A Framework for Large Scale Fused Pellet Modeling (FPM) by An Industry Robot

Zhiyuan Wang, Renwei Liu, Todd Sparks, and Frank Liou

Department of Mechanical & Aerospace Engineering,
Missouri University of Science and Technology, Rolla, MO, 65409

REVIEWED

Abstract

Fused pellet modeling (FPM) is an important method in additive manufacturing technology, where granular material is used instead of filaments. In FPM, prototypes are constructed by the sequential deposition of material layers. As the size of the part increases, the problem of long build times and part deformation becomes critical. In this paper, methods for eliminating the void density during deposition and accuracy control principles for large scale FPM processes are studied. By analyzing the ab initio principles of this process, a mini extruder with variable pitch and progressive diameter screw for the large scale fused deposition is proposed. Based on polymer extrusion theory and non-Newtonian fluid properties, each of the design parameters are analyzed, such as the length of different function sections of screw, die shape of extruder nozzle, and the material properties. According to these analysis results, an extrusion process simulation for controlling the filament shape is carried out with multi-physics modeling software and proved the FPM could increase the building efficiency and deposition quality for large size parts.

Introduction

Layered manufacturing with extruded material is one of the most promising rapid prototyping techniques to demonstrated novel design ideas and reduce the product development cycle. This process fabricates prototypes by extruding the material in semi-fluid status through a heated nozzle in a prescribed pattern onto a platform. Various types of material could be applied in this process including polymer, cement, plaster, and wax.

The deposition material should be extruded continuously, stably and under constant temperature during the layered manufacturing process. "Continuously" means there should be no interruption of extrusion when the nozzle is scanning the deposition path; "Stably" involves the stable extrusion amount and accurate geometry of the semi-molten material; "Thermostatic" is to ensure the bonding quality between deposition tracks.

The fused deposition modeling (FDM) developed by Stratasys Inc., has been a leading rapid prototyping technology, which involves layer by layer deposition of extruded material through a nozzle using feedstock filaments from a spool [1]. The material feeding process of FDM realized by two friction wheels rotate reversely to push the filament into a heated nozzle (Figure 1). Because of the advantages of simple structure and easy control, it has been widely used in most of the fused deposition systems. But the weak points of this method are also very obvious, the extrusion force is limited by the surface compressive strength of filament and the contact area between friction wheels and filament. Insufficient friction will cause slip feeding, and too much compressive force applied on the filament might be break it off, both of these will affect the extrusion quality. To shift from rapid prototype to agile fabrication by broadening the material selection and improve the properties of fused deposition modeling, Anna Bellini et al [2] presented a novel extrusion system which mount on a high precision positioning system and fed with granulated material. Although this screw extrusion system could perform better than other filament based extrusion systems, but the normal single screw is still not the best suitable structure for the fused material extrusion process.

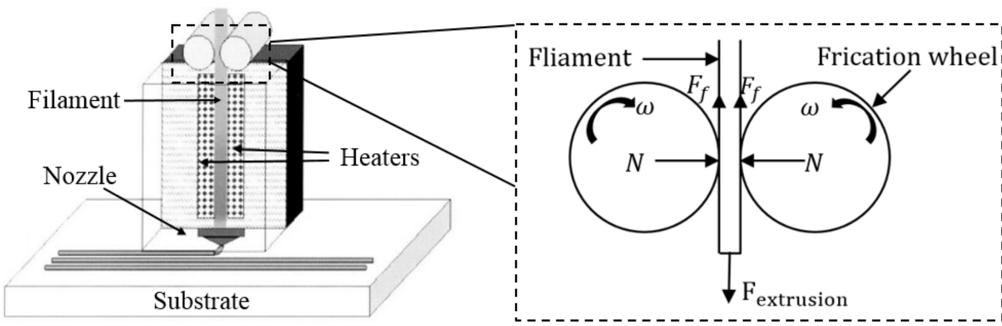


Figure 1 Schematic of filament based extrusion systems

As the size of the part increases, the problem of long build times and part deformation becomes critical. Currently, most FDM machine's extrusion amount is between 12-17 kg/hour, it will take several days to build a big size part. Inner stresses resulting from the contraction of deposition fibers within one layer can affect the prototype size precision, bring about prototype deformation, including warp and inner-layer delaminating or cracking. Similar quality issues widely exist in other rapid prototyping process. Many researchers have investigated the inner stresses. Tian-Ming Wang et al. [3] constructed a mathematical model of the prototype warp deformation to analyze each of the influencing factors. Jayanthi et al. [4] discussed how the scanning pattern of the laser in stereolithography (SLA) influences the resulting deflection of the part. Céline Bellehumeur [5] study the dynamics of bond formation between polymer filaments with thermal analysis and sintering experiments under different conditions and the same group performed a more in-depth study on the mechanisms that control the bond formation under different process conditions [6].

