Investigation of Bond Formation in FDM Process

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Abstract

FDM process fabricates prototypes by extruding a semi-molten filament through a heated nozzle onto a platform. The semi-molten material solidifies with the neighboring material diffusely after deposition. The bonding quality among ABS filaments in FDM2000 process determines the integrity and mechanical property of resultant prototypes. This paper describes heat transfer analysis of the FDM process. Sintering experiments were carried out to evaluate qualitatively the dynamics of bond formation between polymer filaments. Quantitative predictions of the degree of bonding achieved during the filament deposition process were made, based on experimental data used in conjunction with heat transfer and sintering models.

1. Introduction

Polymer sintering is a phenomenon encountered in various industrial applications. Sintering is initiated by the adhesion of particles to each other and further densities toward the formation of a homogeneous system due to the action of surface tension. Sintering is one of the dominant bonding mechanisms in the fused deposition modeling (FDM) process. The sintering process has traditionally been studied for use in ceramic materials and metals. However, as reviewed by Mazur[1], its application in polymer processing has raised interest. Several experimental studies have been reported, and models have been proposed to describe polymer sintering. The analytical models describing the rate of coalescence that occurs by Newtonian viscous flow for various polymers have been proposed and assessed in the literature[2,3,4].

The formation of the bonding in FDM process is driven by the thermal energy of semi-molten material. Yardimci[6] developed a family of numerical models for the fused deposition ceramic (FDC) processes. The three heat transfer models were proposed to describe the temperature profile of the deposited roads for FDC. A heuristic part building model was developed to predict the bonding quality for particle loaded systems. The model may be used to assess the thermal suitability of different binders and particle systems. The heat transfer analysis and the results were presented for the ceramic and the binder employed in FDC process. However, a similar analysis method is applicable to the FDM process that uses acrylonitrile butadiene styrene (ABS) as a raw material.

FDM prototypes are composites of bonded ABS filaments and voids. The bonding quality among filaments in FDM parts is an important factor in determining the integrity and mechanical property of resultant prototypes. This paper is aimed at investigating the formation of bond among ABS filaments during the FDM extrusion process. The rest of the paper is organized as follows: the second section devotes to heat transfer analysis; the third section describes the

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sintering experiments; the fourth section presents quantitative prediction of the degree of bonding achieved during the filament deposition process; and the final section of the paper summarizes the major conclusions.

2. Thermal Process in FDM

Since bonding of thermoplastic components in the material is thermally driven, temperature history of interfaces plays an important role in determining the bonding quality. The heat transfer of the process is a function of the thermal properties of the liquefier, tip and modeling materials, as well as the diameter of the filament and volumetric flow rate. Default liquefier temperature T_o of ABS P400 is usually 270^oC, and envelope temperature T_∞ is 70^oC. When the filament is deposited and is in contact with surrounding material, the interface's temperature is well above glass transition T_g of 94^oC. This condition favors the rapid development of adhesive bonds. The filaments gradually cool down to the envelope temperature. The cooling processes are transient and physically complex in their nature. The heat transfer modeling of the FDM process can provide the temperature profile during the cooling process. In order to construct the heat transfer model, thermal properties and coefficients should be determined.

2.1 Material Properties of ABS P400

The heat transfer modeling relies on the thermal properties of ABS P400. The thermal conductivity and specific heat of the ABS P400 as function of temperature were reported by Rodriguez[7]. When the temperature varies from *50* to 250^oC, thermal conductivity coefficient k ranges from *0.15* to $0.19 W/m\cdot{}^oC$, and specific heat C from *1400* to $2400 J/kg\cdot{}^oC$. The density (ρ) of the material has been provided by *Stratasys*® Inc. as $1050\ kg/m^3$. The FDM2000 head is controlled to travel at a speed of *38.1mm/sec* when extruding.

The free convection from the extruded filament to the envelope air plays a major role during the cooling of an extruded filament. The upper limit of the coefficient of the convection in the FDM process is estimated in this section. The extruded filament was viewed as a fine horizontal wire in air of temperature T_∞. The upper limit of the convection coefficient was obtained assuming that the extruded filament temperature was maintained at a constant temperature T_o. The upper limit of the convection coefficient was approximately $100 W/m^2\cdot{}^oC$. The estimation range of h was then chosen as $h=50 \sim 100 W/m^2\cdot{}^oC$. The large range should cover other heat transfer effects, such as heat transfer between the foundation and extruded the filaments.

