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Temperature Analysis in the Fused Deposition Modeling Process

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***Abstract*—The fused deposition modeling (FDM) is one of the most attractive 3D printing product manufacturing processes. FDM fabricates prototypes by extruding a semi-molten polymer filament through a heated nozzle in a prescribed pattern onto a platform. As the material is deposited, it cools, solidifies, and bonds with the surrounding materials. The temperature distribution among polymer filaments in the FDM process determines the bonding quality, integrity and mechanical properties of the resultant prototypes. A thermal model of FDM has been developed in this paper. The non-linear behavior of thermal conductivity and of specific heat due to temperature changes and phase transformation is considered here. The temperature evolution and the formation of the modelled part are investigated by a finite element analysis method based on the continuous media theory. Through the analysis of the prototypes using acrylonitrile butadiene styrene (ABS) filaments, it is shown that the effect of modelling has a strong influence on thermal evolution by changing the thermal properties of the material.**

Keywords- Fused Deposition Modelling (FDM); Thermal Model; Numerical Simulation; 3D Printing

I. INTRODUCTION

Rapid prototyping (RP) is a process in which a part, even an assembly can be produced using layer-by-layer material deposition. It is much attractive as it has potential to reduce the manufacturing lead time of the products up to 30-50% even the complexity of the part is very high [1, 2]. The RP technology consists of creating geometry model using Computer-Aided Design (CAD) software, determination of suitable deposition paths, part deposition and then post processing operations [3]. There are many effects, such as material temperature [4, 5], scanning speed [6], deposition orientation [3, 7] etc. on lots of key characteristics that determines the final quality and cost of the prototyping products.

The fused deposition modeling (FDM) is one of the most widely used rapid prototyping systems and based on solid freeform fabrication technique. It consists of building a three dimensional object layer by layer out of a semisolid bonded to a material that has already been extruded [8]. In reservoir with heat boosters, the polymer filament melts. The semiliquid is forced out through a nozzle when pressure is applied and solidifies when the temperature decreases, which leads to consolidation. The presence of the semiliquid for a short time leads to a shrinkage of the semisolid-solid mixture. Thus, the properties of the solidified products depend on the temperature evolution [9].

Many researchers devoted to develop a computationally automated capability for designing fused deposition materials with superior structural properties. FD-ABS is one of the most widely used materials in FDM processing. Fodran et al. [10] conducted tensile tests on ABS specimens. Kulkarni and Dutta [11] carried out a combined experimental/analytical study of the influence of deposition path on the “in-plane” tensile moduli of symmetric ABS. Bertoldi et al. [12] performed tensile tests on specimens of different orientation from an ABS cube built with the “pseudo-isotropic” fiber orientation stacking sequence. Rodriguez et al. [13] described the mechanical behavior of ABS materials based the experimental investigation.

At the macro level, the properties of the FDM structures can be investigated as laminates through bonded laminas. The consolidated object is a rigid and porous structure. The voids cannot be thoroughly eliminated. Thus at the micro level, the properties of each lamina are influenced by the properties of the filaments, the quality of the bonds among the filaments, and the void density. Tsai [14] had modeled the lamina properties as a function of constituent properties and geometrical parameters.

The formation of the bonding in the FDM process is driven by the thermal energy of the semi-molten material. Due to temperature variation, mechanical stresses are induced. As a consequence, the final states of the prototype (dimensions, densities, residual stress levels, etc.) strongly depend on the evolutionary process. In most reported works

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about the simulation of FDM, the processing model was always limited to one- or two- dimension space. Rodríguez [15] and Thomas [16] presented various hypotheses of symmetry base on the two-dimension space system.

As we know that the thermal characteristics of the filament material, such as thermal conductivity and heat capacity, are temperature dependent. A fully three dimension thermal model of FDM describing the non-linear effects of deposition has been developed based on ANSYS finite element method. This paper focuses on a model for the evolution of thermal conductivity. Moreover, during depositing, the thermal conductivity depends on the thermal history, since the workpiece structure evolves with time.

II. Thermal Analysis

In the case considered here, the analysis of the FDM process is a three-dimensional, non-linear heat transfer process without volume heat source. The heat transfer function can be expressed as:

$$\rho c \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) = 0 \tag{1}$$

where ρ is the material density, c is the specific heat, T is temperature of boundary unit, t is time. k_x, k_y, and k_z are the heat transfer coefficients in the x, y and z direction respectively. They depend on the temperature and the depositing potential.

