FEA simulation을 이용한 Movable Side Trowel의 효과에 대한 연구

- FEA simulation for studying the effect of the movable side trowel -

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Abstract

이 논문은 CC 프로세스의 movable side trowel 효과를 연구하기 위한 실험과 모델링을 제시한다. FEA simulation을 이용하여 우리는 movable side trowel의 효과와 움직임에 대한 기초적인 이해를 얻어냈다, 단면의 side trowel 보다 양면의 side trowel이 실제의 3D 형상을 만드는 동안에 층간의 최적의 결합을 만들어 준다는 면에서 가장 적합하다는 것을 알아냈다. 우리의 실험이 위의 결과를 입증하였다.

Keywords: Contour Crafting, Trowels, FEA Simulation

1. Introduction

Contour Crafting (CC) is an additive fabrication process developed at the University of Southern California [8]. 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 900 rotation immediately after extrusion.

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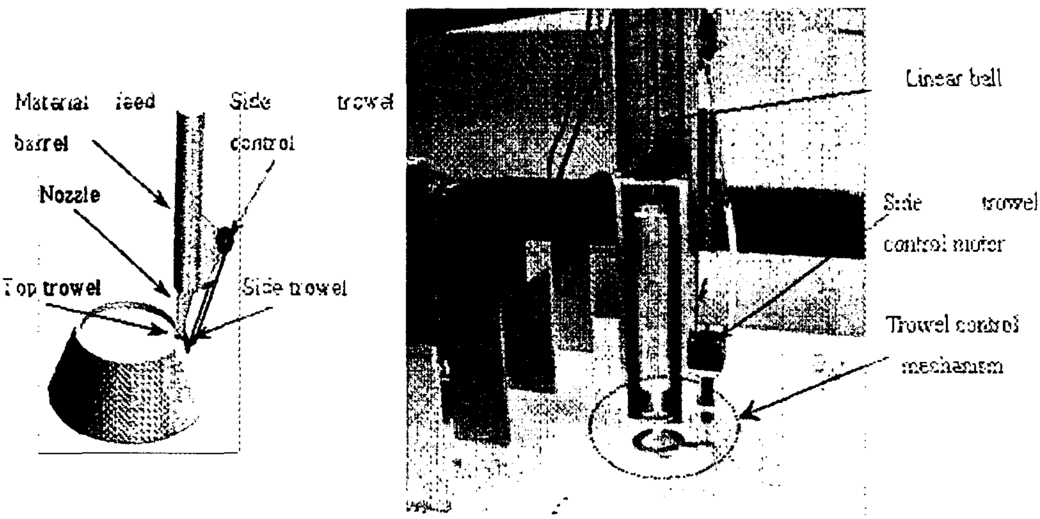
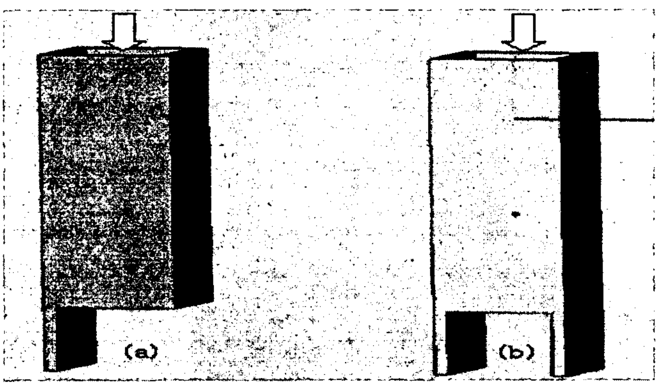
As shown in <Figure 1>, the basic CC process consists of an extrusion orifice, a two perpendicular solid planar surfaces formed by a top trowel and a side trowel. The side trowel smooths out and shapes the external surface of a CC-fabricated part in order to achieve desirable geometric profile and surface 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.

Specifically, we considered the effects of the following two types of side trowel shown in <Figure 2>: (a) single side, and (b) double side trowel, respectively. We undertook simple process modeling described in the following section for understanding process flow characteristics.



