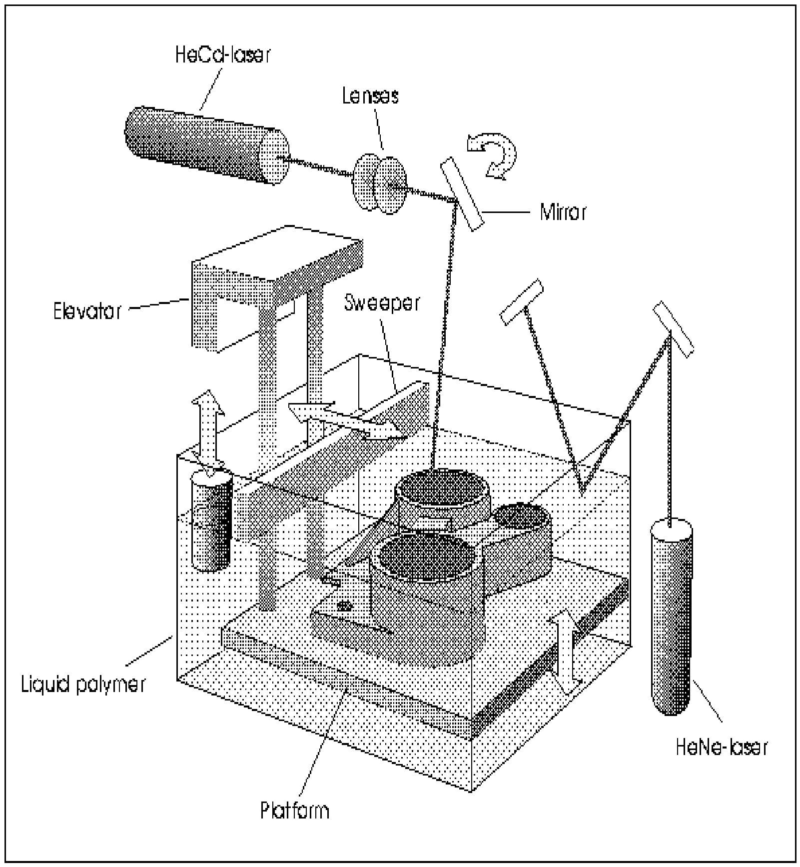


Figure I-1. Schematic overview of the SLA process (Source: Dolenc 1997) then covers the object and layers are reproduced in a similar manner. In this way, the object is fabricated in a layered fashion [Weiss 1997, BIBA 1995, Castle Island Co. 1995, and Griffith 1998].

ADVANTAGES

- Possibility of fabricating parts, which might be impossible to be produced in a conventional process.
- Continuous unattended operation.
- Virtually no limitation on fabricating any geometrical shape.

DISADVANTAGES

- Need of sophisticated sequence of processes.
- Necessity of support structures.
- Unacceptable accuracy to apply to the range of mechanical part manufacturing.
- Restricted application ranges because of given material properties.
- Additional labor requirements for post processing.

Solid Ground Curing (SGC) or masked lamp curing was developed and commercialized by Cubital Ltd. shown in Figure I-2. It is similar to stereolithography in its use of a photopolymer resin that is sensitive to UV-light. Instead of utilizing a laser to expose and harden photopolymer element by element within a layer as is done in stereolithography, it uses a mask for the entire layer to be cured at once by the application of UV-light. There are two cycle processes having a mask creation cycle and a layer fabrication cycle in this RP process. A mask is generated on the glass plate by utilizing the process similar to how a laser printer works. The glass plate with the mask then moves to the exposure cell where it is between the lamp and the surface of the workspace. The intense UV-light passes through the mask, cures the layer quickly and fully in the required pattern, and then the glass mask is cleaned of toner and discharged. After creation of a layer, the uncured resin is vacuumed off, wax is added to fill in the voids created by the removal of the uncured resin and hardened by moving the object to the cooling station, and then the entire surface is milled to accurately control the height. The subsequent layers are repeated layer by layer until the object is fabricated completely. After the entire part is fabricated, it requires the secondary operations to melt and remove the wax from the part [Weiss 1997, BIBA 1995, Castle island Co. 1995, and Griffith 1998].

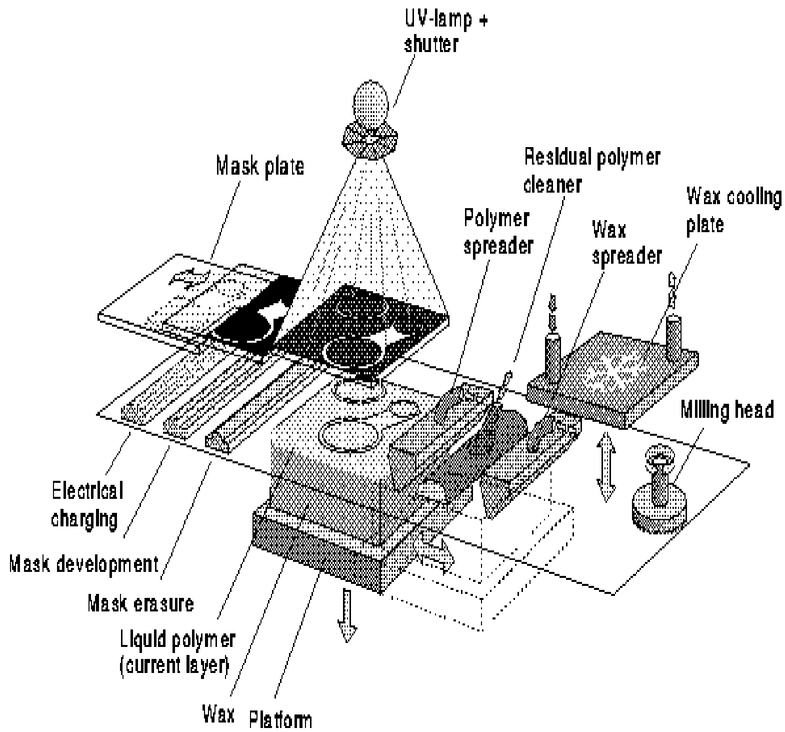


Figure I-2. Schematic overview of the Soild ground curing process (Source: Dolenc 1997)

ADVANTAGES

- Virtually possibility of manufacturing any geometrical part, which is unable to be produced conventionally in a single process.
- Continuous unattended operation.

DISADVANTAGES

- Necessity of sophisticated sequence of processes.
- Limited speed.
- Restricted application areas because of given material properties.
- Labor requirements for post processing because of the necessity to have support structures.

1.2 **Selective sintering**

It is similar to selective photocuring in its use of a heat source such as laser; however, a desired section of a thin layer of thermoplastic or metal powder is exposed to the heat source. The powder particles are then selectively melted and fused to form a single cross section of the object. This process is repeated until the desired object is fabricated completely.

Selective Laser Sintering (SLS) was developed by the university of Texas at Austin and commercialized by DTM Corp. in Figure I-3. It is similar to stereolithography in principle. In this process, however, a laser beam is traced over the surface of tightly compacted powders, which are spread by a roller over the surface of a build cylinder, instead of a liquid polymer. The heat from the laser sinters a layer of the powder. After the layer is completely sintered and hardened, a new layer of powder is evenly spread over the layer previously fabricated. The subsequent layers are then reproduced analogously to fabricate the entire desired object. The powders that are currently used or investigated in SLS processes include metals, wax, plastics, and coated ceramics [Weiss 1997, BIBA 1995, Castle island Co. 1995, and Griffith 1998].

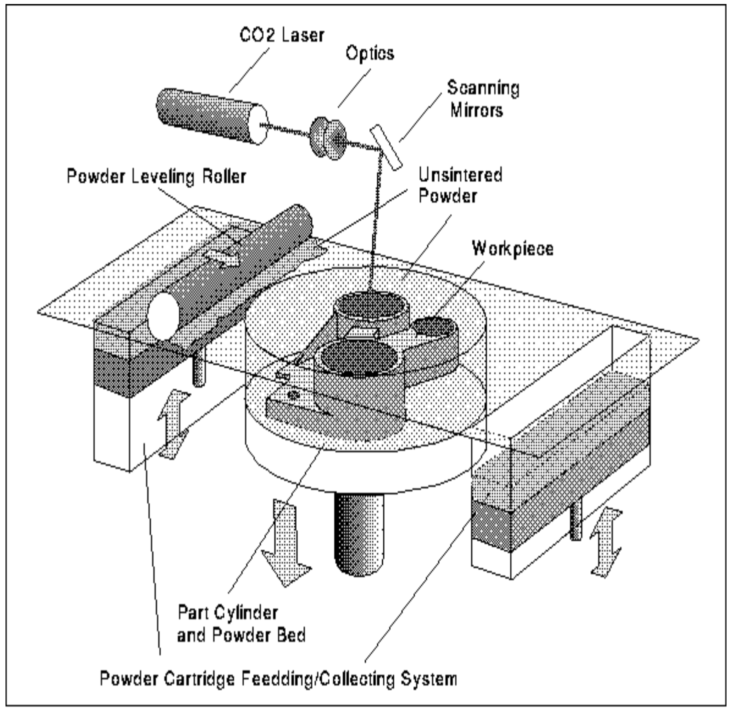


Figure I-3. Schematic overview of the SLS process (Source: Dolenc 1997)

ADVANTAGES

- Various materials can be used like polycarbonate, polyvinyl chloride (PVC), nylon, croning sand for building sand casting cores, and investment casting wax.
- No need of any post-curing except when ceramics are used.
- No need to create a structure to support overhanging geometry, which saves time during creation of the part, as well as post-process.
- Its advanced software allows concurrent slicing of the part geometry files while processing the object.

DISADVANTAGES

- During solidification, additional powder may harden on the borderline.
- Necessity to provide the process chamber continuously with nitrogen to assure safe material sintering.
- Toxic gases emitted from the fusing process have to be handled carefully (especially with PVC).
- The surface roughness is most visible because of a stair step effect when parts contain gradual sloping surfaces.

1.3 Adhesion of cut sheet

It is a hybrid process that consists of a subtractive and an additive processes. In this process, the contour of each 2-dimensional cross section of the desired object is cut (usually by utilizing laser) from sheets of a laminating material precoated with adhesive such as wax, plastic coating, etc. on the undersurface of the paper. The cut layers are successively laminated by heat to fabricate the desired object. This process has the advantage of using inexpensive materials and being able to fabricate relatively large parts.

Laminated Object Manufacturing (LOM) was developed and commercialized by Helysis, Inc. shown in Figure I-4. In this RP process, profiles of the object's cross section are traced and cut from a sheet material by using a laser, which is precoated with adhesive such as wax, plastic coating, etc. on the undersurface of the paper. A layer of paper is laid over the previous layer, and pressed and heated by utilizing the roller, causing it to fuse to the previous layer. This paper is then cut by a laser following the perimeter of the object. This layer wise fashion process is continued until the object is fabricated completely [Weiss 1997, BIBA 1995, Castle island Co. 1995 and Griffith 1998].

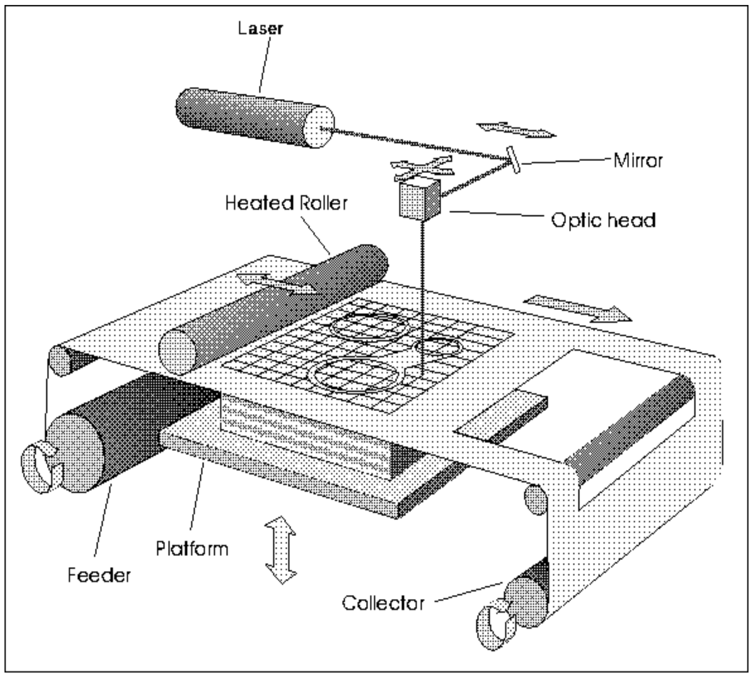


Figure I-4. Schematic overview of the LOM process (Source: Dolenc 1997)

ADVANTAGES

- Variety of organic and inorganic materials can be used such as paper, plastic, ceramic, composite, etc.
- The costs are relatively low.
- The process is much faster than competitive techniques.
- LOM Slice possesses the robust capacity of dealing with imperfect STL files, and created with discontinuities.
- Best suited for building large parts.

DISADVANTAGES

- The bonding strength of the glued layers limits the stability of the objects.
- The application range is relatively restricted to complex parts because the procedure is not well suited for manufacturing parts with thin walls in the z-direction.
- Hollow parts, like bottles, might be difficult to be built.