To avoid most defects of material extrusion steps in a filament-based system, a mini screw extrusion system has been proposed and developed in this paper, and especially designed for building large size object with layered manufacturing technique. The new set-up, called fused pellet modeling (FPM) system and consisting of a mini extruder mounted on an industry robot arm, operates using bulk material in granulated form. This configuration opens up opportunities to use wider range of materials, meanwhile the robot arm making the fused pellet modeling process more flexible and become a viable alternative rapid prototyping for large size part.

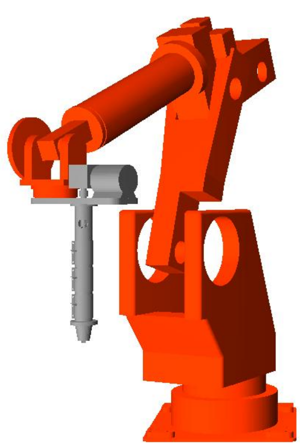
System specification

Screw extrusion has been widely adopted in the polymer manufacturing industry because of its extremely excellent attribute for processing. As the plastic moves along the screw, it melts by the following mechanism. Initially a thin film of molten material is formed at the barrel walls. As the screw rotates it scrapes this film off and molten plastic moves down the front face of the screw flight. When it reaches the core of the screw it sweeps up again, setting up a rotary movement in front of the leading edge of the screw flight. Initially the screw flight contains solid granules but these tend to be swept into the molten pool by the rotary movement. As the screw rotates, the material passes further along the barrel and more and more solid material is swept into the molten pool until eventually only melted material exists between the screw flights.

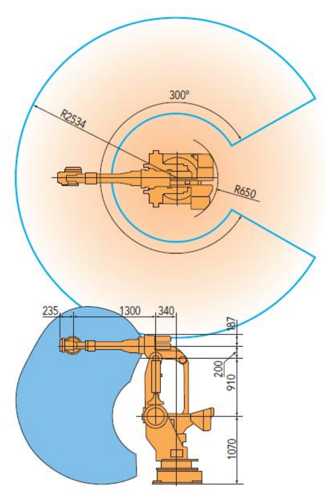
Applying the screw extrusion method into fused deposition process is not simply copy, since the nozzle needs to keep certain scanning speed during the deposition process, it requires that the weight and volume of extrusion unit should be within a certain range. The key component in the system is extrusion screw. Some researchers have tried to use common screw for extrusion, it could work for several kinds of material, like ceramic and plaster, but this structure cannot provide uniform mixing and enough back pressure for polymer material in fused deposition process. To solve these problems, a mini screw with variable pitch and progressive diameter is designed and manufactured for fused deposition purpose.

In combination with the barrel, the purpose of the screw is to convert solid material to the melted status, and finally pump material to the die in an efficient manner. To obtain a good extrusion performance, the screw for FPM system should be designed as three different function sections: feed section, transition section and metering section. The feed section is the first element of the screw where the polymer pallets is introduced to the screw, the wide pitch P_1 and small diameter D_1 the could provide the most feeding volume and frication force for pushing material to move forward. The transition section (or compression section) is where most of the melting of polymer takes place. This is portion of the screw that “transition” from the feed depth to the metering depth and where work is done on the resin causing melting to occur. In this section of screw, the root of the screw gradually becomes shallower forcing the material towards the wall of heated barrel where the melting takes place. The last but not least is the metering section or pumping section of the screw is where the melting of the polymer is completed and pumping to overcome the head pressure takes place.

This mini pallets extruder is mounted on an industry robot as shown in figure 2(a), it has a 4.1 m^2 (cross-section area) operating area and 300^0 rotation range for the base motor (figure 2(b)), which could provide much bigger deposition working envelop than other current fused deposition system. The 6-axis movement mechanism makes the deposition process more flexible to build the model with complex features.