For the FDM process, suppose the machine's initial temperature is T_0, the initial condition can be:

$$T(x, y, z, t)\big|_{t=0} = T_0 \tag{2}$$

The surfaces heat dissipation of the machine is mainly through natural heat convection and heat radiation. And the boundary condition can be:

$$-K \frac{\partial T}{\partial y}\Big|_{y=0} = \varepsilon_\theta \sigma \left(T_{y=0}^4 - T_{sur}^4\right) + h\left(T_{y=0} - T_{env}\right) \tag{3}$$

where ε_θ is the effective radiation ratio, σ is the Stefan-Boltzmann constant, T_{sur} is the environment temperature, T_{env} is the temperature of environment thermal liquid medium, h is the convection heat exchange coefficient.

For FDM processing, the required heat transfer depend on the thermal properties of the liquefier, head tip, and modeling materials, as well as the diameter of the filament and volumetric flow rate. The temperature history of interfaces plays an important role in determining the prototype quality.

There are phase transitions during the FDM process. The latent heat on phase transition can be defined as the absorbent or ejective heat energy among the procedure of phase transition. As polymer materials, such as acrylonitrile butadiene styrene (ABS) the latent heat from phase transition is one of the factors which play an important role and can not be ignored. By defining the enthalpy varied with temperature, the phase transition latent heat can be included ANSYS. The unit of enthalpy is J/m3 and can be defined as following:

$$H = \int \rho c(T)\, dT \tag{4}$$

where H is the enthalpy of the FDM material.

III. Finite Element Model of Temperature Field

A finite element analysis for 3D space discretization combined with a Chernoff strategy for processing time discretization is chosen to solve above differential equations. Magenes et al. [17] has proved that this method affords a full discrete scheme converging to the solution of temperature only if the time step and the meshing size are small enough.

The finite element analysis model of FDM process is created in Fig. 1. The 3-D size of the support platform is 30×10×50 (mm). The ABS filament is modeled as a rectangular with dimension 2×2×50 (mm). The energy dissipation in the model includes the natural convection heat and radiation heat with the surrounding medium.

Firstly the cross section of the support platform and the filament was meshed using ANSYS SHELL281 element which includes mid node at the edges for accuracy. And then the meshed area was extruded along the section normal direction with a distance of 50 mm. Simultaneously the 3D finite element SOLID90 with 20-node is applied to the meshing of the platform and ABS filament.

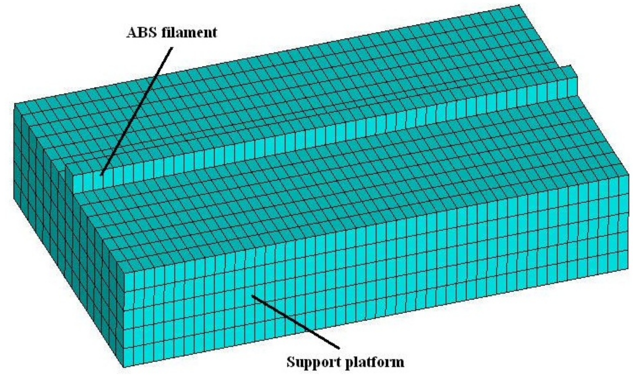


Figure 1. Meshing of the FDM solid model

The heat transfer model has been established and solved under the following assumptions: (1) uniform temperature distribution across the cross-sectional area of the filament; (2) semi-infinite filament length [18].

In the temperature field analysis, the ABS material for fused depositing modelling process is used. And its properties are listed in table 1. Because the mass of the machine foundation is much higher than that of the ABS filament, the conduction between the interfaces would only appreciably change the temperature of the foundation. Thus the conduction heat transfer with the foundation can be considered in the form of convection [18]:

$$\rho c A \frac{\partial T}{\partial t} = A \frac{\partial\left(k \frac{\partial T}{\partial x}\right)}{\partial x} - hP\left(T - T_\infty\right) \tag{5}$$

where A is the area of the filament cross section and it 4 mm^2 in present analysis. And the following boundary condition should be included:

$$T = T_0 \Big|_{x=0}^{t\geq 0}, \qquad T = T_\infty \Big|_{x=\infty}^{t\geq 0} \tag{6}$$

TABLE I. TABLE 1 THERMAL PROPERTIES OF ABS

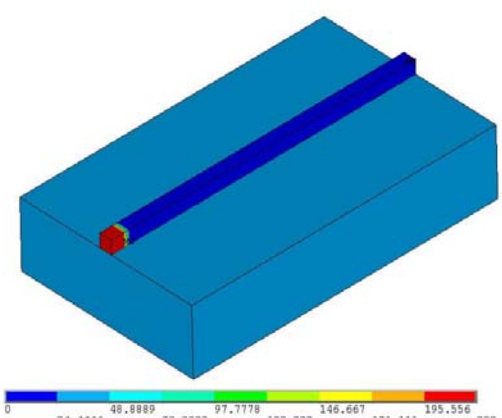
Parameter	Values
Thermal conductivity, k (W/m•K)	0.177
Specific hear, C (J/kg•K)	2082
Density, ρ(kg/m^3)	1050
Glass transition temperature, T_g (^{0}C)	94