1.4 **Robotically guided extrusion**

It uses a thermoplastic material to be forced through an extrusion nozzle, which is moved about by a robotic arm to lay down the molten material in a desired location, to deposit the material layer by layer to fabricate the desired object. The subsequent layers are then repeated analogously to fabricate the entire desired object.

Fused Deposition Modeling (FDM) shown in Figure I-5 was developed and commercialized by Stratasys, Inc. It is a process that uses a thermoplastic filament melted in the cylinder, a liquid, and a paste that is deposited layer by layer to create an object by extruding through a nozzle, like toothpaste extruding out of its tube. As the extrusion nozzle is guided robotically in the required geometry, it deposits a thin bead of extruded plastic to form each layer. The plastic is solidified immediately in an oven chamber where the temperature is just below the melting point of the plastic after being extruded from the nozzle and fused to the previous layer. Any overhanging geometries have to be fabricated with support structures that are later removed in secondary operations. There are several available materials for this process currently accommodating a nylon-like polymer, and both machinable and investment casting wax [Dolenc 1997, Weiss 1997, BIBA 1995, and Griffith 1998].

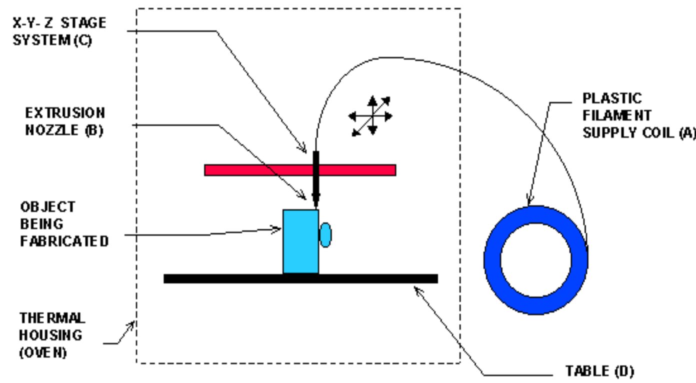


Figure I-5. Schematic side view of the FDM process (Source: Castle Island Co. 1995)

ADVANTAGES

- Quick and cheap generation of models.
- Free from possible exposure to toxic chemicals, lasers, or a liquid polymer bath.
- No waste of given material during production of the model.
- Materials can be changed quickly.

DISADVANTAGES

- Restricted accuracy due to the shape of the material used: wire of 1,27 mm diameter.
- Additional labor requirements for post processing because of the necessity of having support structures.
- The surface roughness is most visible because of a stair step effect when parts contain gradual sloping surfaces.

1.5 Droplet deposition on powder

It utilizes a technique that is similar to that of an ink jet printer. In this process, an adhesive liquid is deposited to a thin powder layer to selectively join the powder particles, forming a solid cross section of the desired object. The subsequent layers are then repeated analogously until the entire desired object is completely created. Secondary operations may be required later to improve the strength of the created part, and to remove the support structures necessary for any overhanging geometries. The other terminology for the process is usually called 3D printing.

Three-dimensional printing shown in Figure I-6 was developed at the Massachusetts Institute of Technology (MIT). Its approach is similar to SLS except that an inkjet head replaces the laser. In this process, a stream of a liquid adhesive compound (binder) is applied to a ceramic powdered material through standard ink-jet nozzles, as are utilized in 2-dimensional ink-jet printing, in successive patterns following cross sections of the desired object.

The ceramic powder and binder comes to be a composite structure after the binder spreads on the surface of the ceramic powder and then goes through a short distance into it. A subsequent layer of ceramic powder is spread and compressed uniformly over the previous layer by the roller after the layer is created, and then the ink-jet process is repeated analogously. In industry, the capability of fabricating ceramic materials directly is of great importance in molding for investment casting, called ceramic shells because of their brittleness and high melting temperature [Dolenc 1997, Weiss 1997, BIBA 1995, and Griffith 1998].

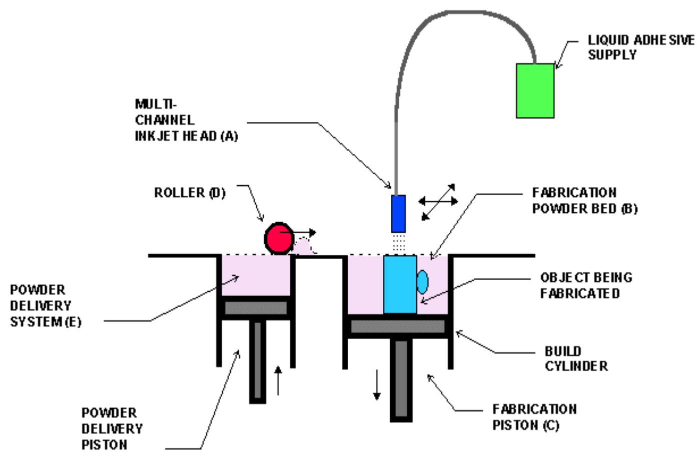


Figure I-6. Schematic side view of the 3D printing process

(Source: Castle Island Co. 1995)

ADVANTAGES

- Non-toxic materials are used.
- Excellent dimensional tolerance and smooth surface finish.
- Super fine layer slices thickness.
- High accuracy.
- Imports .STL, .HPGL, .DXF, Alias .OBJ Data Files.

DISADVANTAGES

- Limited size.
- Limited speed.

Ballistic Particle Manufacturing (BPM) shown in Figure I-7 was developed and commercialized by Sander Prototypes, Inc. It is a process that combines a thermoplastic ink jetting technology with high-precision milling to build prototype models or patterns. This process utilizes the jetting heads to be controlled and eject small droplets of the liquid thermoplastic to form the desired shape. The individual jetting heads receive the liquid thermoplastics

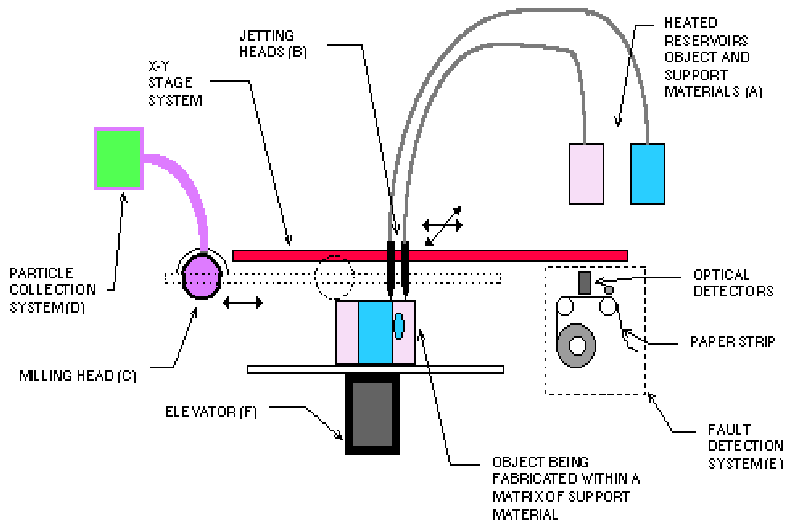


Figure I-7. Schematic side view of the BPM process (Source: Castle Island Co. 1995)

and wax for support material, carried in a melted liquid state at elevated temperature in each reservoir, through thermally insulated tubing. A milling head is passed over the layer to make it a uniform thickness after forming an entire layer of object. The process is repeated layer by layer until the entire object is completed. The support material is then melted and dissolved away in secondary operations [Dolenc 1997, Weiss 1997, BIBA 1995, and Griffith 1998].

ADVANTAGES

- Low cost and good performances.
- Unlike other systems, it does not require industrial power, water, or ventilation.
- Non-toxic materials are used.
- High accuracy.

DISADVANTAGES

- The machine is slow.
- Because the machine is new on the market, no detailed experiences are available

Appendix 2: Applications of RP processes.

2.1 <u>Prototyping</u>

As its name suggests, the primary application of RP processes is to make prototypes quickly for communication and testing purposes. Prototypes dramatically improve communication because three-dimensional objects are easier for most people (including engineers, producers, and customers) to understand than two-dimensional drawings. Such improved comprehension leads to substantial cost and timesavings.

According to Pratt & Whitney executive Robert P. DeLisle, “We’ve seen an estimate on a complex product drop by $100,000 because people who had to figure out the nature of the object from 50 blueprints could now see it” [Bylinsky 1998]. In this era of concurrent engineering, effective communication is especially important to exchange prototypes early in the design stage. Manufacturing can start tooling up for production while the other division starts planning the packaging.

To find out whether a prototype performs as desired or needs improvement, the RP processes are also useful for testing a design while expanding engineers’ capabilities. First, it is now easy to perform iterative testing: build a prototype, test it, redesign, build and test, etc. Such an approach would be far too time-consuming using conventional prototyping techniques, but it is easy using RP processes.

In addition to these, RP processes can do a few things that metal prototypes cannot. For example, Porsche applied a transparent stereolithography model of the

911 GTI transmission housing to visually study oil flow [Langdon 1997]. Snecma, a French turbomachinery producer, performed photoelastic stress analysis on a SLA model of a fan wheel to determine stresses in the blades [Ashley 1995].

2.2 <u>Rapid Tooling</u>

Rapid tooling, the automatic fabrication of production quality machine tools, is another anticipated application of rapid prototyping. One of the slowest and most expensive steps in the manufacturing process is machine tooling because of the extremely high quality required. Tools often have complex geometries, and must have dimensional accuracy within a hundredth of a millimeter.

A useful variant, known as the Keltool powder metal sintering process, uses the rubber molds to produce metal tools. The Keltool process, developed by 3M and now owned by 3D Systems, involves filling the rubber molds with powdered tool steel and epoxy binder. When the binder cures, the “green” metal tool is taken out from the rubber mold and then sintered. At this stage the metal is only 70% dense, so it is infiltrated with copper to bring it close to its theoretical maximum density. The tools have fairly good accuracy, but their size is limited to less than 25 centimeters [Ashley 1995, and Atwood 1997].

Some RP prototypes can be used as investment casting patterns. The pattern must not expand when heated, or it will crack the ceramic shell during autoclaving. Both Stratasys and Cubital make investment casting wax for their machines. Paper LOM prototypes may also be used, as they are dimensionally stable with temperature. The paper shells burn out, leaving some ash to be removed [Atwood 1997].

Shape Deposition Manufacturing (SDM) is a process that was developed at Stanford University to create metal tools from CAD data. Materials consist of 316 stainless steel, Inconel 625, H13 tool steel, tungsten, and titanium carbide cermets. A laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete. Unlike traditional powder metal processing, SDM produces fully dense parts because the metal is melted, not merely sintered. The resulting parts have exceptional mechanical properties, but the process currently works only for parts with simple, uniform cross sections [Li 1999].

2.3 Rapid Manufacturing

Rapid Manufacturing (RM) is a natural extension of the RP process, which is the automated production of functional products directly from CAD data. Currently only a few RP machines may produce functional products, but the number will increase as metals and other materials become more widely available. RM will never completely replace other manufacturing techniques, especially in large production runs where mass-production is more economical.

For short production runs, however, RM is much cheaper because it does not require tooling. RM is also ideal for producing custom parts tailored to the user's exact specifications. The other major use of RM is for products that simply cannot be made by subtractive (machining, grinding) or compressive (forging, etc.) processes.

This includes objects with complex features, internal voids, and layered structures. Therics, Inc. of NYC is using RP's layered build style to develop "pills that release measured drug doses at specified times during the day" and other medical products [Ashley 1995].

Appendix 3: Potential application areas of the CC process

CC has its highest potential in applications involving large parts. Many parts in automotive, aerospace, and ship building concerns are large. These include tooling for car body parts, and structural parts such as chassis. Construction of tooling for aerospace manufacturing and shipbuilding is another application area. CC can be also the key to build models for large casting molds. A wax, plastic, or composite model of a ship propeller to be used in sand casting is a representative example.

3.1 Application to automotive industry

Many parts in automobile are large. These include interior parts such as glove box; structural parts such as chassis; and body parts, such as doors, fenders, hoods, etc. Also, typical toolings that are used in the automotive industry are large. Current rapid prototyping techniques cannot be used for fabrication of such objects. However, Contour Crafting can be effectively utilized for this purpose. Also, CC could make the fabrication of novel parts such as composite chassis a reality.

