FEA(Finite Element Analysis)를 이용한 CC(Contour Crafting)의 노즐모양에 대한 연구

-Effect of Orifice Shape in Contour Crafting using Finite-Element Analysis : A Study of Extrusion and Deposition Mechanisms-

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Abstract

본 논문은 Contour Crafting (CC) 프로세스의 압출과 적층 단계에서 물질 흐름의 형태를 연구하기 위한 실험과 모델링을 보여준다. 특히, 실험재료로써 진흙을 이용한 압출과 적층 메커니즘을 이해하기 위하여 기초적인 유한성분분석 (FEA)을 실행하였다. FEA 시뮬레이션을 이용한, CC의 성능에 있어서 압출구멍의 기하학적인 효과에 대한 분명하고 기본적인 이해를 하게 되었다. 네모난 형상이 원하는 외부 표면특성을 만드는 것뿐만 아니라, 그리고 층간에 최적의 융합을 수행하는데 있어서 가장 적합하다는 것을 알아냈다. 우리의 실험은 이 결과들을 증명한다.

1. Introduction

Contour Crafting (CC) is an additive fabrication process developed at the University of Southern California (Khoshnevis, 1998). It uses computer control to exploit the superior surface-forming capability of a trowel to create smooth and accurate planar and free form surfaces. The object is created layer by layer and

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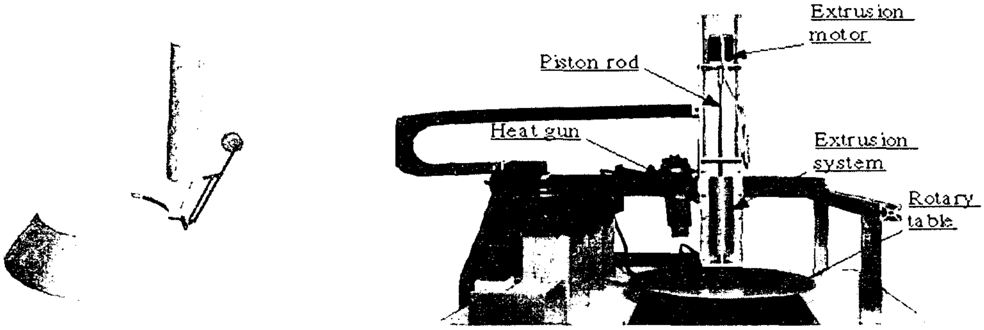


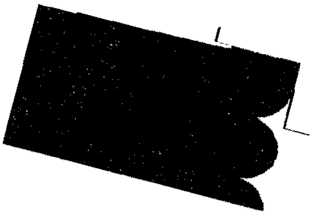
<Figure 1> (a) the extrusion assembly with top and side trowels (b) Contour Crafting machine used for the experiments

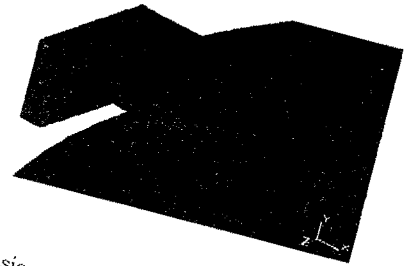
with the manipulation of various trowel tools, complex surface shapes can be created. The distinguishing feature of the CC process is the ability to rapidly produce parts with superior surface finish, at a rapid speed, and using a variety of materials (thermoplastic materials, uncured ceramic slurries, etc.)

As shown in <Figure 1(a)>, the basic CC process consists of an extrusion orifice, and two perpendicular solid planar surfaces formed by a top trowel and a side trowel. The side trowel smoothes out and shapes the external surface of a CC-fabricated part in order to achieve desirable geometric profile and surface finish. The length of the side trowel may extend beyond the thickness of an individual layer of the fabricated part and slightly overlap with the previous layer. The extended side trowel provides a fixed boundary condition for sideward material flow and facilitates better fusion of layers, that in turn leads to better geometric profile and surface characteristics. The machine used for this study is a preliminary version. It consists of a rotary table with a vertical extrusion head that can be moved along 3 linear axes, as shown in <Figure 1(b)>. The two mechanisms of extrusion and deposition comprise the CC process.

1.1 Extrusion

The material in CC is extruded through a ram extrusion mechanism. The material is pushed vertically down through an orifice into a space between the top and side trowel, and a bottom layer. The top trowel is perpendicular to the extrudate flow and the distance between it and the bottom layer determine the layer's thickness. The side trowel is parallel to the extrusion flow and controls the shape of the outer surface of the layer. With this orientation, we can achieve 2.5D control of the layer shape.