In addition to the thermal properties of ABS P400, the polymer viscosity (μ) and surface tension (Γ) are important in predicting the neck growth evolution between adjacent filaments. The viscosity of ABS P400 was determined using a Haake RS150 rotational rheometer. The results of the rheological analysis conducted on ABS P400 are *48000, 14000* and $5100 Pa\cdot s$ at temperatures of *200*, *220* and $240^o C$ respectively. The values of zero-shear viscosity reported here were estimated by fitting the Cross model. The viscosity data were correlated to temperature through an arrhenius-like equation:

$$\mu = \mu_o \exp[-b(T - T_o)] \tag{1}$$

2.2 Modeling of Cooling Process

Since the diameter of the extruded filament is fairly small and the uncertainties exist in the knowledge of the convection coefficient, *lumped-capacity analysis* is applicable to modeling the cooling process of the extruded filament. The method assumes a uniform temperature distribution throughout the cross-section. Thus, the temperature variation in the cross-section area can be ignored. The cooling process of a single filament can be simplified into a one-dimensional transient heat transfer model.

Figure 1 is a schematic diagram of the FDM extrusion process. A single deposition road is modeled as a one-dimensional block. The head moves at a constant speed of *v* along the X-axis when extruding. The origin of the reference coordinate is set at the beginning of the extruded filament. The cross-sectional shape of the deposited filament is an ellipse with area *A*. At time *t*, the tip is at position *l=vt*. The thermal energy analysis for the differential element of thickness *dx*, is studied as follows:

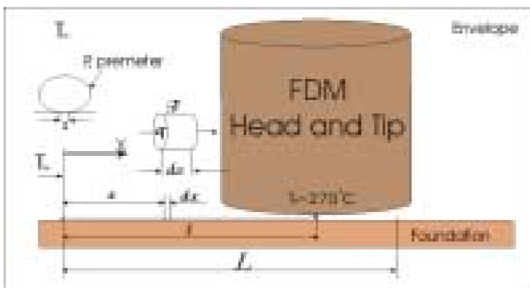


Figure 1: Schematic of heat transfer model

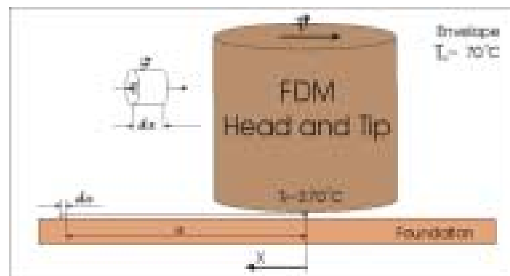


Figure 2: Schematic of semi-infinite model

Energy out the left face $= -kA\dfrac{\partial T}{\partial x}$

Change in the internal energy $= \rho CA\dfrac{\partial T}{\partial t}dx$

Energy in the right face $= -kA\dfrac{\partial T}{\partial x}|_{x+dx} = -A[k\dfrac{\partial T}{\partial x} + \dfrac{\partial (k\dfrac{\partial T}{\partial x})}{\partial x}dx]$

Convection heat transfer with air $= h'(P-S)(T-T_\infty)dx$

Conduction heat transfer with foundation $= h''S(T-T_\infty)dx$

where: T_∞ and T_o are envelope and liquefier temperature respectively; and T represents averaged cross-section temperature; k, $W/m\cdot{}^oC$ is the thermal conductivity of ABS P400; ρ, kg/m^3 is the density of the material; C, $J/kg\cdot{}^oC$ represents the specific heat; h' and h'', $W/m^2\cdot{}^oC$ are convective coefficients of the system; P is the perimeter of the cross-section; and S is the cross-sectional contact length between the filament and the foundation.

Since the mass of the foundation is much higher than that of the filament, the conduction at the interface would not appreciably change the temperature of foundation. The conduction heat transfer with the foundation can be considered in the form of convection, with a convection coefficient h''. For the differential element, the following energy balance is made:

$$\rho CA\frac{\partial T}{\partial t} = A\frac{\partial(k\frac{\partial T}{\partial x})}{\partial x} - hP(T - T_\infty), 0 < x \le vt, t > 0 \quad (2)$$

where $h=h'+h''$, with the range estimated from 50 to $100\ W/m^2 \cdot {}^oC$. This term covers effects of both heat convection with air and conduction with foundation. The boundary condition for the open left side (end) $x=0$ is that heat convected out of surface equals heat conducted into the surface. It can be written as:

$$h(T - T_\infty) = -k\frac{\partial T}{\partial x}, x = 0, t > 0 \quad (3)$$

When the heat loss from the extrusion tip is neglected, the boundary condition for the moving tip side $x=l$ is:

$$T = T_o, x = vt, t > 0 \quad (4)$$

The heat transfer model of FDC presented by Yardimici[6] takes a similar form to the above model when it is reduced to the simplified condition described here. It should be noted that the interactions between the neighboring roads can be considered in a similar way to that for the foundation. Since the frame of reference for the model is fixed to the foundation, the resultant model for the extruding process is a partial differential equation with a heat convection boundary and a moving boundary conditions.