<Figure 1> CC machine with the movable side trowel for fabricating complex 3D part



<Figure 2> Side trowel designs used in experiments

2. Governing relationships

2.1 Process parameters

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

Through the several experimental investigations, it is attempted to calibrate our input and output parameters, as well as to understand the behavior of the material during extrusion. The input parameters were extrusion rate (Ve) [mm/sec], linear speed (Vr) [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 (Dh), and the surface roughness (Ra) 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:

$$S_d = C_d \frac{V_e S_n}{V_r} \quad \text{.......(1)}$$

$$S_d = S_d + \frac{1}{2} * h^2 * \tan(\theta) \quad \text{.......(2)}$$

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

Ve (mm/sec) is the extrusion velocity

Vr (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

Sn (mm2) is the cross sectional areas of the nozzle

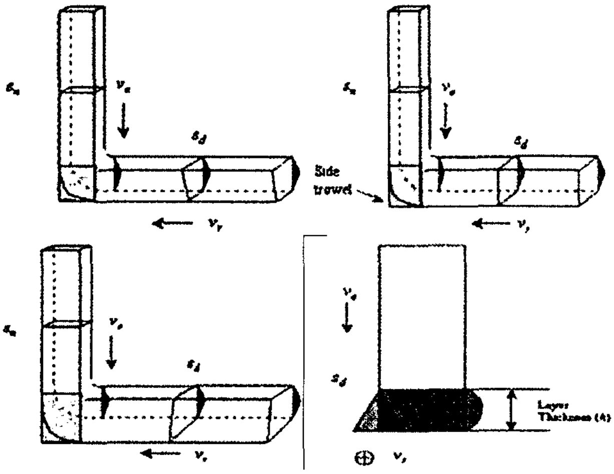
Sd (mm2) is the cross sectional areas of deposited layer

Sd′ (mm2) is the cross sectional areas of deposited layer when θ=0

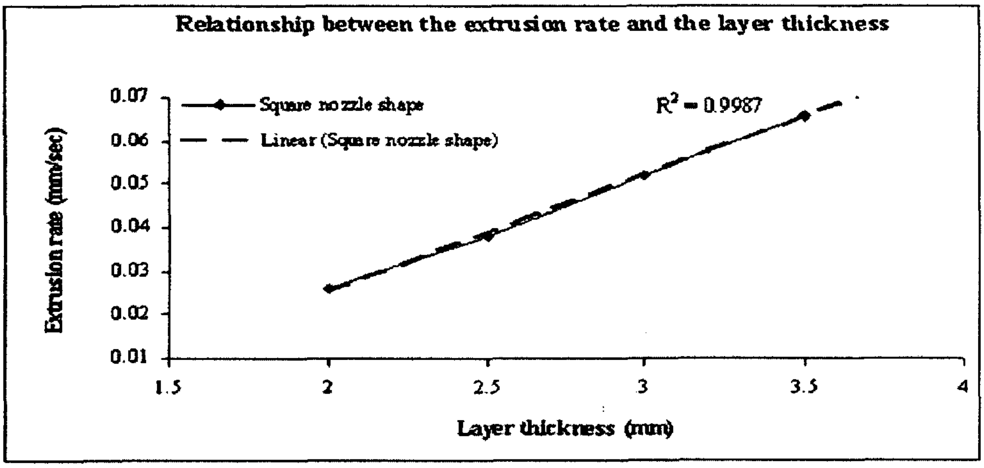
Ve will always increase at the deposition point because the extudated material is partially unbound after the exit of the nozzle. Hence, Sd will increase at the point if other parameters are constant.

As shown in <Figure 3>, Sd 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 4>, the extrusion rate is directly proportional to the layer thickness for a given surface roughness.



<Figure 3> Schematic view of steady flow with different side trowel angles



<Figure 4> The relationship of the layer thickness and the extrusion rate

Thus any 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.