3.2 Naval and Aerospace Applications

The CC process is aptly suited for producing patterns and *patternless molds* for large castings such as ship propellers, turbine blades, etc, some of which are shown in Figure III-1. In order to demonstrate the potential of our process, a sample part that resembles the shell of a turbine blade was fabricated using CC (see Figure III-2). The production of this part took less than 20 minutes. CC can be adapted for making large patterns and molds, mold shells and core using the specific materials

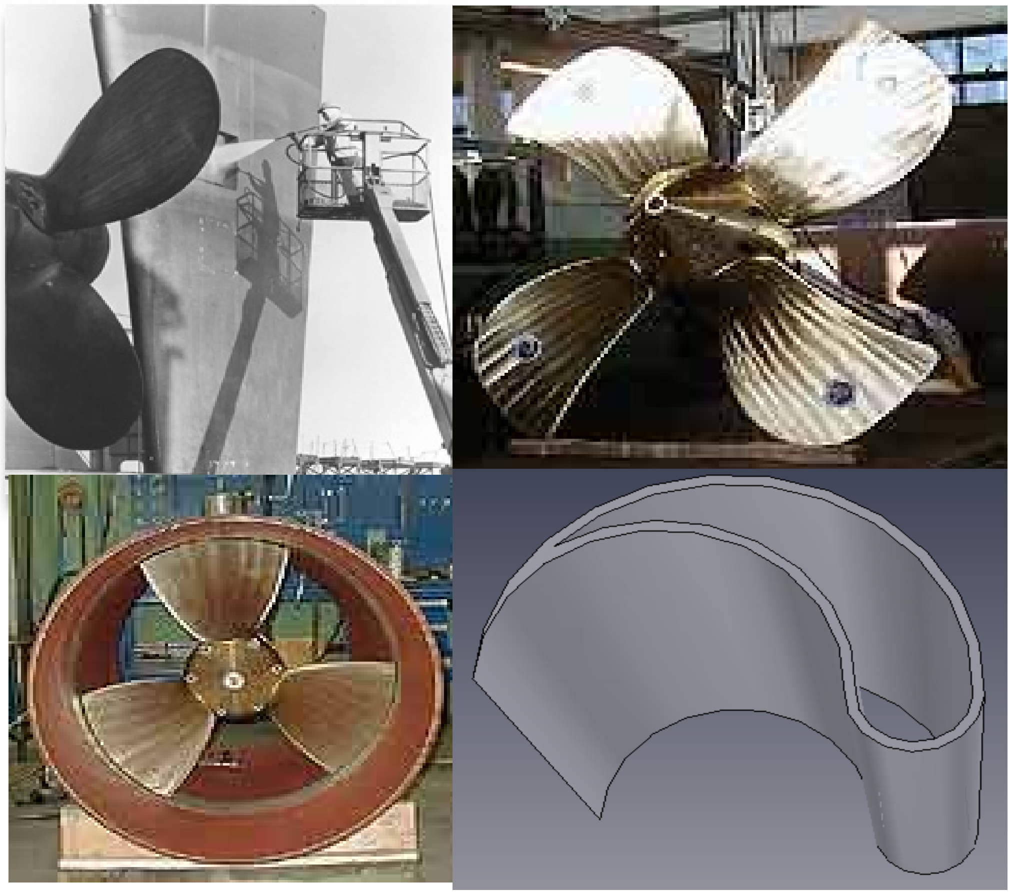


Figure III-1. Typical ship propellers that are apt candidates for economic production using CC

Figure III-2. Complicated profile similar to that of a turbine blade being made using CC used in the respective process i.e., sand molding, resin-coated shell molding, core making, etc.

3.3 Application to construction industry

Layered manufacturing has an excellent potential in the construction of civil structures. Reduction in labor cost, better quality, possibility of using various materials, such as smart concretes, are some of the few advantages that construction automation offers. Because of its scalability and its ability to produce smooth surfaces, CC is an ideal candidate layered fabrication process for construction automation (Everett and Saito, 1996; Pegna, 1997; Warszawski and Navon, 1998; Khoshnevis, 2000).

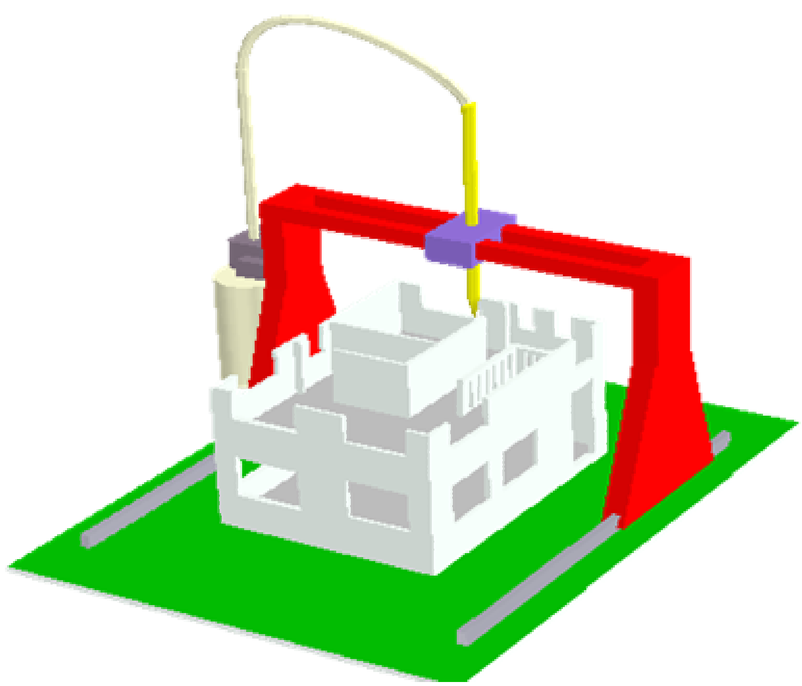


Figure III-3. Residential building construction (Source: Khoshnevis-Japan paper)

Various scales of the CC process may be adapted for construction applications. Since deposition is controlled by computer, accurate amounts of selected construction materials, such as smart concrete, may be deposited precisely in the intended locations. This way the electric resistance, for example, of a carbon filled concrete may be accurately set as dictated by the design. Elements such as strain sensors, floor and wall heaters can be built into the structure in an integrated and fully automated manner (Khoshnevis, 2000).

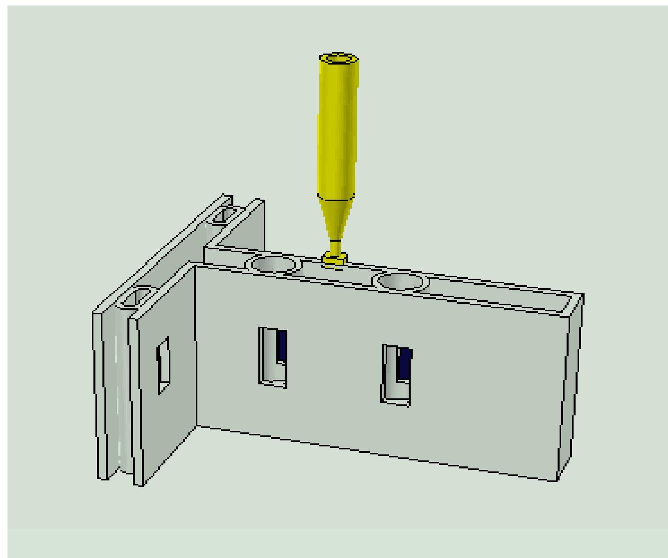


Figure III-4. Imbedding electrical and plumbing conduit (Source: Khoshnevis-Japan paper)

Multiple materials that chemically react may be fed through the CC nozzle system and mixed in the nozzle barrel immediately before deposition. The quantity of each material may be controlled by computer and correlated to various regions of the geometry of the structure being built.

Application in building construction is depicted in Figures III-3 and III-4. Note that as shown in Figure III-4, utility conduits may be built into the walls of a building structure precisely as dictated by the CAD data.

Application of this automated approach can be envisioned for most building structures, but as entry level applications low income housing, emergency housing, and submersible housing may be considered. The pictures depicted in these figures are influenced by the current building design and construction practice. It is conceivable, however, that new architectural approaches could be created that will utilize the capabilities that the new construction technique can offer.

The new mode of construction will most probably be the only feasible approach for building structures on other planets, such as Mars, which is being targeted for human colonization before the end of the new century.

Appendix 4: Composition of clay used in CC

4.1 Pioneer Talc

Pioneer talc is a soft, non-abrasive, inert, white powder that acts as functional filler and is dispersed easily due to the weak bonds [Levy 1998].

It offers excellent resistance to weathering and acid/alkali attack when added to exterior paint and coating formulations. It belongs to the montmorillonite group of clay minerals; they are composed of silica layers held together by van der Waals' bonds. These bonds are readily broken by shear and therefore the montmorillonites are easily cleaved and feel soapy between the fingers [Benbow 1995].

- Swelling:

  The breakdown of montmorillonite particles in water is accompanied by a marked swelling, due to the molecules of water forcing their way between the silica layers.

- Plasticity:

  The montmorillonites are considered to be the most plastic of all clay materials. Their high plasticity is almost certainly due to the inherent smallness of the particles (0.02 to 0.2 microns). The montmorillonites are too plastic and have a drying contraction to be used for the manufacture of ceramic articles but a small portion of such clays may be added to other components to enhance their plasticity.

4.2 Taylor Ball Clay

Ball clays are a kaolin type of clay, made up of alternate sheets of silica (Si_2O_5) and modified gibbsite ($Al_2(OH)_4$) sheets. The whole crystal is held together by hydroxyl bonds, between OH groups of the gibbsite layers and oxygen atoms of the adjacent silica layers. The particles of ball clay cover a wide range of sizes [Levy 1998].

- Wet-to-dry shrinkage:

  The wet-to-dry shrinkage of ball clays is high. Linear shrinkage of up to 15%, and leather-hard moisture contents ranging from 10 to 32%; however, by mixing with other ingredients, the effective shrinkage can be greatly reduced.

- Dry strength:

  Ball clays are noted for their high dry strength; for this reason they are used in pottery bodies. In general, they are low in iron oxide, nearly white after firing, and the most plastic of kaolin-type clays.

4.3 Deflocculation[1]

In a colloidal suspension clay particles approach closely enough for short-range van der Waals' forces to operate and cause the particles to gather together into flocs or aggregates. Such a suspension is unstable, because the large flocs rapidly sediment; it is then said to be flocculated. Furthermore, in a flocculated state, the particles are grouped together in loose aggregates and occupy a much greater

[1] Deflocculant is a source of ions that charge clay particles to repel each other electrostatically, thus producing a slurry with a faster flow rate and low viscosity.

effective volume than that of the individual particles; their apparent viscosity at low shear rates is therefore high. At high shear rates the aggregates may be broken up [Craig 1997].

If the suspension is deflocculated, the aggregates are broken up and dispersed into individual particles, which remain discrete because of their high energies of repulsion. The individual particles now occupy a much smaller effective volume than before, and the viscosity consequently falls. Since clay suspensions are examples of exhibiting *Bingham plastic* approximately, it can be said that the effect of deflocculants assists in causing non-Newtonian behavior [Malkus 1993, and Fox 1985].

- The firing temperatures are:

  Earthenware - Cone 06-3 (1st firing, bisque)

  1945-1950 degrees Fahrenheit

  1063-1066 degrees centigrade

  Glaze firing

  1838 degrees Fahrenheit

  1003 degrees centigrade

Appendix 5: Detail description of the CC machine components

5.1 Machine structure

To build the complicate geometrical parts, the CC machine in Figure VI-1 had been modified. The trowel rotation system, and the linear ball screw were designed and assembled into the CC machine. The linear ball screw was accommodated to reduce the frictions of the piston shaft while fabricating the complex parts. Accordingly, the device turned out the CC process to be more stable, and increased the power for the

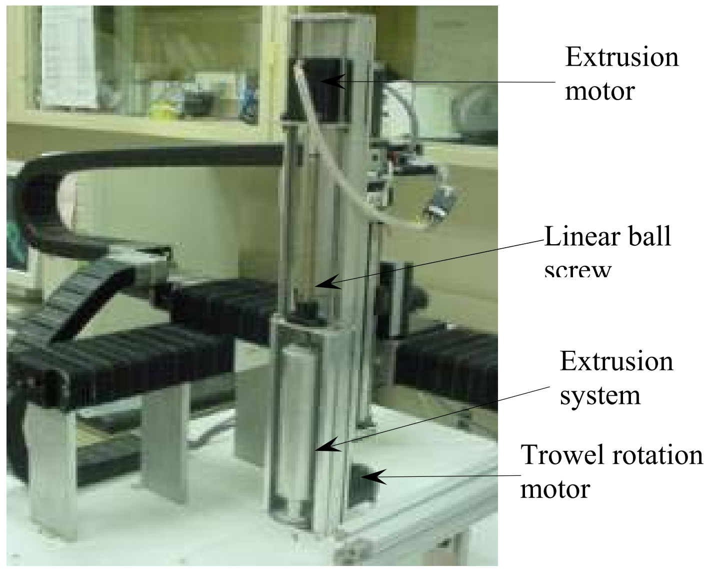


Figure VI-1. CC machine for fabricating the complex geometrical part

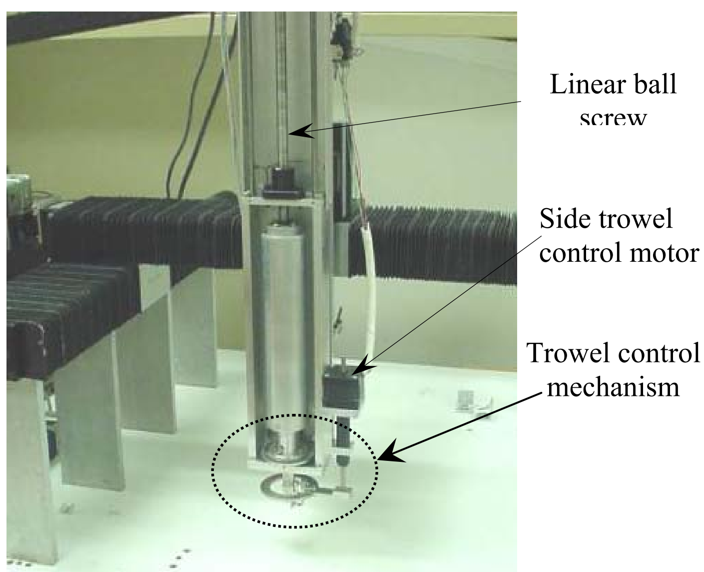


Figure VI-2. CC machine with the pivoting side trowel material to be extruded. To simplify the trowel rotation mechanism, the trowel rotation system consists of a bevel gear, and a connector.