<Figure 2> Graphical schematic of CC process where the compression and flow of extrudate subsequent to deposition are neglected

1.2 Deposition

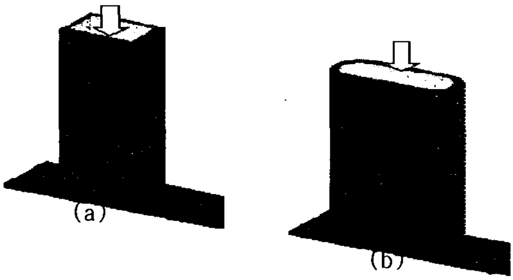
Depending on the material properties, the initial shape of the extrudate without regarding orifice-swell is almost the same as the dimensions of the orifice. However, after exiting the orifice the extrudate is forced round a sharp 90° corner. This creates elasto-plastic stresses in the deposited layer, deforming its cross-section. However, if we ignore the plastic deformation of the extrudate, the resulting part's surface profile will be totally determined by the orifice shape, as shown in <Figure 2>.

A close examination of parts[1]) from CC 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 shape is necessary in order to:

- Facilitate seamless layering, and in addition,
- Arrive at the optimum pressure that not only would achieve the desired external surface profile, but also will create adequate fusion between the layers.

Specifically, we considered the effects of the following two types of orifice shapes shown in <Figure 3>: (a) square, and (b) elliptical, respectively. A reasonable understanding of flow characteristics during extrusion and deposition is necessary for the determination of appropriate geometric characteristics of orifice. We undertook simple process modeling described in Section 2 for understanding process flow characteristics.

Parts made using on oval orifice shape



<Figure 3> Orifice shape designs used in experiments

2. Material characteristics

Here, we studied CC with specific reference to cylindrical geometries from clay. The composition of the material is shown in <Tables 1 and 2>.

The components of the clay exhibit highly plastic properties with very high shear rates. The deflocculants[1] render the clay to be almost Bingham [5]. The Bingham properties of the clay body give it an internal structure that collapses above a yield stress and above which rheological behavior is linear. This linear behavior allows us to model the flow domain as a Newtonian fluid.

Further examination of the clay properties revealed that the clay did not swell upon exiting the orifice, probably due to its readiness to shear and virtual absence of an elastic phase. Thus super-plasticity is demonstrated as shown in Figure 4.

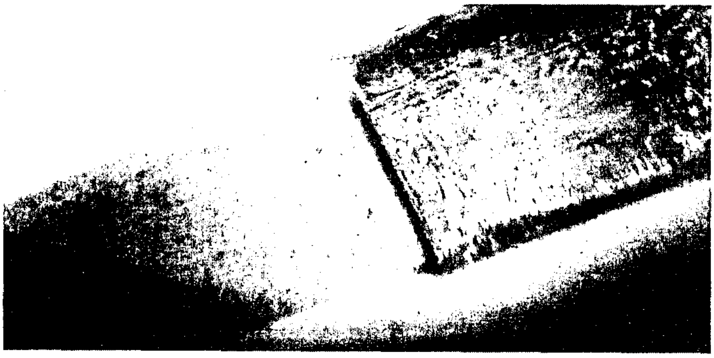
<Table 1> Clay

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

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 at minimum viscosity

<Table 2> 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%



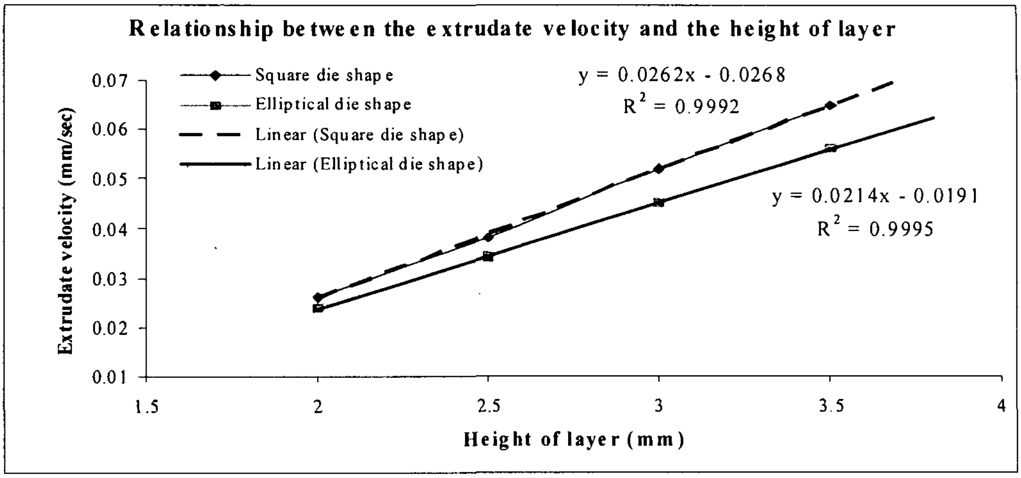
<Figure 4> Extrudate exhibiting no orifice swell