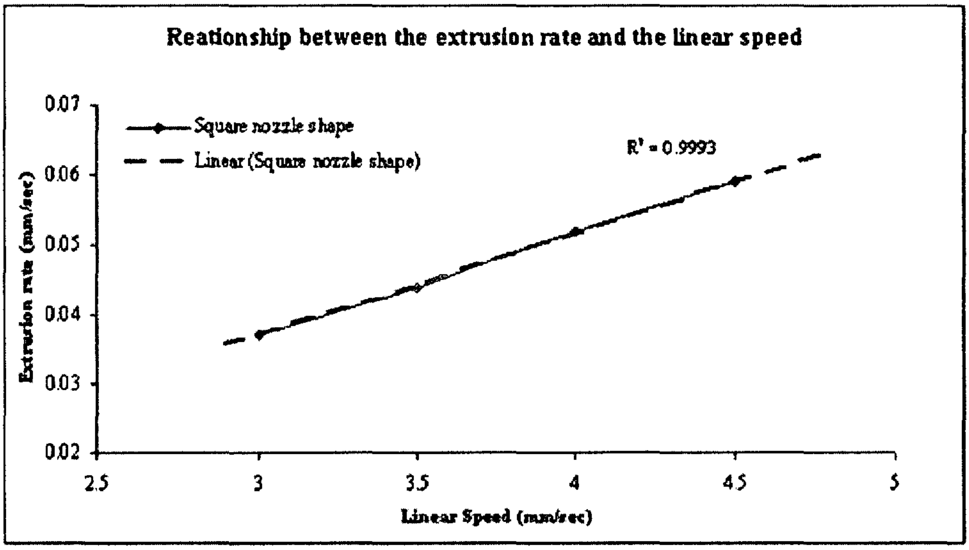
$V_e \propto h$ ....(3)

The extrusion rate is also directly proportional to the linear speed for a given surface roughness as shown in <Figure 5>. 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.

$V_r \propto V_e$ ....(4)

Combining equations 1, 3, and 4

$\frac{V_e}{V_r} \propto h$ ....(5)

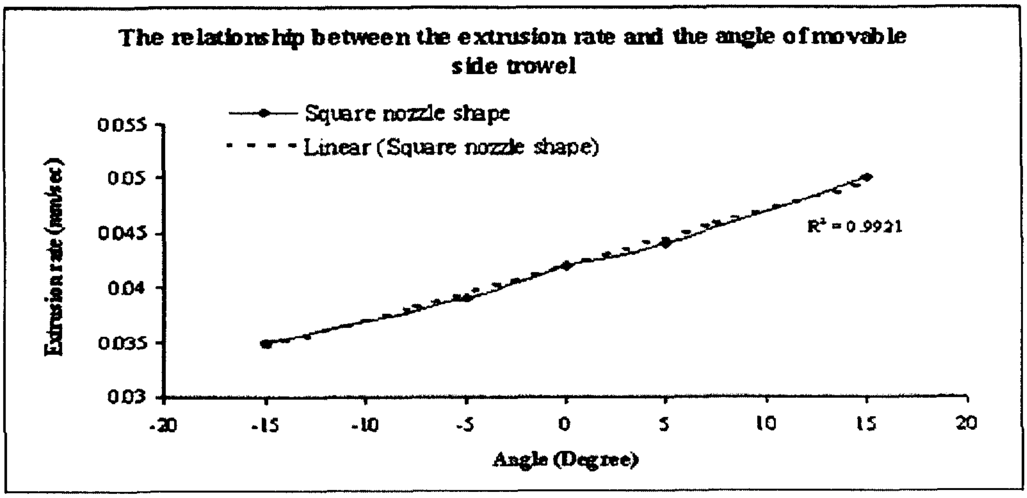


<Figure 5> The relationship of the linear speed and the extrusion rate

For a given surface roughness the angle of the side trowel is also directly proportional to the extrusion rate as shown in <Figure 6>. Thus any change of the 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.

$V_e \propto \theta$ ....(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.



<Figure 6> *The relationship of the extrusion rate and the pivoting angle*

2.2 Assumption 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). 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 [2,4].

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. The flow in its steady state condition exhibits linear rheological properties as a result of the effect of the deflocculant additives [5,6,7]. The compressibility of the clay is neglected, and the flow is assumed to be a single phase, isothermal and laminar[1,3]. Making use of these assumptions, the linearized governing flow equations can be described by

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)+\frac{\partial}{\partial z}(\rho w)=0 \qquad (7)$$

$$\frac{\partial}{\partial z}(\eta\frac{\partial u}{\partial z})-(\frac{\partial P}{\partial x})=0 \qquad (8)$$