The pivoting side trowel was designed and assembled in order to fabricate the complicate 3D geometrical parts such as cones, pyramids, domes, etc. As shown in Figure VI-2, a novel control mechanism with the pivoting side trowel is depicted. Eventually, This mechanism enhanced the capability of the CC process, while fabricating other diverse 3D geometrical parts.

5.1.1 *Orifice shape and flow control*

As a result of the exit geometry, the cross-section of the extrudate is determined during deposition and extrusion. A close examination of parts from CC process also shows that surface quality critically depends on the flow pattern of the material during extrusion and deposition, which in turn is heavily determined by the geometry of the orifice. It will also be necessary to be able to stop and start the fabrication material flow at the end and beginning of each layer and each sharp corner. The material flow pattern during the deposition is also different when the extrusion head is traveling to fabricate a straight wall or when cornering to fabricate a sharp corner.

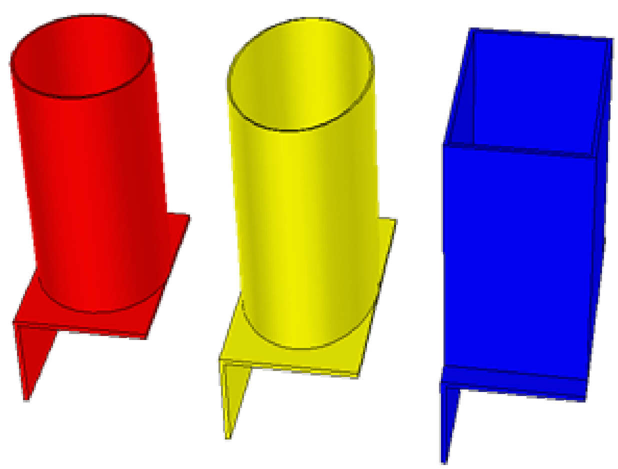


Figure VI-3. Several orifice shape designs used in experiments

Due to these factors, the experimental investigations were conducted with several orifice shapes (as shown in Figure VI-3) in order to study the effects of the orifice shape. A square orifice was found to be aptly suited, both in terms of delivering excellent fusion between layers as well as creating the desired external surface profile.

5.1.2 *Trowel geometry*

The significance of the trowel geometry is the same as that of the nozzle shape because the trowel and nozzle shape together determine the cross-section of the fabricated part and its outer surface. It is also important that the side trowel prevent material from flowing down the outer surface of the previous layer. To prevent such an occurrence, one would want the side trowel to overlap with the previous layer. Overlap of the side trowel with the previous layer, however, may restrict the possible geometries that the fabricator can produce (for example, sharp interior angled corner may prove to be difficult), particularly if the side trowel has a planar geometry.

The machine shown in Figure 1-2 had been designed and constructed to fabricate the cylindrical parts. Its extrusion system in Figure VI-4 consists of the top and

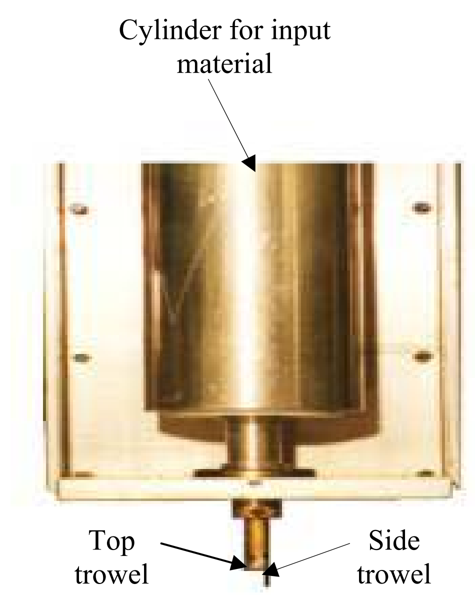


Figure VI-4. Extrusion system

side trowel, the cylindrical orifice shape, and the cylinder for input material. Since the rotary platform table was utilized, the trowel rotation system was not required for this system.

To fabricate the complex 2.5D geometrical parts, further, the machine shown in Figure VI-1 had been modified. Its novel extrusion system in Figure VI-5 also had been designed and assembled into the previous version of the CC machine, which consists of a trowel rotation system, and a vertical extrusion head capable of linear motion along three coordinate axes. This system became accustomed to utilize a narrow side trowel instead of the long top and side trowel. The outstanding effects of a short side towel are following: a) enhance the capability of the CC process by simplifying the nozzle and trowel system, and also b) reduce the geometrical limitations for fabricating the complex parts such as a sharp concave, and convex corners.

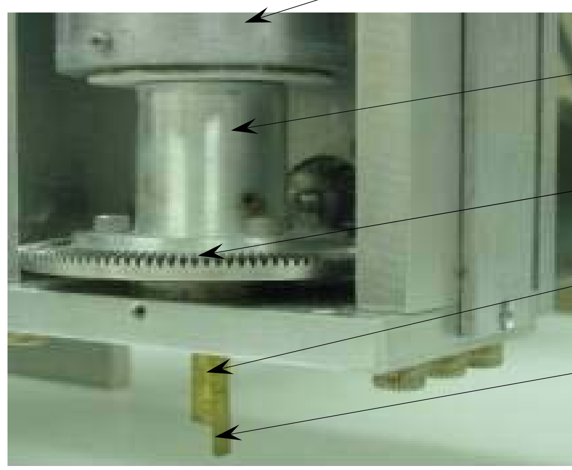


Figure VI-5. Trowel rotation system of CC process

The trowel rotation system consists of a bevel gear, and a connector. The ratio of the bevel gear is 4 to 1, and is derived by the 5th stepper motor. The connection mechanism is rigidly attached into the big bevel gear by four screws, allowed the raw material to flow continuously from the cylinder to nozzle, and can rotate the extrusion system without disturbing the material flow while fabricating the complex curve.

5.1.3 *Pivoting side trowel design and geometry*

In order to enhance the capability of CC for building certain primitive geometries and hybrid geometries made of these primitives, eventually, a nozzle with pivoting side trowel was designed as shown in Figure VI-6, and assembled into the existing CC machine as depicted in Figure VI-7. The control mechanism consists of a circular plate; actuate lever, side trowel links, a nozzle home, a pivoting side trowel, a square nozzle, etc.

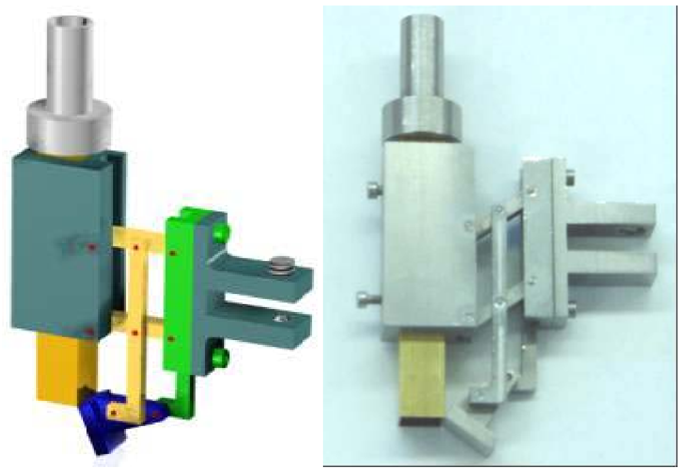


Figure VI-6. Design and two view of the current prototype of the pivoting nozzle assembly

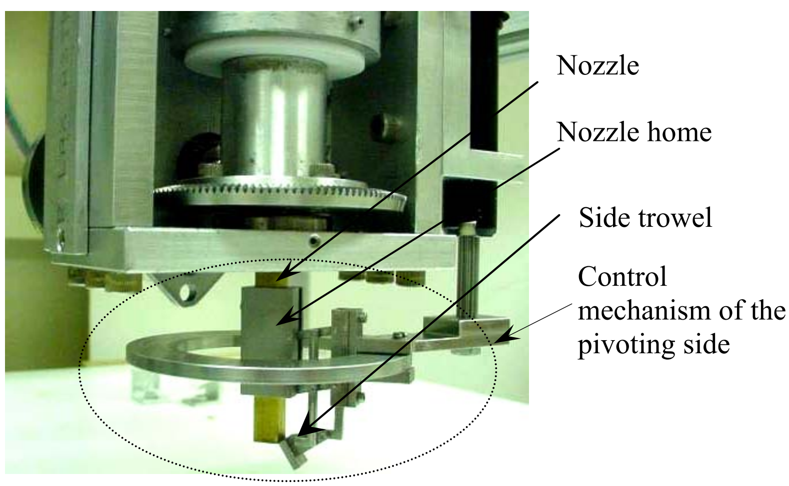


Figure VI-7. Trowel rotation system of the CC process

The circular plate is linked into the 6th stepper motor by a screw, and moves vertically up and down to control the multiple angles of the side trowel. The vertical angle range of the pivoting side trowel is about 130^0 (-40^0 to 90^0), and the horizontal angle is 360^0. There are also other several functions for the circular plate that are following: a) give a guidance to control the horizontal angle of the pivoting side trowel while fabricating complex 2.5D geometrical parts, b) to control the vertical angle of the pivoting side trowel while fabricating primitive 3D geometrical parts such as cone, pyramid, dome, etc., c) give a guidance to combined the previous two functions in order to build true nonsymmetrical 3D part.

The actuate lever, and the side trowel links are assembled together. Both of them are connected into the pivoting side trowel and the circular plate at same time. Their functions are following: a) transfer the kinematics of the 6th stepper motor into the side trowel; b) give a guidance for the side trowel to lie on the edge of a square nozzle without using a hinge to connect them; c) utilized to control the multiple angles of the side trowel with the circular plate. The nozzle home is allowed to hold the nozzle and the side trowel links with several steel pines.

5.2 PMAC motion controller

In order to supervise the process and control the motions of each stepper motors, PMAC (a multi-tasking digital signal processing) board is utilized. These two computer systems communicate with each other through the serial port. As shown in Figure VI-8, the process utilizes a Programmable Multi-Axis Controller

(PMAC), a high-performance servo-motion controller, capable of controlling up to eight axes of motion.

The eight axes can be all synchronized for completely coordinated motion; each axis can be put into its own coordinate system for eight completely independent operations; any intermediate arrangement of axes into coordinate systems is also possible. The motherboard used is a PMAC-PC with a serial communication and a baud rate of 9600. The J4 baseboard connector is 26-pin female flat cable connector that is used to connect the digital converter with the computer. This is used for establishing RS232 serial communication. J7 and J8 port connectors are 60 pin flat cable connectors, which connect the PMAC baseboard to the terminal boards. The terminal boards are connected to two input/output devices connected to the amplifiers that amplify the signal, and then are passed on to each motor. Limit switches were also used to restrict motion to specified limits. The specifications of each motor are provided in Table VI-1. The extrusion system consists of a pivoting side trowel, a cylinder that contains the raw material, and a piston and a linear ball screw that extrudes the raw material through a nozzle. The dimensions of these components are presented in Table VI-2.

Figure VI-8. PAMC-PC control box of CC process

Table VI-1 The specification of the motors

Motor No. & Axis Label	Rotation Speed	Counts per Unit	Range of Motion
#1 motor: X-axis	2,000 steps/rev.	394 counts/mm	333 mm
#2 motor: Y-axis	2,000 steps/rev.	394 counts/mm	379 mm
#3 motor: Z-axis	10,000 steps/rev.	1969 counts/mm	206 mm
#4 motor: Extrusion rod	1,000 steps/rev.	736 counts/mm	246 mm
#7 motor: Side trowel	2,000 steps/rev.	55 counts/deg.	-
#8 motor: Nozzle Rotating	5,000 steps/rev.	55.56 counts/deg.	-

Table VI-2 The dimensions of the extrusion system components

Component	Dimensions	
Side Trowel	Length = 7.5 mm	Width = 6.3 mm
Orifice (Square)	Outer Diameter = 6.3 mm	Inner Diameter = 4.8 mm
Cylinder	Inner Diameter = 38 mm Height = 200 mm	Outer Diameter = 50 mm
Bevel gears	No. of Teeth = 30, & 120 P.D. = 15.9, & 63.5 mm	Ratio = 1: 4
Linear Ball Screws	Shaft Diameter = 12 mm Shaft Root Diameter = 10.6 mm Ball Center Diameter = 12.3 mm	Dynamic load rating = 2.5 kN Rigidity =130N/μm
Piston	Diameter = 38 mm	Thickness = 9 mm Teflon disc pad = 3.5 mm

Appendix 6: Description of experiments for the support materials

When the CC process is required to build the overhanging parts, filler materials should be utilized to fill the solid volumes. To be compatable with uncured ceramic material, several characteristics for the support material are required.