2.1 Governing relationships

2.1.1 Process parameters

The process parameters were the extrusion rate or ram velocity (Ve) [mm/s], the linear speed (Vr) [mm/s], the layer thickness or height of layer (h) [mm], the vertical feeder rate at which the extrusion head moves vertically (Vf) [mm/rev], set length of the square part to be fabricated (r) [mm], and the number of layers (n). The quality variables considered were the diameter of the model (d) [mm], and the surface roughness (Sr).

<Figure 5> shows that the extrudate velocity is directly proportional to the layer thickness, an important factor in our analysis of the clay flow. With change in orifice shape, the velocity characteristics also change. Thus any change in the ram velocity and the orifice shape affects the velocity of the extrudate, and consequently the pressure forming the layer. These observations lead us to the relationships stated in the following subsection.



<Figure 5> Linear relationship between the height of layer and the extrudate velocity by achieving the same surface quality virtually with the same linear speed (4 mm/sec)

2.1.2 Relationship between the process control parameters

The following equations provide the gross relationships between average velocities pressures and surface quality. The basic velocity is given by

$$V_e^2 + V_r^2 = V_R^2 \quad \text{.............................(1)}$$

Where V_e is the extrudate velocity, V_r is the linear velocity, and V_R is the resultant velocity. The extrudate velocity is not known directly. It is a measure of the ram velocity with a constant factor depending upon the orifice shape, as determined from the graph of V v/s V_r, where V is the ram extrusion velocity.

In our examination of the paste flow from a cylindrical barrel into a cylindrical die land we identified the following:

(a) P1: a pressure differential needed to cause the paste in the barrel to flow into the die land,

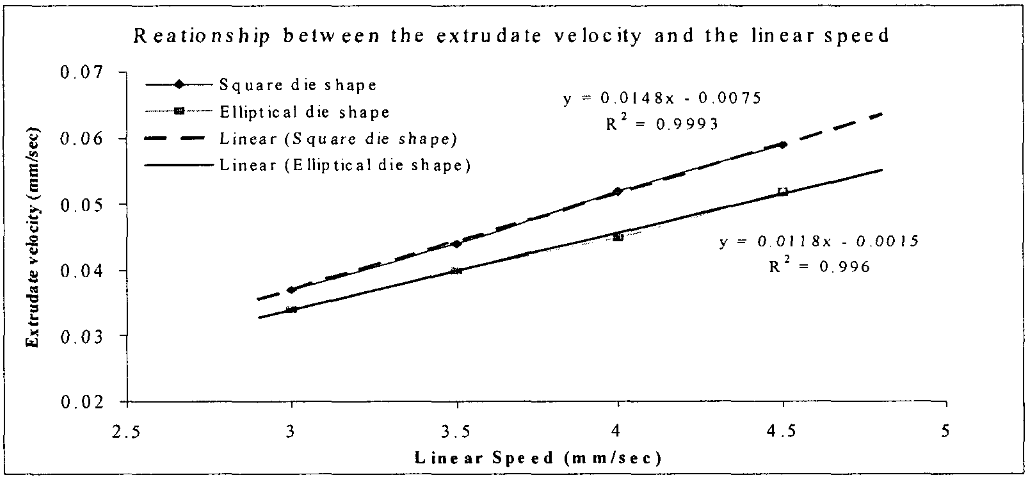
(b) P2: a pressure differential required to permit the paste to overcome the shear stress at the wall of the die land.

$$P = f(P_1 \leftrightarrow [\sigma_0 + \alpha V_2],\ P_2 \leftrightarrow [\tau_0 + \beta V_e]) \quad \text{......................................(2)}$$

Where σ is a uniaxial yield stress extrapolated to zero velocity, α is a factor characterizing the effect of velocity (thus $\sigma_0 + \alpha V$ can be regarded as the bulk yield stress corrected for shear rate), and τ_0 and β are parameters characterizing the paste. 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.