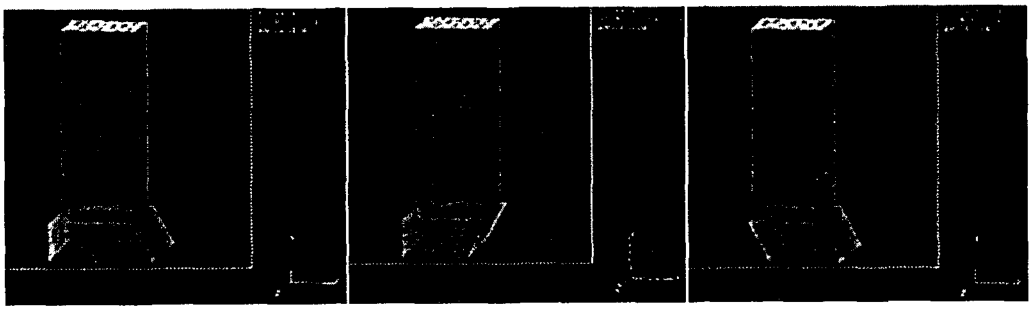
$$\frac{\partial}{\partial z}(\eta\frac{\partial v}{\partial z})-(\frac{\partial P}{\partial y})=0 \qquad (9)$$

where is the viscosity, P is the pressure, is the density, and u, v, and w are the velocities in the x, y, and z direction at the boundary condition (u = 0, v = Vr, and w = Ve). With these assumptions FEA simulation is detailed in the following subsection.

3. FEA simulation

3.1 Pre-processing of FEA simulation

A commercial CFD package is also used for simulating the side trowel angle. To form a computational grid as shown <Figure 7>, 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). As same as the orifice simulation, the viscosity (η) measured in terms of the damping ratio and density (ρ) were set at 15 %, and 24 kN/m3 respectively. The flow was considered to be laminar and isothermal[9,10,11].

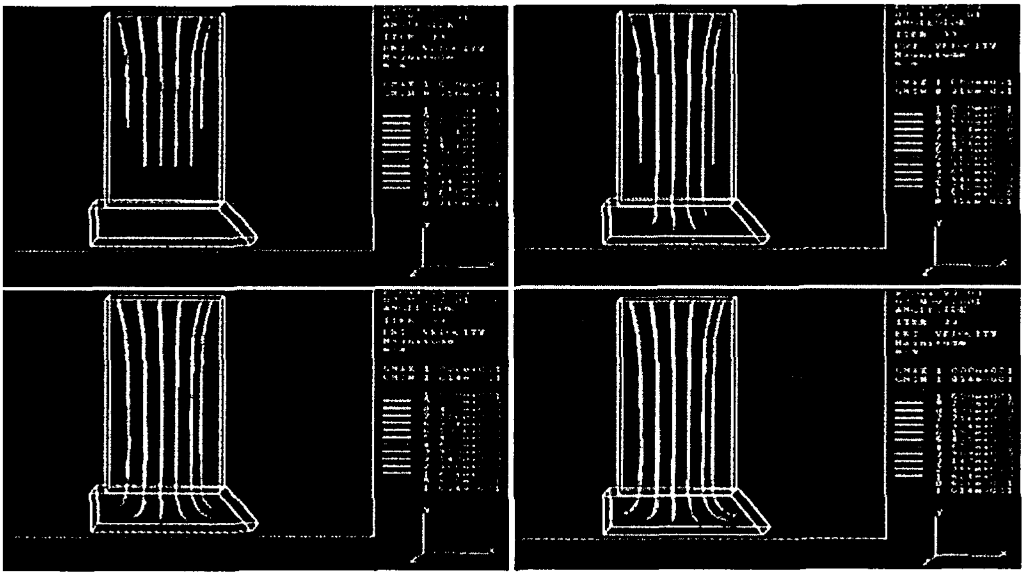


<Figure 7> Grid structure for (a) an exterior angle, (b) an interior angle, and (c) two side trowels