- Since the uncured ceramics used in the CC process has 5 to 6 % shrinkage after the first curing, *the ideal support material must have the same shrinkage ratio*.
- To reduce overall process time, *the curing time of the filler should be faster than that of the clay in order to fabricate the other object on it*.
- To fill the exact void volume, it should be *simple to handle the amount of the support material*.
- The filler should have *a high strength after settung* in order to support the fabricated part, and the pressure during the extrusion process.
- The filler should be *easily removed from main object* after the parts are fabricated.
- From an economic and environmental point of view, it is better if *the filler is recyclable*.

Wax: First, after a small 2.5D part such as a square shape is fabricated, the small pieces of a solid wax are melted by utilizing a heat gun. An approximate amount of the liquid wax is poured to fill the area defined by the outside edge of the part. The part with the liquid wax is left at room temperature until the wax is solidified. The liquid wax takes 20 to 30 min to solidify. Using wax as the support material reveals several advantages and disadvantages:

Advantages

- Fast curing time.
- Simply to handle the approximate amount of the liquid wax, and to make the top surface flat.
- Strong enough to support the fabricated part (such as roof, overhanging, etc.), and the pressure during the extrusion process.

Disadvantages

- Difficult to remove from main object after the parts are fabricated.
- Difficult to recycle.
- Has very low shrinkage ratio compared to the uncured ceramic (5 to 6 %),

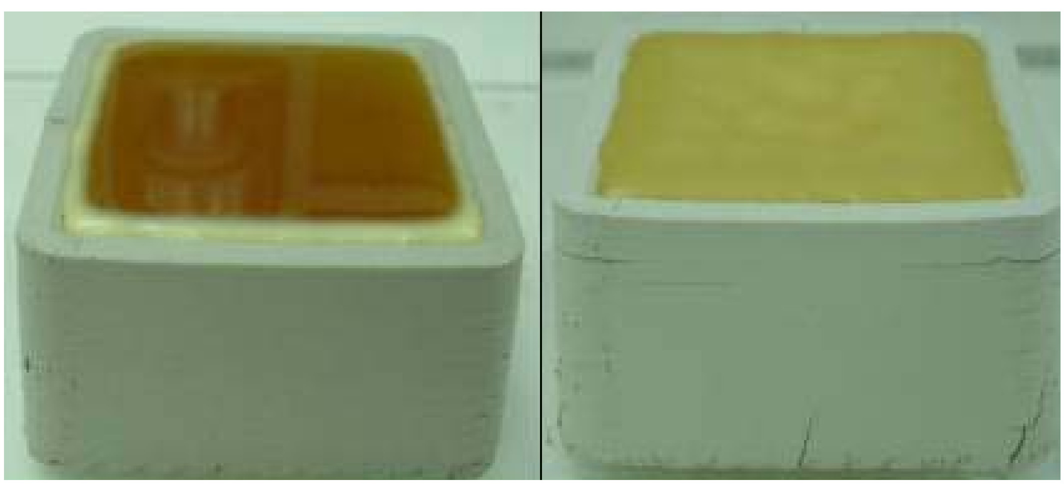


Figure VII-1. Effect of a wax: (a) after the part filled with the liquid wax, and (b) after the part solidified hence, the part has surface cracks after the first curing as shown in Figure VII-1.

Paste: The experimental procedure of the paste is similar to that of the wax. Since the procured paste is almost in a plastic state, pre-process is required to make softer paste that can be poured easily to fill the void area. By mixing the paste with an agent such as Isopropyl alcohol, softer paste can be made. However, the top surface of the paste should be smoothed manually to make a flat surface after the void area is filled. The part with the softer paste is left at room temperature until the part is solidified. During this solidification, the softer paste takes more than 3 days to cure. By experimenting with the paste, several advantages and disadvantages are observed:

Advantages

- Strong enough to support the fabricated part, and the pressure during the extrusion process.
- The part has no surface cracks after the first curing as shown in Figure VII-2,

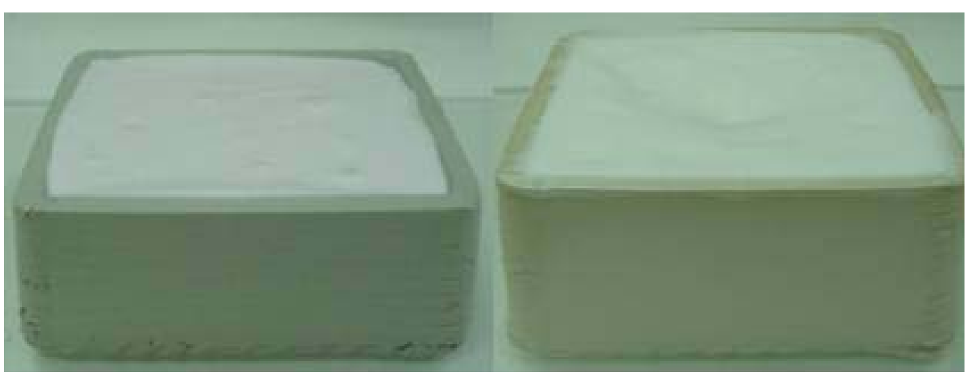


Figure VII-2. Effect of a paste: (a) after part being filled with the soft paste, and (b) after the part is solidified hence, It may compensate the shrinkage ratio of the uncured ceramic (5 to 6 %).

Disadvantages

- Curing time is too long.
- Difficult to approximate the amount of the paste needed, and to spread it evenly over the top surface.
- Difficult to remove from main object after the parts are fabricated.
- Difficult to recycle.

Sand: The filling procedure with the sand is similar to that with the wax and the paste without any pre-processing. After the void area is filled with sand, the top surface of the sand should be smoothed manually to make a flat surface. Several advantages and disadvantages are observed on the experimentation:

Advantages

- Does not require any curing time.
- May compensate the shrinkage ratio of the uncured ceramic because it can be removed before the fabricated second part is cured.
- Can be removed easily from main object after the parts are fabricated
- Can be recyclable.

Disadvantages

- As shown in Figure VII-3, it is not strong enough to hold the pressure during the extrusion process. Sand has some excellent properties and it was thought that the critical disadvantage of strength could be alleviated by using it in combination with other substances.

- Difficult to approximate the amount of the sand needed to fill the void volume.
- Necessitates the preparation of the flat surface manually.

Sand with wax: The experimental procedure of the sand and the wax is similar to the combination of the sand, and the wax. First, the void area is filled with the sand, and then the top surface of the sand should be smoothed manually to make a flat surface. Second, the wax is utilized to coat the topmost surface of the sand because the sand by itself does not have enough strength to sustain the pressure during the extrusion process. With this combination, an overhanging part such as roof can be fabricated as shown in Figure VII-4. Third, after the second part is fabricated, the sand can be removed through a hole on the platform to give a space for the shrinkage of the fabricated object. Finally, the fabricated part with wax put into the oven to melt away the wax.

Figure VII-3. Effect of sand: (a) after part being filled with the sand, and (b) during the fabrication of the second part

Figure VII-4. Process steps: (a) Fabricate the first part, (b) Fill the sand into the first part, (c) Coat its top surface with wax, (d) Wetting the top surface of the topmost layer, (e) Fabricating the second part on it, and (f) Completing the second part