The .determination of the resultant (V_R) helps us to understand the direction in which the pressure acts on the underlying layer as also to determine the flow of the clay on exiting the orifice.

During experimentation, to maintain the same surface quality with varying layer thickness, it has been noted that if the linear velocity is kept constant, the extrusion rate is directly proportional to the layer thickness in <Figure 5>.



<Figure 6> Linear relationship between the linear speed and the extrudate velocity by achieving the same surface quality virtually with the same layer height (3 mm)

Similarly, if the layer thickness (h) is kept constant, and the liner velocity (V_r) varied to maintain the same surface quality, the linear velocity (V_r) can be found to be directly proportional to the extrusion rate (V_e) as shown in <Figure 6>.

The graph in Figure 6 also shows that for a constant surface quality the layer thickness (h) of the part varies proportionally to the ratio of the extrudate velocity (V_e) and the linear velocity (V_r). From this relationship it can be seen that as the height reduces to zero, the linear speed approaches infinity, or the extrudate velocity reduces.

2.2 FEA modeling

The CC process is unique from the modeling standpoint. This is because the CC process has attributes of extrusion as well as injection molding. The similarities to normal extrusion processes are obvious. In the case where the clay is being packed under pressure as a result of contact with the semi-solid base layers and the trowels, the process somewhat resembles injection molding.

The exit geometry for the CC process is another issue. The trowels and the orifice are part of the exit geometry and they play a significant role on affecting the flow of the clay. The trowels dramatically effect the CC process and the resulting part wall cross-sectional shape.

However, the surface quality is determined by a multitude of parameters like the design of the extrusion system, the material, the fluid properties, the test parameters (variants of the system) and alike.

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

The analysis of any non-Newtonian flow is very complicated. However, the following assumptions were introduced for the finite element analysis. The flow in its steady state condition observes 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

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \qquad \cdots\cdots(3)$$

$$\frac{\partial}{\partial z}[\eta \frac{\partial u}{\partial z}] - [\frac{\partial P}{\partial x}] = 0 \qquad \cdots\cdots(4)$$

$$\frac{\partial}{\partial z}[\eta \frac{\partial v}{\partial z}] - [\frac{\partial P}{\partial y}] = 0 \qquad \cdots\cdots(5)$$

where h is the viscosity, P is the pressure, ρ the density, and u, v, w are the velocities in the x, y, and z direction.

2.2.1 Boundary conditions

The solution domain showed in <Figure 7> is defined by four boundaries: the die land wall (1), the free surface boundary (2), and the walls of the trowel (3). 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. For the energy equation, the conditions are set for isothermal ones. 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.

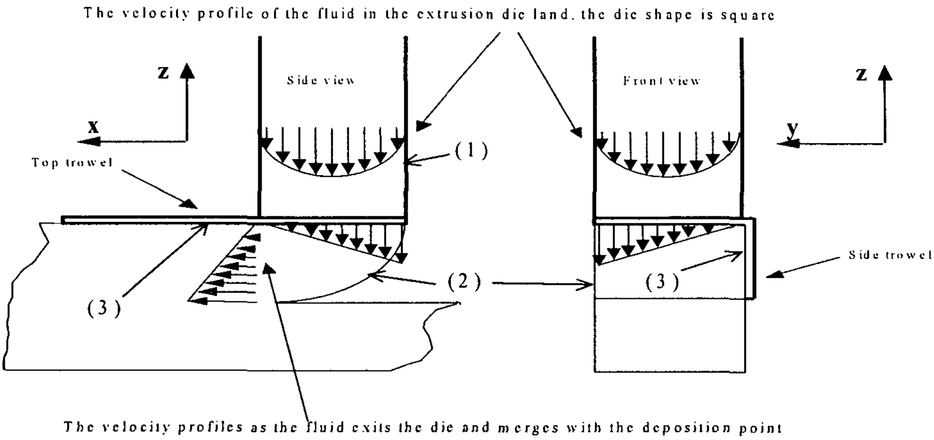
(2) The free surface boundary: The free surface boundary conditions are based on the requirement that no momentum flux may cross the free surface of the fluid. The stress tensor normal and tangent to the free surface are 0.

(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 vanish there.