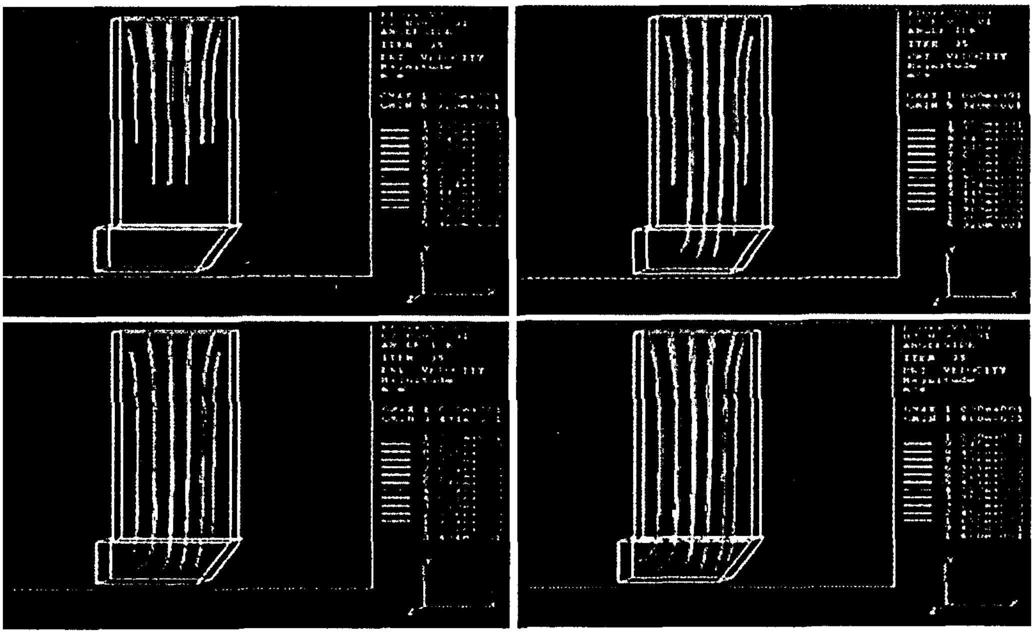
3.2 Post-processing of FEA simulation

<Figure 8> shows the flow profiles of the particulate flow with the exterior angle at condition: is 15 %, is 24 kN/m3, and Ve is 2.112 mm/sec, Vr is 4 mm/sec. As shown in <Figure 9>, the flow profiles of the particulate flow with the interior angle are at conditions: is 15 %, is24 kN/m3, and Ve is 1.471 mm/sec, Vris 4 mm/sec. The flow profiles of the particulate flow with the two side trowel

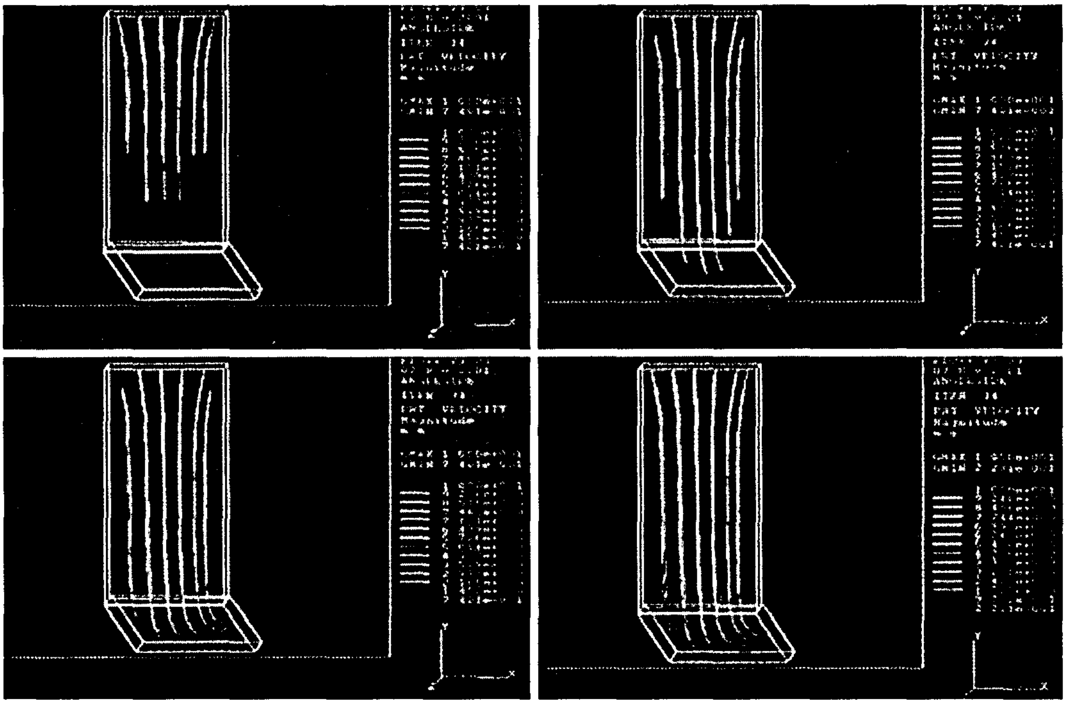
in <Figure 10> are at conditions: is 15 %, is 24 kN/m3, and Ve is 2.188mm/sec, Vr is 4 mm/sec.