Appendix 7: Description of GUI coding

```
'Initialize the variables used for setting the parameters for the base and body
Option Explicit
Dim counter As Integer
Dim status As Long
Dim lsb, lsbo, nlb, nlbo, ltb, ltbo, frb, frbo, orgn, stangle As Long

'Initialize the change button used for changing the other shapes of CNC program
Private Sub Change_Click()
Form1.Show
End Sub

'Initialize the FirstMake button used for fabricate the first parts
Private Sub FirstMake_Click()
Dim response As String
Dim status As Long
Dim DV

'Make the close loop of all functioned motors
status = PTalk1.GetResponse(response, "i13=8")
status = PTalk1.GetResponse(response, "#1 j/ ")
status = PTalk1.GetResponse(response, "#2 j/ ")
status = PTalk1.GetResponse(response, "#3 j/ ")
status = PTalk1.GetResponse(response, "#4 j/ ")
status = PTalk1.GetResponse(response, "#7 j/ ")
status = PTalk1.GetResponse(response, "#8 j/ ")
'Specify the coordination system and the scale unit of all functioned motors
status = PTalk1.GetResponse(response, "undefine all")  'clear all cordination systems
status = PTalk1.GetResponse(response, "&1 #1->394x")    '(counts per mm)
status = PTalk1.GetResponse(response, "&1 #2->394y")    '(counts per mm)
status = PTalk1.GetResponse(response, "&1 #3->1969z")  '(counts per mm)
status = PTalk1.GetResponse(response, "&2 #4->736b")    '(counts per mm)
status = PTalk1.GetResponse(response, "&1 #7->508.4u") '(counts per angle)
status = PTalk1.GetResponse(response, "&1 #8->55.5556c") '(counts per degree)
'Specify the variable links for communicating GUI with CNC motion program
status = PTalk1.GetResponse(response, "p5=" & Str(lsb))     'linear speed for base
status = PTalk1.GetResponse(response, "p6=" & Str(lsbo))   'linear speed for body
status = PTalk1.GetResponse(response, "p7=" & Str(ltb))      'base layer thickness
status = PTalk1.GetResponse(response, "p8=" & Str(ltbo))    'body layer thickness
status = PTalk1.GetResponse(response, "p9=" & Str(frb))     'base feedrate
status = PTalk1.GetResponse(response, "p10=" & Str(frbo))  'body feedrate
status = PTalk1.GetResponse(response, "p13=" & Str(orgn))  'Radius in cm
```

```
status = PTalk1.GetResponse(response, "p3=" & Str(90))       '
status = PTalk1.GetResponse(response, "p11=" & Str(stangle)) '

'Specify the message box for minimizing user error at the starting point
DV = InputBox("Enter a number(0) for the base or a number(1) for the body: ",
"Decision Variable"):
If DV = "" Then
  MsgBox "You did not type anything or pressed Cancel."
  Exit Sub
End If
If Not IsNumeric(DV) Then
  MsgBox "Invalid number!"
  Exit Sub
End If
status = PTalk1.GetResponse(response, "p2=" & Str(DV))          'basic flag
If DV = 0 Then
   status = PTalk1.GetResponse(response, "p4=" & Str(nlbo))     'body layer numbers
   status = PTalk1.GetResponse(response, "p1=" & Str(nlb))      'base layer numbers
   status = PTalk1.GetResponse(response, "p12=" & Str(nlb + nlbo))  'total layer
   status = PTalk1.GetResponse(response, "&1b60r")                   'run CNC code
   MsgBox "Done for moving to the oregin of the part"
Else
   status = PTalk1.GetResponse(response, "p4=" & Str(nlbo))
   status = PTalk1.GetResponse(response, "p12=" & Str(nlb + nlbo))
   status = PTalk1.GetResponse(response, "&1b60r")
   MsgBox "Done for moving to the oregin of the part"
End If
status = PTalk1.GetResponse(response, "&1b68r")
FirstMake.Enabled = False
End Sub

'Initialize Ptalk to interface with VB in load form
Private Sub Form_Load()event
Dim response As String
PTalk1.ShowPropertyPage
PTalk1.SaveSettings
PTalk1.LoadSettings
PTalk1.Enabled = True
lsb = Val(Text1.Text)    'lsb= linear speed base
lsbo = Val(Text2.Text)  'lsbo=linear speed body
nlb = Val(Text3.Text)    'nlb=Number of layers of base
nlbo = Val(Text4.Text)  'nlbo=Number of layers of body
ltb = Val(Text5.Text)     'ltb= Layer thickness of base in cm
```

```
ltbo = Val(Text6.Text)  'ltbo=Layer thickness of body in cm
frb = Val(Text7.Text)    'frb= Feed rate of base
frbo = Val(Text8.Text)  'frbo=Feed rate of body
orgn = Val(Text9.Text)  'orgn= Length of the square in mm
stangle = Val(Text15.Text) 'stangle= Angle of the side trowel (degree)
End Sub

'Show the error message box when existing some errors on the control system
Private Sub Ptalk1_OnError(ByVal ErrorNumber As Long, ErrorString As String)
Text12.Text = "Comm Failiure and Error Number: " + Str(ErrorNumber)
End Sub

'Initialize the roof form for fabricate the second object on the first object, which
'codes are the same as that of the first form. Also, this form can work independently.
Private Sub Roof_Click()
Dim response As String
Dim status As Long
Dim DV

status = PTalk1.GetResponse(response, "i13=8")
status = PTalk1.GetResponse(response, "#1 j/ ")
status = PTalk1.GetResponse(response, "#2 j/ ")
status = PTalk1.GetResponse(response, "#3 j/ ")
status = PTalk1.GetResponse(response, "#4 j/ ")
status = PTalk1.GetResponse(response, "#7 j/ ")
status = PTalk1.GetResponse(response, "#8 j/ ")
status = PTalk1.GetResponse(response, "undefine all")
status = PTalk1.GetResponse(response, "&1 #1->394x")
status = PTalk1.GetResponse(response, "&1 #2->394y")
status = PTalk1.GetResponse(response, "&1 #3->1969z")
status = PTalk1.GetResponse(response, "&2 #4->736b")
status = PTalk1.GetResponse(response, "&1 #7->508.4u")
status = PTalk1.GetResponse(response, "&1 #8->55.5556c")

status = PTalk1.GetResponse(response, "p5=" & Str(lsb))
status = PTalk1.GetResponse(response, "p6=" & Str(lsbo))
status = PTalk1.GetResponse(response, "p7=" & Str(ltb))
status = PTalk1.GetResponse(response, "p8=" & Str(ltbo))
status = PTalk1.GetResponse(response, "p9=" & Str(frb))
status = PTalk1.GetResponse(response, "p10=" & Str(frbo))
status = PTalk1.GetResponse(response, "p13=" & Str(orgn))
status = PTalk1.GetResponse(response, "p3=" & Str(90))
status = PTalk1.GetResponse(response, "p11=" & Str(stangle))
```

```
DV = InputBox("Enter a number(0) for the base or a number(1) for the body: ",
"Decision Variable"):
If DV = "" Then
  MsgBox "You did not type anything or pressed Cancel."
  Exit Sub
End If
If Not IsNumeric(DV) Then
  MsgBox "Invalid number!"
  Exit Sub
End If
status = PTalk1.GetResponse(response, "p2=" & Str(DV))
If DV = 0 Then
   status = PTalk1.GetResponse(response, "p4=" & Str(nlbo))
   status = PTalk1.GetResponse(response, "p1=" & Str(nlb))
   status = PTalk1.GetResponse(response, "p12=" & Str(nlb + nlbo))
   status = PTalk1.GetResponse(response, "&1b90r")
   MsgBox "Done for moving to the oregin of the part"
Else
   status = PTalk1.GetResponse(response, "p4=" & Str(nlbo))
   status = PTalk1.GetResponse(response, "p12=" & Str(nlb + nlbo))
   status = PTalk1.GetResponse(response, "&1b90r")
   MsgBox "Done for moving to the oregin of the part"
End If
status = PTalk1.GetResponse(response, "&1b91r")
Roof.Enabled = False
End Sub

'Initialize the roof form for fabricate the second object on the first object, which
'codes are the same as that of the first form. Also, this form can work independently.
Private Sub SecondMake_Click()
Dim response As String
Dim status As Long
Dim DV

status = PTalk1.GetResponse(response, "i13=8")
status = PTalk1.GetResponse(response, "#1 j/ ")
status = PTalk1.GetResponse(response, "#2 j/ ")
status = PTalk1.GetResponse(response, "#3 j/ ")
status = PTalk1.GetResponse(response, "#4 j/ ")
status = PTalk1.GetResponse(response, "#7 j/ ")
status = PTalk1.GetResponse(response, "#8 j/ ")
status = PTalk1.GetResponse(response, "undefine all")
status = PTalk1.GetResponse(response, "&1 #1->394x")
```

```
status = PTalk1.GetResponse(response, "&1 #2->394y")
status = PTalk1.GetResponse(response, "&1 #3->1969z")
status = PTalk1.GetResponse(response, "&2 #4->736b")
status = PTalk1.GetResponse(response, "&1 #7->508.4u")
status = PTalk1.GetResponse(response, "&1 #8->55.5556c")
status = PTalk1.GetResponse(response, "p5=" & Str(lsb))
status = PTalk1.GetResponse(response, "p6=" & Str(lsbo))
status = PTalk1.GetResponse(response, "p7=" & Str(ltb))
status = PTalk1.GetResponse(response, "p8=" & Str(ltbo))
status = PTalk1.GetResponse(response, "p9=" & Str(frb))
status = PTalk1.GetResponse(response, "p10=" & Str(frbo))
status = PTalk1.GetResponse(response, "p13=" & Str(orgn))
status = PTalk1.GetResponse(response, "p3=" & Str(90))
status = PTalk1.GetResponse(response, "p11=" & Str(stangle))

DV = InputBox("Enter a number(0) for the base or a number(1) for the body: ",
"Decision Variable"):
If DV = "" Then
  MsgBox "You did not type anything or pressed Cancel."
  Exit Sub
End If
If Not IsNumeric(DV) Then
  MsgBox "Invalid number!"
  Exit Sub
End If
status = PTalk1.GetResponse(response, "p2=" & Str(DV))
If DV = 0 Then
   status = PTalk1.GetResponse(response, "p4=" & Str(nlbo))
   status = PTalk1.GetResponse(response, "p1=" & Str(nlb))
   status = PTalk1.GetResponse(response, "p12=" & Str(nlb + nlbo))
   status = PTalk1.GetResponse(response, "&1b55r")
   MsgBox "Done for moving to the oregin of the part"
Else
   status = PTalk1.GetResponse(response, "p4=" & Str(nlbo))
   status = PTalk1.GetResponse(response, "p12=" & Str(nlb + nlbo))
   status = PTalk1.GetResponse(response, "&1b55r")
   MsgBox "Done for moving to the oregin of the part"
End If
status = PTalk1.GetResponse(response, "&1b56r")
SecondMake.Enabled = False
End Sub
```

```
'Initialize the slider form for changing the speed of each motor
Private Sub Slider1_Click()
Dim response As String
Dim status As Long
Select Case Slider1.Value
Case 1
image2.Picture = LoadPicture("bitmaps\one35.bmp")
status = PTalk1.GetResponse(response, "i122=8 i222=8 i322=12 i422=8 i722=8
i822=8")
Case 2
status = PTalk1.GetResponse(response, "i122=6 i222=6 i322=10 i422=6 i722=6
i822=6")
image2.Picture = LoadPicture("bitmaps\eighty.bmp")
Case 3
status = PTalk1.GetResponse(response, "i122=4 i222=4 i322=8 i422=4 i722=4
i822=4")
image2.Picture = LoadPicture("bitmaps\sixty.bmp")
Case 4
status = PTalk1.GetResponse(response, "i122=2 i222=2 i322=4 i422=2 i722=2
i822=2")
image2.Picture = LoadPicture("bitmaps\forty.bmp")
Case 5
status = PTalk1.GetResponse(response, "i122=1 i222=1 i322=2 i422=1 i722=1
i822=1")
image2.Picture = LoadPicture("bitmaps\twenty.bmp")
Case 6
status = PTalk1.GetResponse(response, "i122=.5 i222=.5 i322=1 i422=.5 i722=.5
i822=.5")
image2.Picture = LoadPicture("bitmaps\ten.bmp")
Case 7
status = PTalk1.GetResponse(response, "i122=.1 i222=.1 i322=0.5 i422=.1 i722=.1
i822=.1")
image2.Picture = LoadPicture("bitmaps\five.bmp")
End Select
End Sub

'Initialize the second motor for locating the Y-axes motor into a negative direction
Private Sub SSCommand1_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#2j-")
End Sub
```

```
Private Sub SSCommand1_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#2j/")
End Sub

Private Sub SSCommand10_Click()
Unload BackgroundForm
Unload mainfrm
Unload Me
End Sub

'Initialize the forth motor for locating the extrusion motor into a positive direction
Private Sub SSCommand11_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#4j+")
End Sub
Private Sub SSCommand11_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#4j/")
End Sub

'Initialize the forth motor for locating the extrusion motor into a negative direction
Private Sub SSCommand12_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#4j-")
End Sub
Private Sub SSCommand12_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#4j/")
End Sub
```

```
'Initialize the eighth motor for locating the nozzle rotation motor into an count clock
'wise direction
Private Sub SSCommand13_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#8j-")
End Sub
Private Sub SSCommand13_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#8j/")
End Sub

'Move to the home position
Private Sub SSCommand14_Click()
Dim status As Integer
Dim response As String
status = mainfrm.PTalk1.GetResponse(response, "#1 j= -1")
status = mainfrm.PTalk1.GetResponse(response, "#2 j= 1")
status = mainfrm.PTalk1.GetResponse(response, "#3 j= 0")
status = mainfrm.PTalk1.GetResponse(response, "#7 j= 0")
status = mainfrm.PTalk1.GetResponse(response, "#8 j= 0")
End Sub

'Initialize the eighth motor for locating the nozzle rotation motor into an clock wise
'direction
Private Sub SSCommand15_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#8j+")
End Sub
Private Sub SSCommand15_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#8j/")
End Sub
```

```
'Initialize the first motor for locating the X-axes motor into a negative direction
Private Sub SSCommand2_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#1j-")
End Sub
Private Sub SSCommand2_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#1j/")
End Sub

'Initialize the first motor for locating the X-axes motor into a positive direction
Private Sub SSCommand3_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#1j+")
End Sub
Private Sub SSCommand3_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#1j/")
End Sub

'Initialize the third motor for locating the Z-axes motor into a negative direction
Private Sub SSCommand4_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#3j-")
End Sub
Private Sub SSCommand4_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#3j/")
End Sub
```

```
'Initialize the third motor for locating the Z-axes motor into a positive direction
Private Sub SSCommand5_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#3j+") 'modified from "#3j-" to "#3j+" on
6/30/98 by HK
End Sub
Private Sub SSCommand5_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#3j/")
End Sub

'Initialize the second motor for locating the Y-axes motor into a positive direction
Private Sub SSCommand6_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#2j+")
End Sub
Private Sub SSCommand6_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#2j/")
End Sub

'Initialize the home position setting
Private Sub SSCommand7_Click()
Dim status As Integer
Dim response As String
status = mainfrm.PTalk1.GetResponse(response, "#1 j/ hmz")
status = mainfrm.PTalk1.GetResponse(response, "#2 j/ hmz")
status = mainfrm.PTalk1.GetResponse(response, "#3 j/ hmz")
status = mainfrm.PTalk1.GetResponse(response, "#4 j/ hmz")
status = mainfrm.PTalk1.GetResponse(response, "#7 j/ hmz")
status = mainfrm.PTalk1.GetResponse(response, "#8 j/ hmz")
End Sub
```

```
'Initialize the seventh motor for pivoting the movable trowel into a positive angle
Private Sub SSCommand8_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#7j+")
End Sub
Private Sub SSCommand8_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#7j/")
End Sub

'Initialize the seventh motor for pivoting the movable trowel into a negative angle
Private Sub SSCommand9_MouseDown(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#7j-")
End Sub
Private Sub SSCommand9_MouseUp(Button As Integer, Shift As Integer, x As
Single, y As Single)
Dim status As Integer
Dim response As String * 250
status = PTalk1.GetResponse(response, "#7j/")
End Sub

'Initialize the stop button for stopping the CNC program and all functioned motors
Private Sub Stop_Click()
Dim status As Long
Dim response As String
counter = 0
status = PTalk1.GetControlResponse(response, 11)
FirstMake.Enabled = True
Roof.Enabled = True
SecondMake.Enabled = True
'timer1.Enabled = False
'timer2.Enabled = False
SSCommand1.Enabled = True
SSCommand2.Enabled = True
SSCommand3.Enabled = True
SSCommand4.Enabled = True
```

```
SSCommand5.Enabled = True
SSCommand6.Enabled = True
SSCommand7.Enabled = True
SSCommand8.Enabled = True
SSCommand9.Enabled = True
SSCommand13.Enabled = True
SSCommand15.Enabled = True
Slider1.Enabled = True
End Sub

'Control the linear speed of base
Private Sub Text1_Change()
lsb = Val(Text1.Text)
End Sub

'Control the angle of the side trowel
Private Sub Text15_Change()
stangle = Val(Text15.Text)
End Sub

'Control the linear speed of body
Private Sub Text2_Change()
lsbo = Val(Text2.Text)
End Sub

'Control the number of base layer
Private Sub Text3_Change()
nlb = Val(Text3.Text)
End Sub

'Control the number of body layer
Private Sub Text4_Change()
nlbo = Val(Text4.Text)
End Sub

'Control the number of total base layer
Private Sub Text5_Change()
ltb = Val(Text5.Text)
End Sub

'Control the number of total body layer
Private Sub Text6_Change()
ltbo = Val(Text6.Text)
End Sub
```

```
'Control the feed rate of base
Private Sub Text7_Change()
frb = Val(Text7.Text)
End Sub

'Control the feed rate of body
Private Sub Text8_Change()
frbo = Val(Text8.Text)
End Sub

'Control the size of parts
Private Sub Text9_Change()
orgn = Val(Text9.Text)
End Sub

'Initialize sub routine for calling timer for PMAC
Private Sub timer1_Timer()
Static response As String
Static return_value As Long

'Modified from "RX0" to "M0" to initialize Ptalk1
return_value = PTalk1.GetResponse(response, "M0")
Text11.Text = response
status = PTalk1.GetControlResponse(response, 16)
Text13.Text = response
status = PTalk1.GetResponse(response, "I822")
Text10.Text = "Linear Speed per Radius " + response
status = PTalk1.GetResponse(response, "I422")
Text12.Text = response
status = PTalk1.GetResponse(response, "I322")
Text14.Text = response
status = PTalk1.GetResponse(response, "I722")
Text16.Text = response
End Sub
```

Appendix 8: Description of the motion control program

CNC motion control program for the cylindrical shapes was developed to experiment the capabilities of CC process. The several versions of CNC program for the cylindrical shapes are located in C:\pewin1\pewin\HK\Cylinder. The several 3D shapes (cone, pyramid, dome, etc) of CNC program also are located in C:\pewin1\pewin\HK. To build various geometrical parts, each motor follows certain tool path that is programmed with the customized G and M code located in C:\pewin1\Gmcode.pmc. The detail G and M codes are well described in PMAC manual.