2.2.2 Pre-processing

We used Flo++[1] 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 8 and 9>. After the grid generation the conditions at all boundaries of the grid were supplied. In our case, 3 boundary conditions were applied; the trowel walls (blue), the die land walls (blue), the inlet boundary (red), the free surface boundaries (light blue), the moving bottom layer (gold), and the outlet boundary (green). The viscosity and density were set at arbitrarily large values (material specific properties were not known). The flow was considered to be a laminar,

1) Flo++ is a general-purpose finite volume computational fluid dynamics program for the solution of industrial fluid flow and heat transfer problems. It solves the basic conservation equations of fluid dynamics and produces results in the form of pressures, temperatures and other flow variables. (http://www.softflo.com/) Flo++ is generally employed for computational fluid dynamics analysis of industrial fluid flow and heat transfer processes. It solves the basic conservation equations of fluid dynamics and produces results in the form of color plots of velocities, pressures, temperatures and other flow variables. The software is developed for Windows 95 or Windows NT and is intended to be practical and accessible to practicing engineers and analysts. The format of text and graphical output is also fully compatible with Windows'data base products, which enables numerical simulation and writing reports in a fully integrated environment.



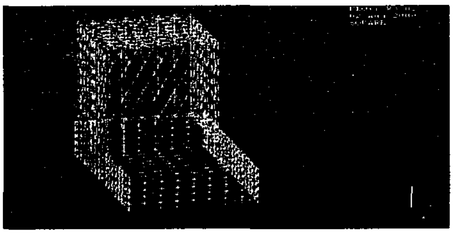
<Figure 7> Schematic of material flow in CC

isothermal flow in the program. The completion of these three steps made it possible to solve the flow through the domain. The partial differential equations describing the fluid flow were discretized over the mesh. An iterative method internal to Flo++ was used to solve this system of equations.

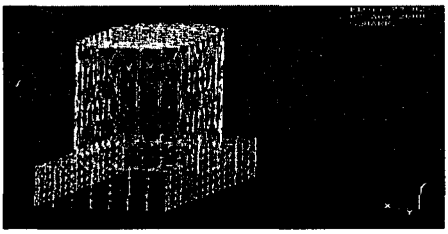
2.2.3 Post-processing

<Figure 10> shows the flow profiles of the particulate flow with the square die shape at conditions (h is 15 %, r is 24 kN/m3, and u is 0 mm/sec, v is 0.05mm/sec, w is 4 mm/sec). As shown in Figure 11, the flow profiles of the particulate flow with the elliptical die shape are at conditions (h is 15 %, r is 24 kN/m3, and u is 0 mm/sec, v is 0.04 mm/sec, w is 4 mm/sec). These simulation results indicate the complex flow conditions occurring in the flow domain.

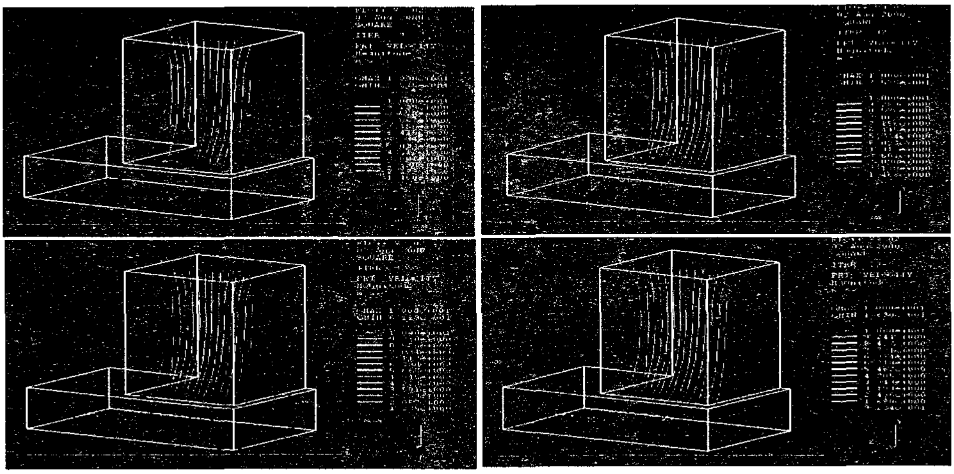
The effect of the boundary conditions on the flow profile of the particles becomes very evident and forms a basis to understand the flow phenomenon of the CC process. The friction at the walls and side trowel retard the flow, which explains why we get the above flow profile as indicated by different colors.