Based on APDL (ANSYS Parametric Design Language) strategy, the ABS material 'birth' during depositing processing is simulated using APDL program to provide the parameter input of ABS filament and heat reservoir at different time and position. At the beginning of the solution, the first cycle is supposed that the model has uniform initial temperature and initial boundary conditions. At the following analysis, remove the heat reservoir input of current finished cycle, and then, add new heat reservoir at current position. And the solution process will repeat until the last filament element set is solved. In the solution of the temperature field, the element birth and dead technology is used.

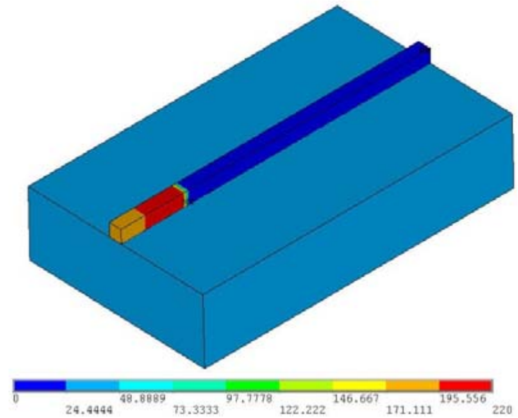
IV. RESULTS AND DISCUSSIONS

During the analysis, let the extruding head moving speed is 0.05 m/s. And suppose the rate of heat absorption is 0.095. Time step of 1s is accepted during the solution. For the simplicity, only one scan road is simulated.

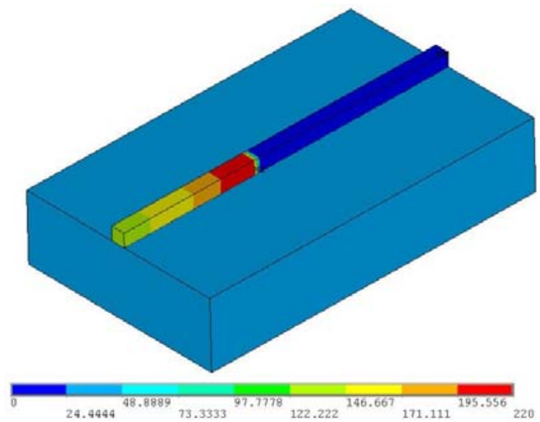
Figure 2 shows the temperature distribution in the ABS filaments and the support platform at time of 1s, 5s, 10s and 20s. The temperature distribution is similar to the actual manufacturing processing. At the beginning of extruding ABS, the other ABS filament material is in 'dead' state and their temperature is zero. The temperature data are produced in succession during the FDM processing. Under the natural conditions, the temperature field in the extruded materials is even and smooth. As above mentioned, the machine support platform has little effect on the temperature distribution of the ABS filament. Because of the high density and mass, the temperature of the support platform is almost keeping at room temperature. In the real product manufacturing stage this case is needed for improving the prototype qualities.



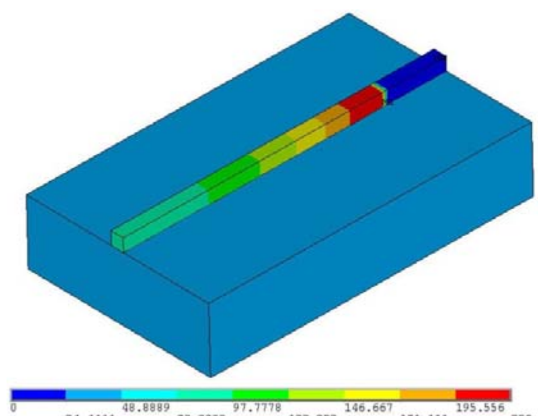
(a) Temperature field at time 1s



(b) Temperature field at time 5s



(c) Temperature field at time 10s



(d) Temperature field at time 20s

Figure 2. Temperature distribution in the FDM processing

Figure 3 lists the temperature change with processing time at the position where the first part of the whole filament was extruded. It shows that the temperature varies nonlinearly with the extruding time. At the beginning of the deposition i.e. at time 0s, the temperature of the extruded ABS filament material is 2200C in accord with the heat booster temperature. The model includes the evolution of the thermal conductivity due to the dependence of the thermal conductivity on the temperature. As soon as the temperature is high enough the conductivity grows. And the latent heat on phase transition makes the temperature exhibit transition properties.