8.1 Motion control program for fabricating the cylindrical parts

```
Close ;close all the
  del gat
 undefine all
  &1
   #1->394x         ;counts per mm(10k counts per inch)
   #2->394y        ;counts per mm(10k counts per inch)
   #3->1969z        ;counts per mm(50k counts per inch)
   #7->508.4u       ;counts per angle(2k counts per revolution)
   #8->55.5556c   ;counts per degree(5k counts per revolution)
  &2
   #4->736b         ;counts per mm(18.7k counts per inch)

   p1=1              ;# of base layers
  p2=0              ;Decide whether to make the base or body, p2=0 makes the base
  p3=90             ;Angle for each corner(degree)
  p4=10             ;# of body layers
  p5=2.3            ;Linear speed of base(mm/sec)
  p6=4              ;Linear speed of body(mm/sec)
  p7=0              ;Layer thickness of base(mm)
  p8=2.5            ;Layer thickness of body(mm)
```

```
p9=0.05          ;Feed rate of base(mm/sec)
p10=0.036        ;Feed rate of body(mm/sec)
p11=90           ;Angle of the side trowel (degree)
p12=(p1+p4)      ;# of total layers
p13=20           ;Origin of the square (mm)
p14=5            ;The length of the side trowel (mm)
p15=1            ;The pause time for starting each layer for the base (sec).
p16=1            ;The pause time for starting each layer for the body (sec)
p30=12           ;Speed of the trowel rotation motor (RPM)

//define user variable with P-vabriable//
#define NLB     p1
#define Degree  p3
#define NLBO    p4
#define LISB    p5
#define LISBO   p6
#define LTB     p7
#define LTBO    p8
#define FRB     p9
#define FRBO    p10
#define STA     p11
#define TLC     p12
#define Orgn    p13
#define LST     p14
#define PTB     p15
#define PTBO    p16
#define RPM     P30

open prog10
clear
 I122=10
 I222=10
 I722=10
 g00 g90 x(Orgn) z(LTB)  ;Move to the starting point of the wall
 g00 g90 u(STA)          ;Move to the side trowel with rapid, absolute mode
 close

open prog15
clear
if (p2=0)                ;Check whether the base for the cylinder is needed or not
  p21=0                  ;Initialize an incremental variable
  while(p21<NLB)         ;Make the base of a cylinder
  g17
  g94
```

```
    I122=(394*LISB)/1000      ;Define the X-axis linear speed for the base (cts/msec)
    I222=(394*LISB)/1000      ;Define the Y-axis linear speed for the base (cts/msec)
    I322=(1969*LTBO)/1000  ;Define the Z-axis speed for the base(cts/msec)
    I422=(736*FRB)/1000       ;Define the extrusion speed for the base(cts/msec)
    I822=(5000*RPM)/60000  ;Define RPM of the rotation motor (#8)(cts/msec)
    m03                              ;Spline the extrusion motor (#4)
    g04 p(PTB)                    ;Pause the extrusion motor until the clay being extruded
    f(60*LISB)
    g03 X(-Orgn) C(180) I(-Orgn)
    g03 X(Orgn)  C(360) I(Orgn)
    g00 g90
    m05
    I322=(1969*(LTBO/0.2))/1000
    g00 g91 Z(LTBO)
   P21=p21+1                    ;Increment p21
   Endwhile
  p2=p2+1                       ;Increment p2 to make the body of a cylinder
Endif

 if (p2=1)                        ;Check whether the base for the cylinder is needed or not
    p21=0                         ;Initialize an incremental variable
    while(p21<NLBO)         ;Make the body of a cylinder
    g17
    g94
    I122=(394*LISBO)/1000    ;Define the X-axis linear speed of the body (cts/msec)
    I222=(394*LISBO)/1000    ;Define the Y-axis linear speed of the body (cts/msec)
    I322=(1969*LTBO)/1000   ;Define the Z-axis speed of the body (cts/msec)
    I422=(736*FRBO)/1000    ;Define the extrusion speed of the body (cts/msec)
    I822=(5000*RPM)/60000   ;Define RPM of the rotation motor (cts/msec)
    g00 g90                          ;Change the mode into rapid, absolute way
    m03                               ;Spline the extrusion motor (#4)
    f(60*LISBO)
    g03 X(-Orgn) C((2*(p21+1)*180)+180) I(-Orgn)
    g03 X(Orgn)  C((2*(p21+1)*180)+360) I(Orgn)
    g00 g90
    m05
    I322=(1969*(LTBO/0.2))/1000
    g00 g91 Z(LTBO)            ;Move up to the lay thickness
   P21=p21+1                      ;Increment p21
  Endwhile
  Endif
 g00 g91 Z(10)
close
```

8.2 Motion control program for fabricating the conical parts

```
 open prog24
 clear
 if (p2=0)                    ;Check whether the base for the cylinder is needed or not
   p21=0                      ;Initialize an incremental variable
   while(p21<NLB)             ;Make the base of a cone
   g17
   g94
   I122=(394*LISB)/1000      ;Define the X-axis linear speed for the base (cts/msec)
   I222=(394*LISB)/1000      ;Define the Y-axis linear speed for the base (cts/msec)
   I322=(1969*LTBO)/1000  ;Define the Z-axis speed for the base(cts/msec)
   I422=(736*FRB)/1000       ;Define the extrusion speed for the base(cts/msec)
   I822=(5000*RPM)/60000  ;Define RPM of the rotation motor (#8) (cts/msec)
   m03                        ;Spline the extrusion motor (#4)
   g04 p(PTB)                 ;Pause the extrusion motor until the clay being extruded
   f(60*LISB)
   g03 X(-Orgn) C(180) I(-Orgn)
   g03 X(Orgn)  C(360) I(Orgn)
   g00 g90
   m05
   I322=(1969*(LTBO/0.2))/1000 ;Change the Z-axis speed for taking 0.2(sec/layer)
   I722=10                     ;Define the speed of the side trowel motor (cts/msec)
   Orgn = Orgn-Delta           ;Calculate a new radius
   Q0=LTBO          ;Save the layer thickness in Q0 for calculating the trowel angle
   Q1=Delta         ;Save the offset in Q1 variable for calculating the trowel angle
   STA=ATAN2(Q1)              ;Calculate the angle of the side trowel
   g00 g91 Z(LTBO)            ;Move up to the lay thickness
   g00 g90 X(Orgn) U(STA)    ;Move up to a new radius and a trowel angle together
  P21=p21+1                   ;Increment p21
  Endwhile
 p2=p2+1                      ;Increment p2 to make the body of a cylinder
Endif

if (p2=1)                     ;Check whether the base for the cylinder is needed or not
   p21=0                      ;Initialize an incremental variable
   while(p21<NLBO)            ;Make the body of a cone
   g17
   g94
   I122=(394*LISB)/1000      ;Define the X-axis linear speed for the base (cts/msec)
   I222=(394*LISB)/1000      ;Define the Y-axis linear speed for the base (cts/msec)
   I322=(1969*LTBO)/1000  ;Define the Z-axis speed for the base(cts/msec)
   I422=(736*FRB)/1000       ;Define the extrusion speed for the base(cts/msec)
   I822=(5000*RPM)/60000  ;Define RPM of the rotation motor (#8) (cts/msec)
```

```
  g00 g90
   m03                              ;Spline the extrusion motor (#4)
   g04 p(PTBO)
   f(60*LISBO)
   g03 X(-Orgn) C((2*(p21+1)*180)+180) I(-Orgn)
   g03 X(Orgn)  C((2*(p21+1)*180)+360) I(Orgn)
   g00 g90
   m05
   I322=(1969*(LTBO/0.2))/1000 ;Change the Z-axis speed for taking 0.2(sec/layer)
   Orgn = Orgn-Delta          ;Calculate a new radius
   g00 g91 Z(LTBO)            ;Move up to the lay thickness
   g00 g90 X(Orgn)            ;Move up to a new radius
  P21=p21+1                   ;Increment p21
 Endwhile
Endif
g00 g91 Z(10)
close
```

Appendix 9: Description of the program coding for CFD simulation

9.1 Orifice shape simulation

9.1.1 Case for an elliptical orifice simulation

```
// Pre processing

/* 3D Flow from an elliptical orifice during the CC process is demonstrated. */

reset

// *** Mesh generation ****************************
// Block 1: nozzle
cgroup 1
mcreate 0 4.66 6 5.67 10.33 6 6 15 3
cp

//Block 2: nozzle (oval 1)
cgroup 2
csys 0
local, 2, cyli,2.33,10.33,6
mcrea 0 2.33 3 0 180 8 0 9 3
view 1 2 3
cp

//Block 3: nozzle (oval 2)
cgroup 3
csys 0
local, 2, cyli,2.33,5.67,6
mcrea 0 2.33 3 180 360 8 0 9 3
cp
vmerge all 0.05
save 1
resume 1

// Block 4: Flow domain between the bottom layer and the top trowel
csys 0
cset none
cgroup 4
```

```
mcreate 0 5.5 7 3.34 12.66 12 3 6 5
view 1 2 3
cp

// Block 5: Flow domain between the bottom layer and the top free surface (front)
cgroup 5
mcreate 0 5.5 7 12.66 13.2 1 3 6 5
cp

//Block 6:Flow domain between the bottom layer and the top free surface (back)
cgroup 6
mcreate 0 5.5 7 0.5 3.34 3 3 6 5
cp
vmerge cset 0.001
save 2
resume 2

cset all
view 1 -2 3
cp

 //Coupling using arbitrary mesh interface
esfind 2 4 0.1 180 1 1
esfind 3 4 0.1 180 1 1
cset none
cset eset
cp

essurf on
cp
view 1 -2 3
cp
save 3

resume 3

cset none
cset cglist 1 2 3
view 1
plty hsur
cp
bview 1         // boundary for the wall
```

```
view -1
cp
bview 1         // boundary for the wall

view 0 1
cp
bview 1 90    // boundary for the wall

view 0 0 1
cp
bview 2        // boundary for the inlet

view 0 -1
cp
bview 1 90     // boundary for the wall

cset none
cset cglist 4 5 6
view 1 -2 3
cp

view -1
cp
bview 1        // boundary for the wall

view 1
cp
bview 4        // boundary for the free surface

view 0 0 1
cp
bview 1         // boundary for the wall

view 0 0 -1
cp
bview 5        // boundary for the moving surface

view 0 -1
cp
bview 3        // boundary for outlet

view 0 1
cp
bview 4          // boundary for free surface
```

```
save 4

resume 4
cset all
view 1 2 3
vup 0 0 1
cp

// *** Material properties and initial conditions ***
density const 24
visc const 15

// *** Cell and boundary group definitions ********
bgdef 1 wall constant 2
0 0 0 0
bgdef 2 inlet constant 6
0 0 0 -1.206 24
bgdef 3 pres
0 0 0
bgdef 4 wall constant 15
0 0 0 0
bgdef 5 wall cons 1
0 0 -0.6 0

// *** Solution control ******************************
iter 200 10 1
conv 0.001
// *** Writing data for the solution stage **********
vmerge all 0.1
cset all
cp
wmesh
wdef

// *** Save the modeling status ******************
cset all
view -1 3 2
vup 0 0 1
save
view -1 3 2
vup 0 0 1
plty wire
bp
```