<Figure 8> Boundary condition of the square



<Figure 9> Boundary condition of the die shape elliptical die shape



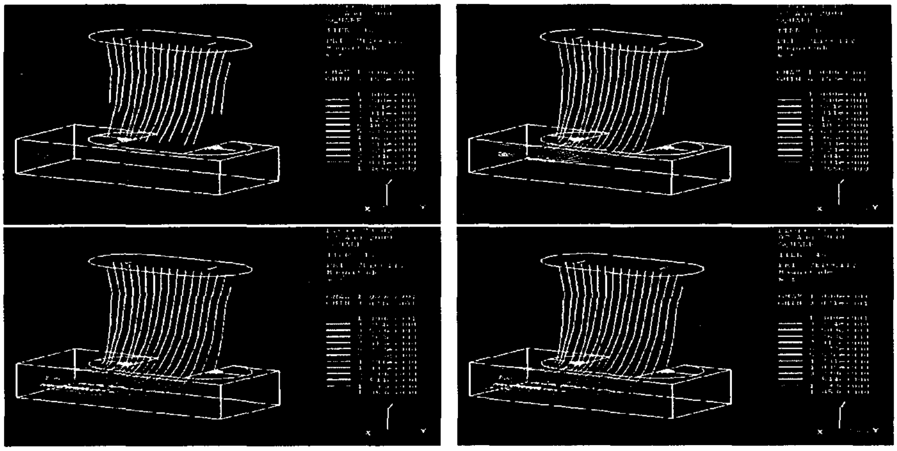
<Figure 10> A particle flow line of the square die shape

The photographs of CC taken on-line, shown in <Figure 12, and 13> with the square nuzzle, confirm the results obtained by the simulation in Figure 10. The photographs of CC taken on the actual process, shown in <Figure 14, and 15> with the elliptical nuzzle, confirm the results obtained by the simulation in <Figure 11>.

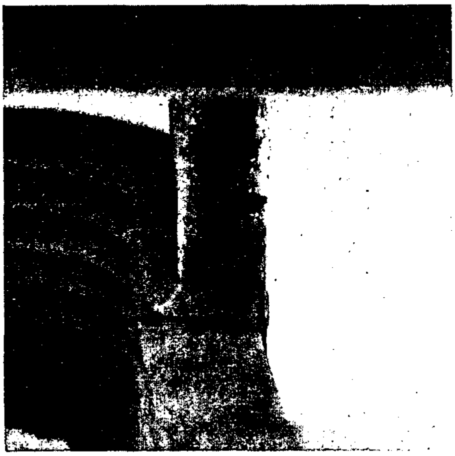
3. Qualitative analysis of the fabricated parts: The effect of the die design on the surface quality

With each of the two chosen die shapes, we optimized the process parameters to achieve desirable surface quality and geometric characteristics. For the parts resulting from our experimentation, we carried out a visual inspection and noted that the surface quality was not the same with each orifice shape, but close to the same shown in <Figure 16 and 17>. However, it was observed that the geometric profile varied significantly with orifice shapes in <Figure 18 and 19>.

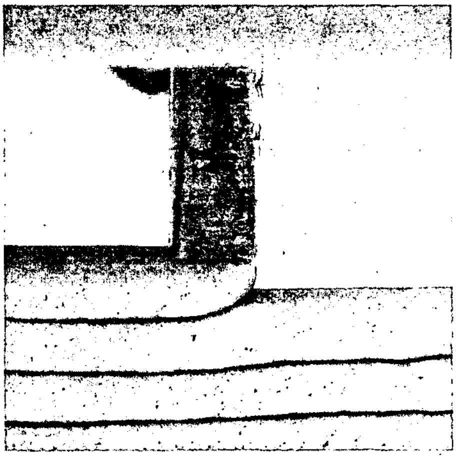
From examination of the inner walls of the above parts it can be seen that cross-section of each layer bears a resemblance to the die shape through which it was extruded. Parts made using the square die have cross-sections were the inner walls of the part have flatter walls, compared to the parts fabricated by the elliptical die whose inner walls have curved, bulging out profiles.



<Figure 11> A particle flow line of the elliptical die shape



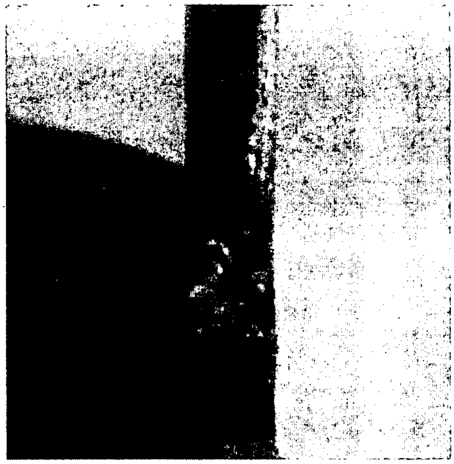
<Figure 12> Actual material flow from front view with the near optimal case