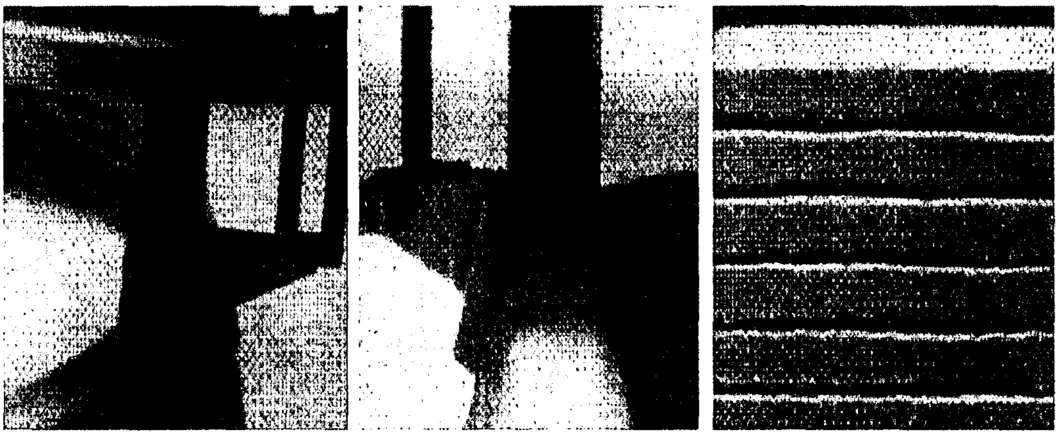
<Figure 8> Particle flow lines with an exterior angle



<Figure 9> Particle flow lines with an interior angle



<Figure 10> Particle flow lines with two side trowels

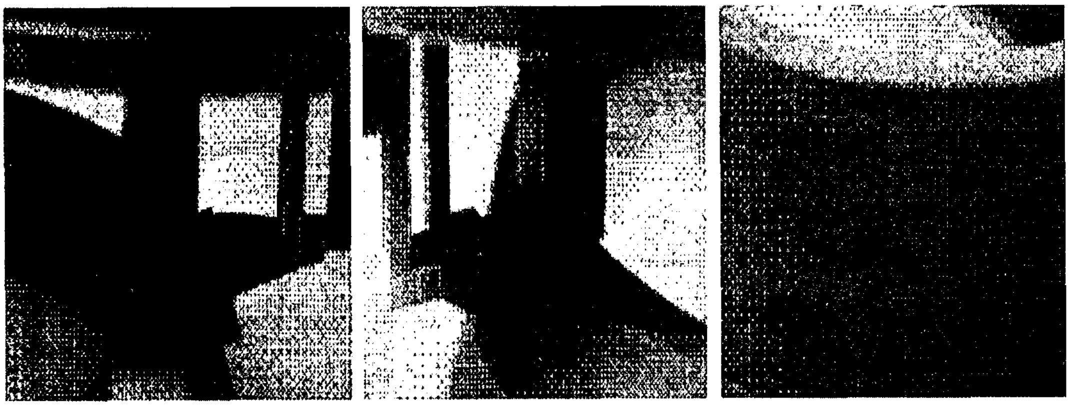


<Figure 11> On-line process with an exterior angle: (a) font view, (b) back side view, and (c) surface quality