(a) Assembly model of FPM system



(b) Robot working envelop

Figure 2 Assembly model of FPM system on the industry robot and working envelop

Accuracy control of extrusion process

The void density caused by gap and overlap between deposition tracks is inevitable defects of filament based FDM system, it also will result the part deformation and failure deposition. To analyze the effect of void density in deposition process, L. Li [7] proposed a method to calculate it theoretically. In an orthotropic laminate, in the plane normal to filaments or axis d, define ρ_1 as the area void density, g as the gap size.

When g =0, there is no gaps among filaments, the ideal cross section is shown in Figure 3, the cross section shape of filament is an ellipse with a and b as the idealized lengths of semi-major axis.

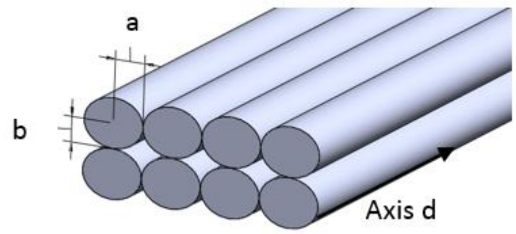


Figure 3 Ideal cross section of deposited filament

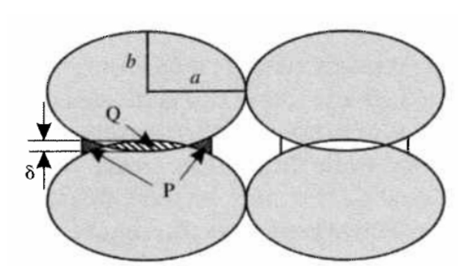
In the actual process, the top and bottom surface of filament would flatten when deposited onto previous layers, this is resulted from the vertical force of extrusion and it is in semi-molten state. Therefore the modified calculation model is shown in Figure 4(a) when considering the flattening effect with δ that can be measured experimentally. Assuming that the total cross sectional area stays unchanged, the relation between area Q and P should be:

$$Q = 2P \tag{1}$$

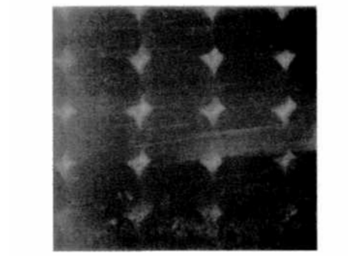
Assuming the δ is a small amount, the flatten area has the same length as the long semi-axis of filaments ellipse, thus the void density can be calculated using the following equation:

$$\rho_1 = 1 - \frac{\pi ab}{2a(2b-\delta)} \tag{2}$$

The real cross section for this situation also indicated in the microscopic photo of Figure 4(b).



(a) Schematic diagram of deposited filament with flattening effect

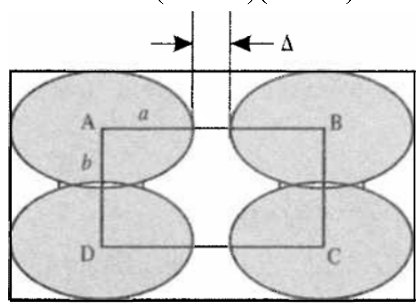


(b) Microscopic cross section of deposited filament

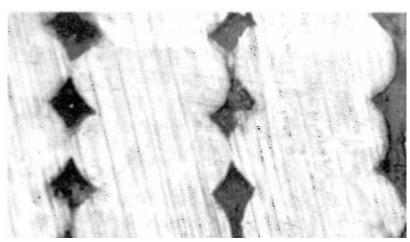
Figure 4 Deposited filament with flattening effect and photo of microscopic cross section

When $g = \pm\Delta$, which means there is a gap or overlap between deposition tracks, shown in figure 5 and figure 6, and cross section photo taken under microscopic, respectively.

$$\rho_1 = 1 - \frac{\pi ab}{(2a \pm \Delta)(2b - \delta)} \tag{3}$$

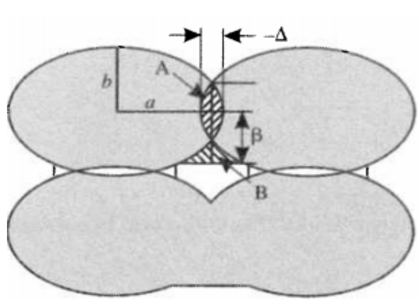


(a) Schematic diagram of deposited filament with positive gap

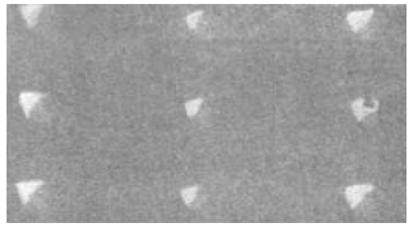


(b) Microscopic cross section of deposited filament

Figure 5 Deposited filament with positive gap and photo of microscopic cross section