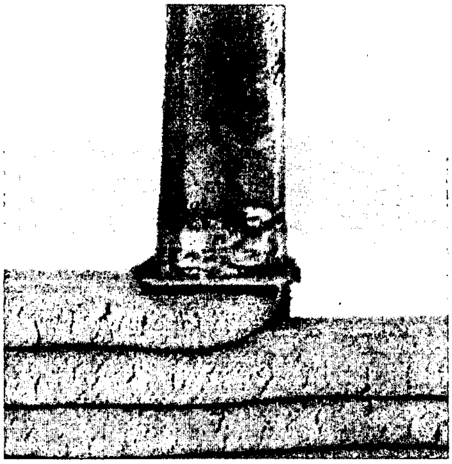
<Figure 13> Actual material flow from inside view with he near optimal case

3.1 Surface finish profile

The graph in <Figure 20> below shows the various surface finish profiles of parts made using different dies. It can be seen that the elliptical shape results in parts having interlayer grooves and the layers show a slight bulging outward. This is a determinant of the problem of the use of higher compression pressures with elliptical dies.

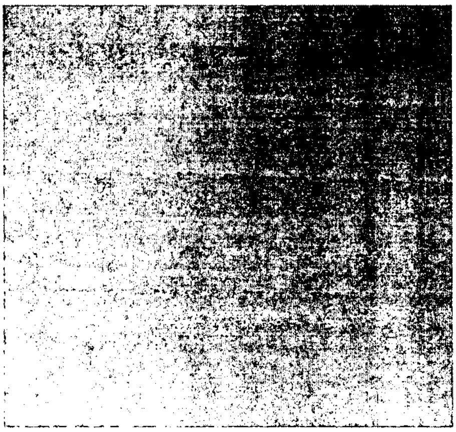


<Figure 14> Actual material flow from front view with the near optimal case

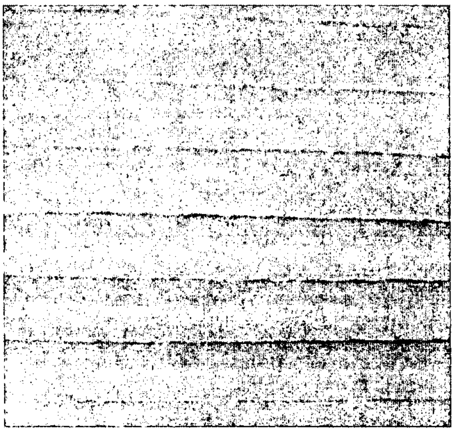


<Figure 15> Actual material flow from inside view with the near optimal case

By far, the square shaped die, showed best results as far as maintaining the geometry and surface profile was concerned. These results led us into determining the surface roughness using a quantitative approach.



<Figure 16> Surface quality while filling the gap between the layers with the square orifice

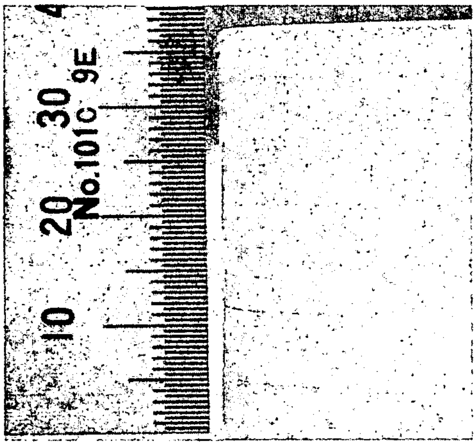


<Figure 17> Surface quality while filling the gap between the layers with the elliptical orifice

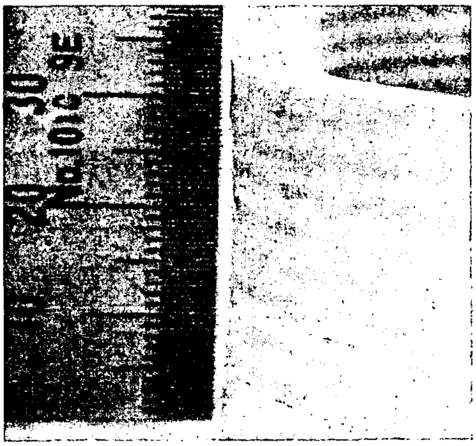
4. Quantitative Analysis

We next determined the variation of the Standard Error of surface finish for the different sample parts, considering various sample lengths of each individual part, against Ve/(Vr.h). From <Figure 21>, it is evident that the square shaped die gives better surface quality as compared to the hybrid and the oval shaped dies at lower values of extrudate velocity and hence extrusion pressure. In general, the Ve/(Vr*h) ratio is low as compared to that of other die shapes. To achieve a near equal surface roughness value with the hybrid and the oval dies, we need higher velocities in that order. This is explained since we know that the presence of unfilled regions between the consecutive layers increases the surface roughness.