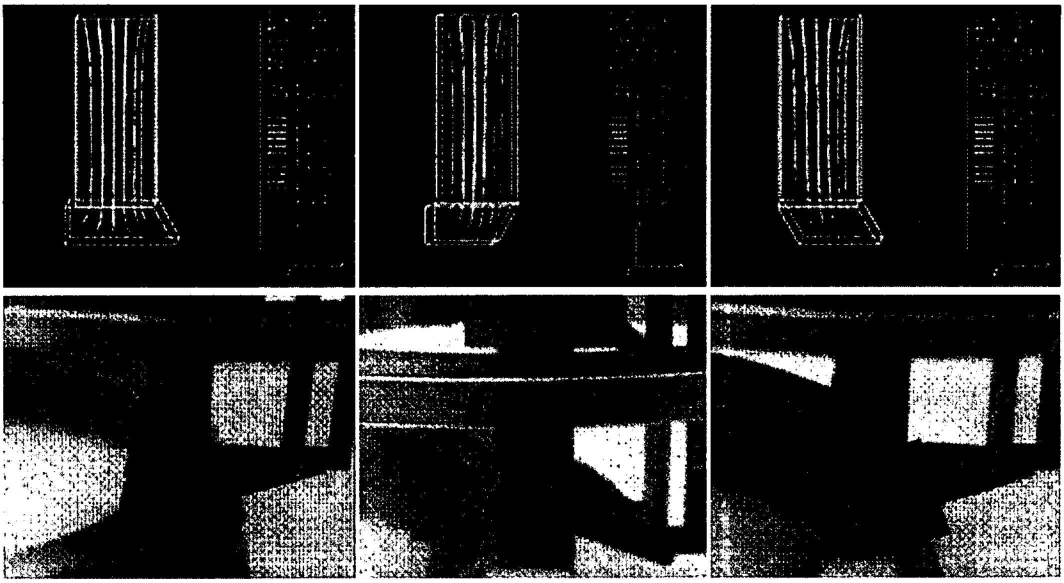
As shown in these simulation results, the complex flow conditions were occurred in the flow domain. Since the friction at the boundary, especially the walls, retards the flow, the flow in the center of the nozzle is much rapid. Also, the flow patterns are changed on the deposited point relating to the 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 11>, confirm the results obtained by the simulation in <Figure 8>. The photographs with an interior side trowel angle taken on-line, shown in <Figure 12>, confirm the results obtained by the simulation in <Figure 9>. The photographs taken on the actual CC process with the two side trowels, shown in <Figure 13>, confirm the results obtained by the simulation in <Figure 10>.

<Figure 12> On-line process with an interior angle: (a) font view, (b) back side view, and (c) surface quality



<Figure 13> On-line process with two side trowels: (a) font view, (b) back side view, and (c) surface quality

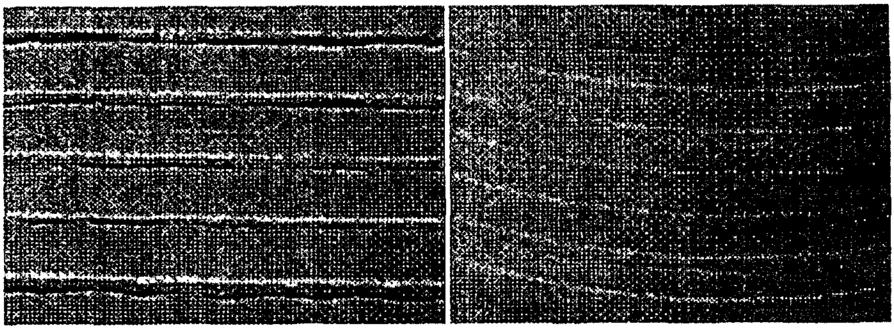


<Figure 14> Comparison with the partial lines vs. on-line process under near optimal conditions: (a)an exterior, (b)an interior, and (c) two side trowels

4. Discussion

To achieve desirable surface quality, the process parameters are optimized under each of the three different conditions. As shown in the <Figure 14 (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 14 (c)>. the material is tend 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 13 (c)>. When the angle of the side trowel is interior as shown in <Figure 14 (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 12 (c)>.

By smoothing out the presence of unfilled regions between the consecutive layers at the exterior angle in <Figure 11 (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 15>.



<Figure 15> Surface finish at the sup-optimal condition: (a) a side trowel with an exterior angle, and (b) two trowels with an exterior angle

5. References

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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.
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