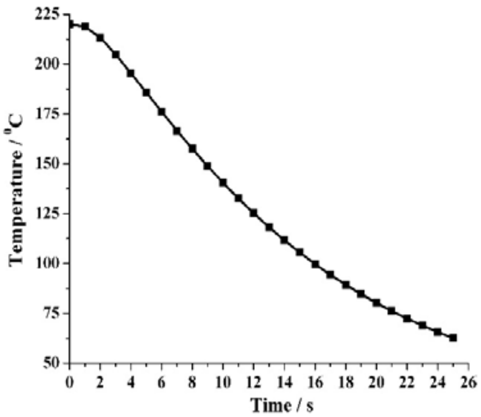


Figure 3. Temperature variation of the initial position

Figure 4 shows the temperature distribution along the ABS filament length direction at 22s. The natural cooling procedure of the deposited ABS material exhibits strong nonlinear character. At 22s, the non-deposited ABS is still in non-active state and the temperature is zero which agrees with the real case.

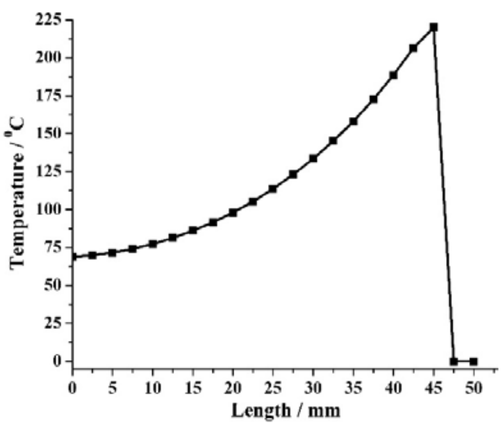
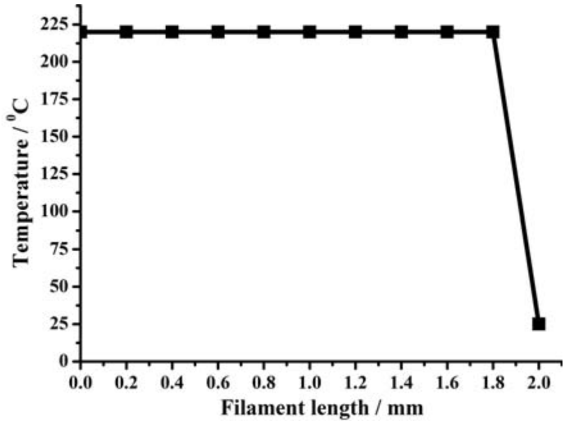
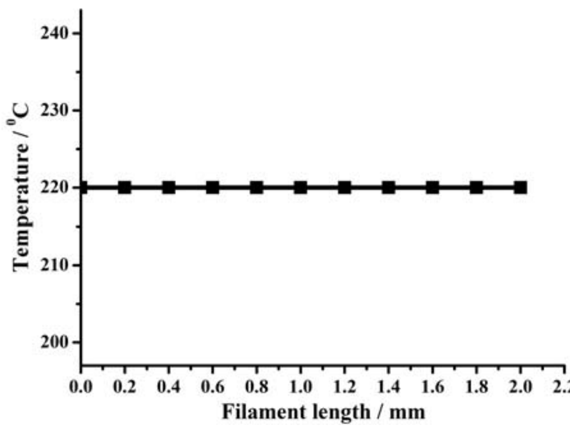


Figure 4. Temperature distribution along the filament length

Figure 5 shows the ABS filament section temperature distribution at one time. The Figure 5(a) is the temperature of the outer profile line vertical to the platform. Because of the common node between and filament and the platform, there is a sharp decrease of the temperature curve. The Figure 5(b) is the temperature of the outer profile line parallel to the platform. The temperature is a constant because there is no common node used by different temperature materials. And the case is agree with the real situation.



(a) Temperature along the vertical direction of the filament section



(a) Temperature along the horizontal direction of the filament section

Figure 5. Temperature distribution of the filament section

V. CONCLUSIONS

Including the phenomenon of the latent heat of phase transition and the variable thermal properties, the transient temperature field distribution during FDM processing is simulated. When the finite element model for analysis of three dimensional temperature fields is established, the effect of the variable thermal property parameters, such as heat conduction and heat capacity should be taken into account. During modeling the three dimensional temperature fields about FDM, the latent heat of phase transition can be treated as enthalpy. The producing procedure of FDM material by extruding method can be solved using 'dead' and 'birth' technology built-in ANSYS APDL. In the course of FDM, the temperature distribution along the ABS filament is almost even.

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