Thus, we require a higher extrusion pressure to fill up these voids in case of the hybrid and oval dies. However, if the pressure were increased over the



<Figure 18> Showing a straight profile with using the square orifice



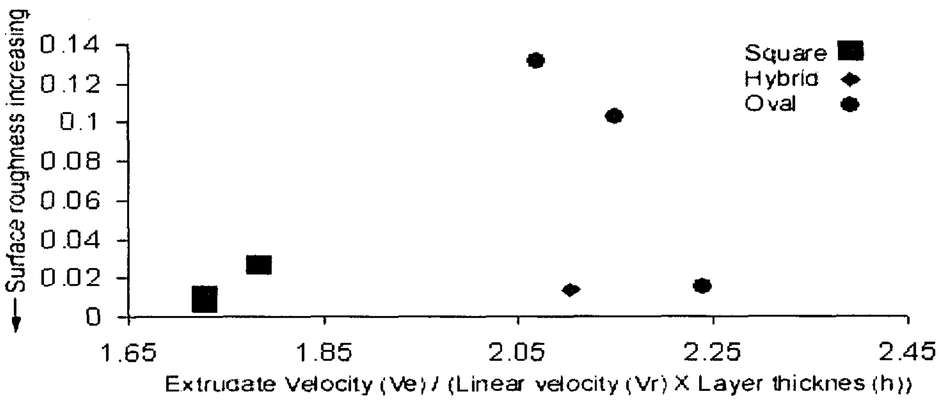
<Figure 19> Showing a non- straight profile with using the elliptical orifice

it would cause loss of the desired geometric profile, thus deteriorating the surface quality. A close study shows that the experimental results are consistent with the flow characteristics of the FEM model.

<Figure 20> Cross section of the fabricated parts by (a) a square orifice, and (b) an elliptical orifice

5. Conclusion

The simulation program results play an important role in gaining a better insight into the flow process. They enable the prediction of the consequences of variations in boundary conditions, different die shapes and changes in other flow parameters of the process and material. The experimental results form a basis to come to the conclusion that, of the three different die shapes that we used, the results obtained with the square cross-section were the best, even when we consider the trade-off between using extrusion pressures high enough for the layers to fuse with each



<Figure 21> Relationship between the surface roughness and the process control parameters

other with a uniform flow pattern, and low enough to avoid distortion of the part (maintaining the geometric profile). The various graphs obtained help in establishing the required relationships between the consequent parameters, the manipulation of which is not difficult to accommodate any change in the material of construction.

6. Scope of future study

The problem of paste flow discussed here is of a complex nature especially due to the non-linearity aspect and considering the fact that we are experimenting with Bingham (non-Newtonian) fluids such as clay. The relationships established between the flow patterns and surface roughness have been reasonably validated. However, for generalization of the foregoing results, we need to find a means to study the correlations between the pressure and surface quality under experiments involving different trowel designs and fabrication materials.

We need to look into any possible modifications to the simulation program to accommodate factors such as the fourth boundary formed by the semi-solid underlying layer. This calls for better programming practices so that the results are more realistic in nature and help in further explaining the flow process in depth. The refinement of these results will help us in bettering upon the CC process itself to achieve the desired surface quality of parts manufactured.

7. References

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저 자 소 개

권 홍 규 : 동국대학교 산업공학과를 졸업하고 USC(남가주대학) 산업시스템학과에서 공학석사 및 박사학위를 취득하였으며, 현재 충주대학교 산업경영학과 겸임교수로 재직중임. 주요관심 분야: CIM, FMS, 생산관리 및 생산자동화, Simulation

김 용 범 : 명지대학교 산업공학과를 졸업하고 동 대학원에서 공학석사 및 박사학위를 취득하였으며, 현재 충주대학교 경영학과 부교수로 재직중임. 주요관심 분야: 품질경영, 생산관리 및 생산자동화

저 자 주 소

권 홍 규 : 충북 충주시 이류면 검단리 123번지 충주대학교 산업경영공학과

김 용 범 : 충북 충주시 이류면 검단리 123번지 충주대학교 경영학과