9.1.2 Case for a square orifice simulation

```
// Pre processing

/* 3D Flow from a square orifice during the CC process is demonstrated. */

reset

local, 3, CART, 1,1,1, -90

// *** Mesh generation ****************************
// Block 1: nozzle
cgroup, 1
mcreate 0 5.5 7 4.5 10 8 6 15 4
view  0 1
plty hsur
vnumbers off
cp
bview 2            // boundary for the inlet
view 1
plty hsurf
cp
bview 1           // boundary for the wall

view -1
plty hsurf
cp
bview 1

view 0 0 1
plty hsurf
cp
bview 1

view 0 0 -1
plty hsurf
cp
bview 1

cset all
plty hsurf
view 1 2 3
cp
```

```
// Block 2: Flow domain between the bottom layer and the top trowel
cset none
cgroup, 2
mcreate 0 6.3 8 4.5 10 8 3 6 5
view -1
plty hsurface
cp
bview 1          // boundary for the wall

view 1
plty hsur
cp
bview 4          //boundary for the free surface

view 0 1
plty hsur
vnum off
cp
bview 4

view 0 -1
plty hsurface
cp
bview 5            //boundary for the moving surface

cset all
view 1 2 3
plty surf
cp

// Block 3: Flow domain between the bottom layer and the top trowel
cset none
cgroup, 3
mcreate 0 6.3 8 10 11.4 2 3 6 5
view -1
plty hsurface
cp
bview 4            // boundary for the  free surface
view 1
plty hsurface
cp
bview 4
```

```
view 0 1
plty hsurface
cp
bview 4
view 0 -1
plty hsurface
cp
bview 5            //boundary for the moving surface
view 0 0 -1
plty hsurface
cp
bview 4           //boundary for the free surface
cset all
view 1 2 3
plty hsurface
cp
//Block 4: Flow domain between the bottom layer and the top trowel
cset none
cgroup, 4
mcreate 0 6.3 8 0 4.5 7 3 6 5
view -1
plty hsurface
cp
bview 4
view 1
plty hsurface
cp
bview 4          //boundary for the free surface
view 0 1
plty hsurface
cp
bview 4
view 0 -1
plty hsurface
cp
bview 5           //boundary for the moving surface
view 0 0 1
plty hsurface
cp
bview 3          //boundary for the outlet
cset all
```

```
view 1 2 3
plty hsurface
cp

// *** Material properties and initial conditions ***
density constant 24
visc constant 15

// *** Cell and boundary group definitions ********
bgdef 1 wall constant 2
0 0 0 0
bgdef 2 inlet constant 6
0 0 -1.206 0 24
bgdef 3 pres const
0 0 0
bgdef 4 wall constant 15
0 0 0 0
bgdef 5 wall constant 1
0 2 0 1

// *** Solution control ******************************
iter 200 10 1
conv 0.001

// *** Writing data for the solution stage **********
cset all
vcdistance all
vmerge all 0.2
view 1 2 3
cp
vcompress all
ccompress all
wmesh
wdef

// *** Save the modelling status ******************
view 1 2 3
cset all
save
view 1 2 3
plty wire
bp
```

9.2 Simulation for the angle of the movable side trowel

9.2.1 Case for an exterior angle

```
// Pre processing

/*3D Flow of the CC process is demonstrated at the condition of an exterior angle. */

reset

local, 3, CART, 1,1,1, -90

// *** Mesh generation ****************************
// Block 1: Nozzle
cgroup, 1
mcreate 3 8.5 8 6 11.5 8 6 21 5
view  1
plty hsurface
cp
bview 1            //boundary of the wall

view  -1
plty hsurface
cp
bview 1

view 0 1
plty hsur
cp
bview 2           //boundary of the inlet

view 0 0 1
plty hsur
cp
bview 1

view 0 0 -1
plty hsur
cp
bview 1
cset all
view 1 2 3
cp
```

```
// Block 2: Flow domain between the bottom layer and the top trowel
cset none
#def vmx vmax
v vmx + 1 2.31 14.25 3
v vmx + 2 10 14.25 3
v vmx + 3 8.5 14.25 6
v vmx + 4 2.31 14.25 6
vcop 2 4 vran vmx + 1 vmax 1 0 -2.75 0
cgro 2
c vmx + 1 vmx + 2 vmx + 3 vmx + 4 vmx + 5 vmx + 6 vmx + 7 vmx + 8
cset cgro 2
cref 9 5 4 cset

view -1
plty hsur
cp
bview 4          //boundary of the free surface

view 1
plty hsur
cp
bview 4 45       //boundary of the free surface with an angle

view 0 -1
plty hsur
cp
bview 5         //boundary of the moving surface

view 0 1
plty hsur
cp
bview 4



view 0 0 -1
plty hsur
cp
bview 3         //boundary of the outlet
cset all
view 1 2 3
cp
```

```
// Block 3: Flow domain between the bottom layer and the top trowel
cset none
#def vmx vmax
v vmx + 1 2.31 11.5 3
v vmx + 2 10 11.5 3
v vmx + 3 8.5 11.5 6
v vmx + 4 2.31 11.5 6
vcop 2 4 vran vmx + 1 vmax 1 0 -5.5 0
cgro 3
c vmx + 1 vmx + 2 vmx + 3 vmx + 4 vmx + 5 vmx + 6 vmx + 7 vmx + 8
cset cgro 3
cref 9 5 8 cset

view -1
plty hsur
cp
bview 4          //boundary of the free surface

view 1
plty hsur
cp
bview 1 45       //boundary of the wall (side trowel) with an angle

view 0 -1
plty hsur
cp
bview 5          //boundary of the moving surface

view 0 1
plty hsur
cp
bview 4

cset all
view 1 2 3
cp
// Block 4: Flow domain between the bottom layer and the top trowel
cset none
#def vmx vmax
v vmx + 1 2.31 6 3
v vmx + 2 10 6 3
v vmx + 3 8.5 6 6
v vmx + 4 2.31 6 6
vcop 2 4 vran vmx + 1 vmax 1 0 -1.375 0
```

```
cgro 4
c vmx + 1 vmx + 2 vmx + 3 vmx + 4 vmx + 5 vmx + 6 vmx + 7 vmx + 8
cset cgro 4
cref 9 5 2 cset

view -1
plty hsur
cp
bview 4           //boundary of the free surface

view 1
plty hsur
cp
bview 4 45        //boundary of the free surface with an angle

view 0 -1
plty hsur
cp
bview 5           //boundary of the moving surface

view 0 1
plty hsur
cp
bview 4

view 0 0 1
plty hsur
cp
bview 4
cset all
view 1 2 3
cp


// *** Material properties and initial conditions ***
density const 24
visc const 15

// *** Cell and boundary group definitions ********
bgdef 1 wall constant 2
0 0 0 0

bgdef 2 inlet constant 6
0 0 -2.112 0 24
```

```
bgdef 3 pres constant 10
0 0 0

bgdef 4 wall constant 15
0 0 0 0

bgdef 5 wall cons 1
0 4 0 -0.25

// *** Solution control *******************************
iter 200 10
conv 0.001
// *** Writing data for the solution stage **********
cset all
vcdistance all
vmerge all 0.1
view 1 2 3
cp
vcompress all
ccompress all
wmesh
wdef

// *** Save the modelling status ******************
view 1 2 3
cset all
save

view 0.5 0.5 3
plty wire
bp
```

9.2.2 Case for an interior angle

```
// Pre processing

/*3D Flow of the CC process is demonstrated at the condition of an interior angle. */

reset

local, 3, CART, 1,1,1, -90

// *** Mesh generation ****************************
// Block 1: Nozzle
cgroup, 1
mcreate 3 8.5 8 6 11.5 8 6 21 5
view  1
plty hsurface
cp
bview 1          // boundary of the wall

view  -1
plty hsurface
cp
bview 1

view 0 1
plty hsur
cp
bview 2         //boundary of the inlet

view 0 0 1
plty hsur
cp
bview 1

view 0 0 -1
plty hsur
cp
bview 1
cset all
view 1 2 3
cp
```

```
// Block 2: Flow domain between the bottom layer and the top trowel
cset none
#def vmx vmax
v vmx + 1 2.31 14.25 3
v vmx + 2 7 14.25 3
v vmx + 3 8.5 14.25 6
v vmx + 4 2.31 14.25 6
vcop 2 4 vran vmx + 1 vmax 1 0 -2.75 0
cgro 2
c vmx + 1 vmx + 2 vmx + 3 vmx + 4 vmx + 5 vmx + 6 vmx + 7 vmx + 8
cset cgro 2
cref 9 5 4 cset

view -1
plty hsur
cp
bview 4         //boundary of the free surface

view 1
plty hsur
cp
bview 4 45      //boundary of the free surface with an angle

view 0 -1
plty hsur
cp
bview 5         //boundary of the moving surface

view 0 1
plty hsur
cp
bview 4

view 0 0 -1
plty hsur
cp
bview 3         //boundary of the outlet
cset all
view 1 2 3
cp
```

```
// Block 3: Flow domain between the bottom layer and the top trowel
cset none
#def vmx vmax
v vmx + 1 2.31 11.5 3
v vmx + 2 7 11.5 3
v vmx + 3 8.5 11.5 6
v vmx + 4 2.31 11.5 6
vcop 2 4 vran vmx + 1 vmax 1 0 -5.5 0
cgro 3
c vmx + 1 vmx + 2 vmx + 3 vmx + 4 vmx + 5 vmx + 6 vmx + 7 vmx + 8
cset cgro 3
cref 9 5 8 cset

view 1
plty hsur
cp
bview 1 45      //boundary of the wall (side trowel) with an angle

view -1
plty hsur
cp
bview 4         //boundary of the free surface

view 0 -1
plty hsur
cp
bview 5         //boundary of the moving surface

view 0 1
plty hsur
cp
bview 4
cset all
view 1 2 3
cp

// Block 4: Flow domain between the bottom layer and the top trowel
cset none
#def vmx vmax
v vmx + 1 2.31 6 3
v vmx + 2 7 6 3
v vmx + 3 8.5 6 6
v vmx + 4 2.31 6 6
vcop 2 4 vran vmx + 1 vmax 1 0 -1.375 0
```

```
cgro 4
c vmx + 1 vmx + 2 vmx + 3 vmx + 4 vmx + 5 vmx + 6 vmx + 7 vmx + 8
cset cgro 4
cref 9 5 2 cset

view -1
plty hsur
cp
bview 4          //boundary of the free surface

view 1
plty hsur
cp
bview 4 45     //boundary of the free surface with an angle

view 0 -1
plty hsur
cp
bview 5         //boundary of the moving surface

view 0 1
plty hsur
cp
bview 4

view 0 0 1
plty hsur
cp
bview 4

cset all
view 1 2 3
cp

// *** Material properties and initial conditions ***
density const 24
visc const 15

// *** Cell and boundary group definitions ********
bgdef 1 wall constant 2
0 0 0 0

bgdef 2 inlet constant 6
0 0 -1.471 0 24
```

```
bgdef 3 pres constant 10
0 0 0

bgdef 4 wall constant 15
0 0 0 0

bgdef 5 wall cons 1
0 4 0 1

// *** Solution control ******************************
iter 200 10 1
conv 0.001

// *** Writing data for the solution stage **********
cset all
vcdistance all
vmerge all 0.2
view 1 2 3
cp
vcompress all
ccompress all
wmesh
wdef

// *** Save the modelling status ******************
view 1 2 3
cset all
save

view 0.5 0.5 3
plty wire
bp
```

10.2.2 Program cording for the post processing of the simulations

```
// Post processing
resume

// *** Read the results
rresults


// *** Show cell geometry
plme off
view 1 2 3
edge on
cp

// Contour plots of the velocity
plty hsurf
plop cont
vload m
cp

// Contour plots on plan from an inside
view 1 0 0
plty plan
plop cont
pnorm 1 0 0
ppoi 5 0 0
cp

// Contour plots of the pressure
view 1 2 3
plty hsurf
plop cont
vload p
cp

// Contour plots on plan from an inside
view 1 0 0
plty plan
plop cont
pnorm 1 0 0
ppoi 5 0 0
cp
```

```
// Vector plot on plane
view 1 1 3
plty hwir
plop vect
pnorm 1 0 0
ppoi 5 0 0
plop vect
cload m
cp

plmesh off
cset all
view 1 0 0
plty plan
pnorm 1 0 0
ppoi 5 0 0
edge on
plmesh off
cset all
plmesh off
plop vect

// Particle tracking for a array
view 2 1 -2
p 1 6 6.21 20.8 0 10 0 0.5 50 25 1
pcopy 14 1 pran 1 1 1 0 0.4 0 0 0 0 0.00511
plocate all n
// Switch the drag and body forces off to get the effect of massless particles.
pmome off unco stan

pcol 14 veloc
edge on
plty norm
plop geom
pptra 2 0.1
pplot tracks cont

pptra 4 0.1
pplot tracks cont

pptra 7 0.1
pplot tracks cont
```

```
pptra 9 0.1
pplot tracks cont

pptra 14 0.1
pplot tracks cont

pptra 18 0.1
pplot tracks cont

pptra 22 0.1
pplot tracks cont

// Particle tracking for the matrix format
view -0.1 0.1 3
p 1 3.5 6.21 20.8 0 10 0 0.5 50 25 1
p 2 4.5 6.21 20.8 0 10 0 0.5 50 25 1
p 3 5.5 6.21 20.8 0 10 0 0.5 50 25 1
p 4 6.5 6.21 20.8 0 10 0 0.5 50 25 1
p 5 7.5 6.21 20.8 0 10 0 0.5 50 25 1
p 6 8 6.21 20.8 0 10 0 0.5 50 25 1
pcopy 6 6 pran 1 6 1 0 1.0 0 0 0 0 0.00511
plocate all n
// Switch the drag and body forces off to get the effect of massless particles.
pmome off unco stan

pcol 14 veloc
edge on
plty norm
plop geom
pptra 2 0.1
pplot tracks cont

pptra 4 0.1
pplot tracks cont

pptra 7 0.1
pplot tracks cont

pptra 9 0.1
pplot tracks cont

pptra 12 0.1
pplot tracks cont
```

```
pptra 18 0.1
pplot tracks cont

pptra 22 0.1
pplot tracks cont

pptra 26 0.1
pplot tracks cont

pptra 30 0.1
pplot tracks cont
```