(a) Schematic diagram of deposited filament with negative gap



(b) Microscopic cross section of deposited filament

Figure 6 Deposited filament with negative gap and photo of microscopic cross section

The smaller of area void density means better deposition quality, it could be found that increase δ and use minus gap setting will decrease the ρ_1, but this requires more deposition layers and denser deposition tracks, it will result longer building time and δ also has a limitation because the structure of nozzle.

The polymer material changed three different physical states sequentially from it been fed into the barrel to be extruded out through the nozzle: glass state, high elastic state and viscous flow state. Molten polymer has a high viscosity and significant elasticity, it should be considered as a kind of viscoelastic material and exhibit non-Newtonian fluid properties. One important feature of non-Newtonian fluid is Barus effect [8], which is an expansion phenomenon of a non-Newtonian fluid when it emerges from a nozzle to an open space so that the diameter of the emerging stream can be several times the nozzle diameter and the expansion ratio is varied from the edges to corners. When the molten polymer extruded out from the nozzle, it will expend along the edge, the longer of the edge the more obvious of expansion. This will result the filament shape of extruded material is different from the shape of nozzle (figure 7). Therefore, if the expected filament shape is a rectangle, the shape of nozzle should be similar with third one in figure 7.

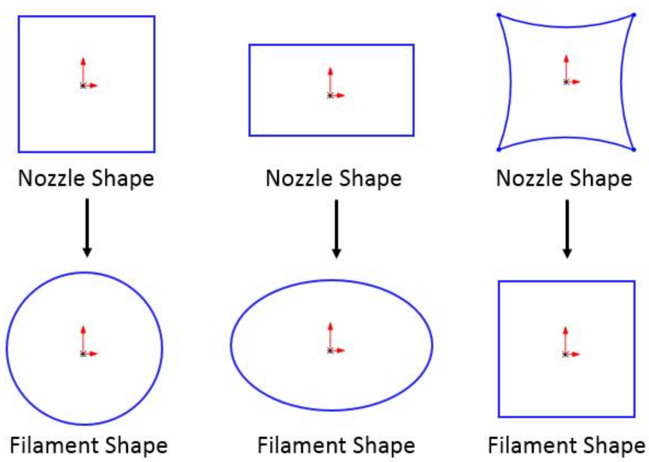
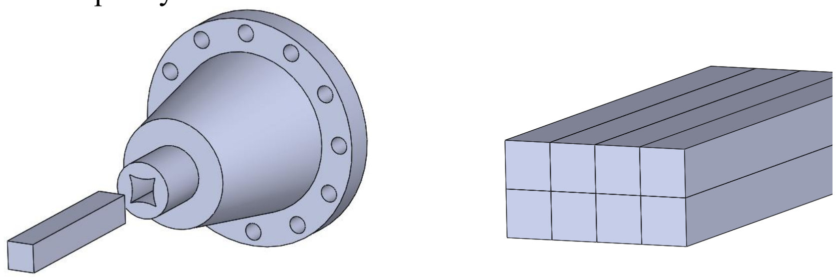


Figure 7 Barus effect of different shape nozzle

By controlling the parameters of extrusion process and the shape the nozzle, a rectangle shape of filament as shown in figure 8 could obtained for decreasing the void density and enhance the deposition quality.



(a) (b)

Figure 8 Model of nozzle for extruding rectangle filament and ideal deposition results

Extrusion process modeling and discussion of simulation results

For non-Newtonian flow, μ denotes the viscosity (kg/(m·s)), u the velocity (m/s), ρ the density of the fluid (kg/m^3) and p the pressure (Pa). The equations to solve are the momentum and continuity equations.

$$\rho\frac{\partial u}{\partial t}-\nabla\cdot\mu(\nabla u+(\nabla u)^T)+\rho u\cdot\nabla u+\nabla p=0 \tag{4}$$

$$\nabla\cdot\mu=0 \tag{5}$$

In the Carreau model, the viscosity depends on the shear rate, $\dot{\gamma}$, which for an axisymmetric model in cylindrical coordinates is defined according to Equation 2:

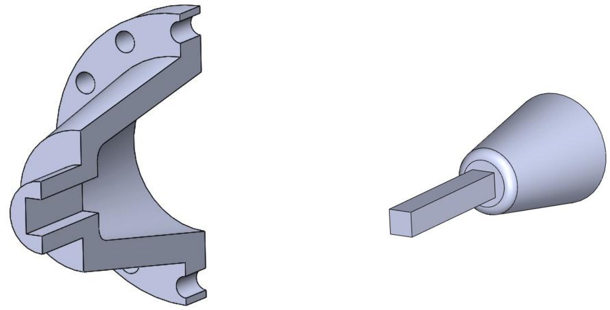
$$\dot{\gamma}=\sqrt{\frac{1}{2}\left((2u_r)^2+2(u_r+v_r)^2+(2v_z)^2+4(\frac{u}{r})^2\right)} \tag{6}$$

The viscosity is given by

$$\mu=\mu_\infty+(\mu_0-\mu_\infty)[1+(\lambda\dot{\gamma})^2]^{\frac{(n-1)}{2}} \tag{7}$$

where μ_∞ is the infinite shear rate viscosity, μ_0 is the zero shear rate viscosity, λ is a parameter with units of time, and n is a dimensionless parameter.

The section view of nozzle in this FPM system is shown as Figure 9(a). To analysis the flow behavior of molten polymer material in COMSOL multi physics, an inside volume model of the nozzle has been built as shown in Figure 9(b).



(a) (b)

Figure 9 Cross section view of nozzle and the inside volume model

To analysis the Barus effect of the extruded molten polymer, three different shapes nozzle are designed and the inside volume models of the nozzle are also modeled respectively (Figure 10). Shape-1 represents the original rectangle shape die, the length of edge is 0.5 inch; Shape-2 represents the modified shape die, the edge contracted inward obviously, the radius of arc is equal to the length of the rectangle and the arcs are tangent to each other; Shape-3 represents the improved shape die, the edge contracted inward slightly, the radius of the arc is 0.7 inch, the radius of fillet at each corner is 0.01 inch.

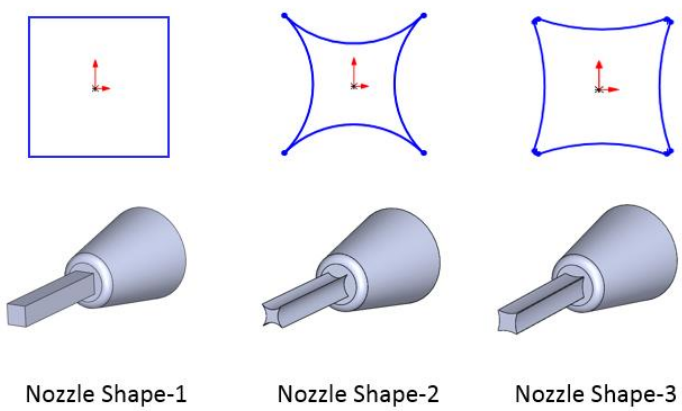


Figure 10 Cross section sketch and 3d model of three different shapes nozzle

The inside volume model represents the material which is extruding out from barrel through the die of nozzle. The flow behavior of melted material follows the above non-Newtonian flow equations. Because of the symmetry geometry feature and for the computation efficiency, the model could be simplified as single quadrant and imported into COMSOL multi physics. The material subdomain settings for low density polyethylene (LDPE) at around 220 degree centigrade [9] are shown in table 1.

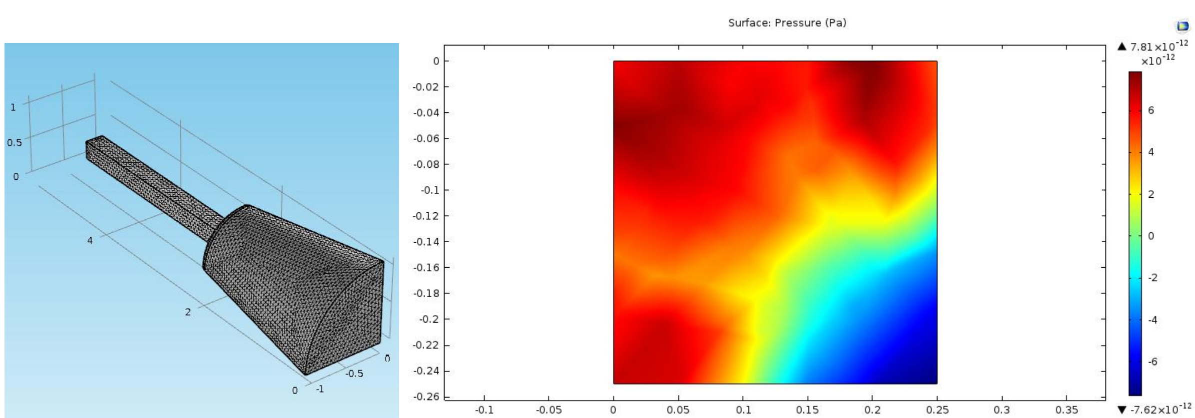
Viscosity model type	Carreau model
Density of melt LDPE (rho)	743 kg/m^3
Zero shear rate viscosity	1437.4Pa.s
Model parameter (n)	0.39
Model parameter (λ)	0.015s

Table 1 Subdomain settings for LDPE

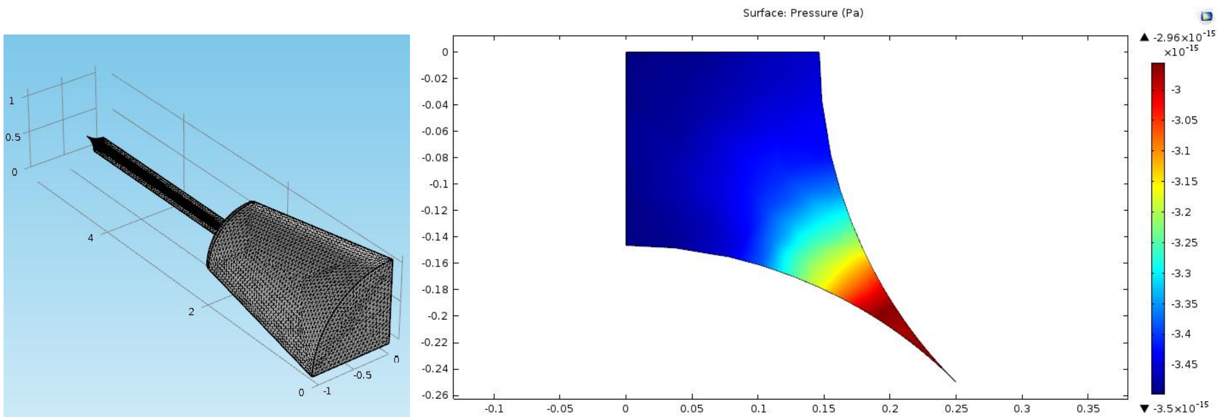
When non-Newtonian flow comes out from the nozzle with certain speed and back pressure, the inner pressure of the flow will force the material expend in the open space, this the macro phenomenon of Barus effect, which will result the extruded material to swell and comes out with oval shape or other unexpected shape, this phenomenon could be reflected in the cross section pressure plot of simulation results. Figure 11 shows the meshed inside single quadrant volume models of three different shape nozzle and the cross section pressure distribution plot at the outlet of nozzle, respectively.

As shown in figure 11(a), the pressure along rectangle edge is higher than the pressure at the corner section, the filament surface will expend to a round similar shape, figure 11(b) shows the modified shape, which shrank too much for each edge and the pressure is concentrated at the corner because of the stress cusp effect. The results illustrate that simulation correspond the non-Newtonian flow’s characteristic and these two design cannot achieve the object of extruding rectangle shape filament, because the molten polymer cannot expend averagely.

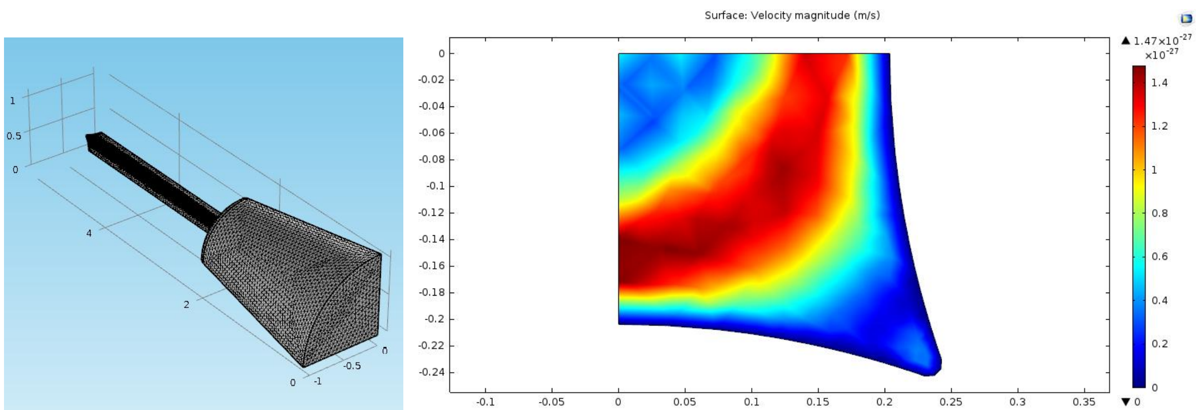
This problem can be solved by optimizing the die geometry and trying to even the stresses at the corners. Figure 11(c) shows the pressure distribution plot of the improved shape die, the pressure at the corner areas is smaller than the edges area and the pressure distribution is nearly uniform and symmetrical, the stress cusp effect could also be eliminate by adding a fillet feature. The comparison between these three different nozzles shows that filament extrusion quality could be controlled with optimization of the die shape. Moreover, the rectangle shape filament will improve the deposition accuracy and efficiency for large scale objects.



(a)



(b)



(c)

Figure 11 Meshed single quadrant inside volume models and the cross section pressure distribution plot at the outlet of nozzle

Conclusions and Future Work

Filament based fused extrusion deposition has been innovated and developed for a long period. It has the advantage of simple system structure and economical in cost, but the low extrusion speed and enclosed workspace limited applying this technique into building large size prototype. To solve these problem, a fused pellet modeling (FPM) method is proposed in this paper. A screw with variable pitch and progressive diameter is designed for providing sufficient extrusion material at high speed, also with a certain back pressure; By analyzing the cause of void density of fused deposition and based on Carreau model, the die shape was optimized for LDPE material in COMSOL. For the next step, this project will investigate the coupling affection of multi-physic fields (including hydromechanics, thermodynamics and phase change) on the deposition process of fused pellet modeling (FPM), to achieve building high quality large size prototype and with efficiency.

Acknowledgement

This research was supported by Laser Aided Manufacturing Processes (LAMP) Laboratory at Missouri University of Science and Technology. Their support is greatly appreciated. The author would like to thanks Maxwell Mulholland and Huixu Deng from Department of Mechanical & Aerospace Engineering at Missouri S&T for their valuable contribution to the project. Also all people attached directly or indirectly to the project.

References

[1] Masood S H. Intelligent rapid prototyping with fused deposition modelling[J]. Rapid Prototyping Journal, 1996, 2(1): 24-33.
[2] Bellini A, Shor L, Guceri S I. New developments in fused deposition modeling of ceramics[J]. Rapid Prototyping Journal, 2005, 11(4): 214-220.
[3] Wang T M, Xi J T, Jin Y. A model research for prototype warp deformation in the FDM process[J]. The International Journal of Advanced Manufacturing Technology, 2007, 33(11-12): 1087-1096.
[4] Jayanthi S, Keefe M, Gargiulo E P. Studies in stereolithography: influence of process parameters on curl distortion in photopolymer models[C]. Solid Freeform Fabrication Symposium 1994. University of Texas, Austin, 1994: 250-258.
[5] Bellehumeur C, Li L, Sun Q, et al. Modeling of bond formation between polymer filaments in the fused deposition modeling process[J]. Journal of Manufacturing Processes, 2004, 6(2): 170-178.
[6] Sun Q, Rizvi G M, Bellehumeur C T, et al. Effect of processing conditions on the bonding quality of FDM polymer filaments[J]. Rapid Prototyping Journal, 2008, 14(2): 72-80.
[7] Li L, Sun Q, Bellehumeur C, et al. Composite modeling and analysis for fabrication of FDM prototypes with locally controlled properties[J]. journal of Manufacturing Processes, 2002, 4(2): 129-141.
[8] Hori Y, Okubo S. On the normal stress effect and the Barus effect of polymer melts[J]. Journal of Rheology (1978-present), 1980, 24(1): 39-53.
[9] Bogale K. Simulation and Design of Extrusion Dies[D]. Arcada University of Applied sciences, Finland, 2011.