2.3 Cooling Temperature Profile

To obtain the cooling temperature profile of a filament with certain length, a new reference coordinate is defined in Figure 2, with its origin placed at the extrusion tip. In the FDM process, a typical road has a length more than a hundred times of its cross-sectional diameter. Therefore, for modeling purposes, the road can be idealized further into a semi-infinite line. In addition, constant properties are assumed in order to obtain a closed solution for temperature. The approximate solution can be obtained, as shown in Figure 3.

The upper and lower limits as well as averaged values of thermal coefficients are used to estimate the cooling profile. The three surfaces in the figure represent fast, average and slow cooling respectively. The values were obtained by substituting extreme values of coefficients into the model. For the average case, the cooling profile is listed in Table 1. It takes 5 seconds for the end of the filament, $x=0$ to cool from 270 to 100^oC. A transient heat transfer analysis of the FDM process was conducted by Rodriguez[7] using a finite element (FE) method. The results agree generally with what we obtained here.

3. Sintering of ABS 400

3.1 Sintering Process

The schematic sintering process is shown in Figure 4. The cross-sections of filaments are idealized as circles in the figure. The first step of the process is the establishment of interfacial molecular contact by wetting. The molecules then undergo motions toward preferred configurations to achieve the adsorptive equilibrium[5]. Molecules diffuse across the interface, forming an interfacial zone, and/or react to form primary chemical bonds across the interface. The randomization can be reached only after extensive inter-diffusion of chain segments under critical conditions. The magnitude of the neck formed between the filaments gives a partial

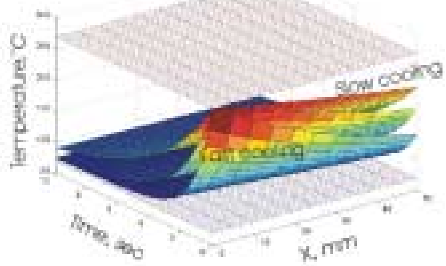


Figure 3: The cooling process temperature profiles for average and extreme cases.

Table 1: Cooling conditions for ABS P400 in the FDM process

Time *sec*	Temperature *°C*	Time *sec*	Temperature *°C*
0	270	5	89.31
0.5	228.31	5.5	85.28
1	195.30	6	82.10
1.5	169.18	6.5	79.57
2	148.50	7	77.58
2.5	132.14	7.5	76.00
3	119.18	8	74.75
3.5	108.93	8.5	73.76
4	100.81	9	72.97
4.5	94.39	9.5	72.35

indication of the quality of the bonding. The dimensionless sintering neck growth is calculated as the ratio of neck radius y with cylinder radius a, as indicated in Figure 4 (a) and (b).

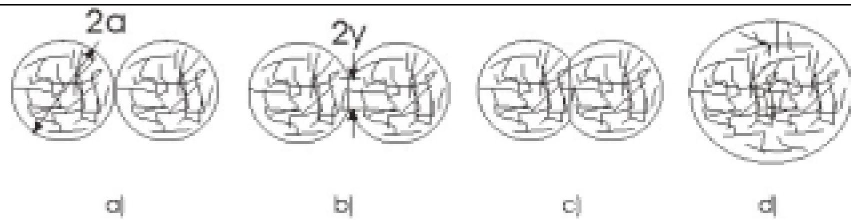


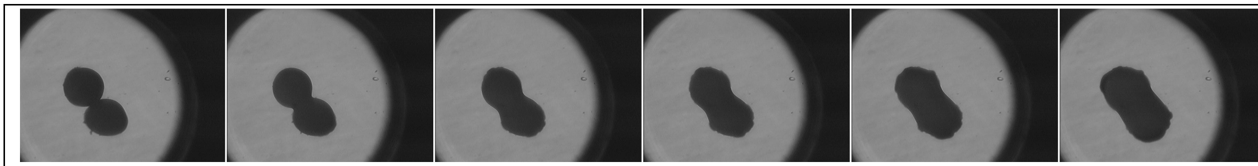
Figure 4: The sintering process between two laid fibers. a) surface contacting, b) wetting, c) diffusion, d) randomization.

3.2 Sintering Experiment

Sintering experiments were carried out to evaluate qualitatively the dynamics of bond formation between polymer filaments. The experiments were performed using a Mettler FP82 hot stage. The sintering process was monitored using a CCD camera coupled to an optical microscope. Each sample consisted of two cylindrical particles of diameter of 470 microns and thickness of 300 microns, approximately. The samples were produced by cutting thin sections of filaments extruded from the FDM machine.

The sintering experiments were carried out at two different conditions: constant temperature and ramped temperature. Under isothermal conditions, the material's viscosity and surface tension are not expected to vary during the experiments. The experiments conducted under non-isothermal conditions were used as a reference to assess the estimates of the material surface tension and its temperature dependence. Isothermal experiments were conducted at 200, 220 and 240^{o}C, respectively. The hot stage was pre-heated to 190^{o}C and the sample placed inside the heat chamber. The temperature was then rapidly increased to the set sintering temperature. For the non-isothermal experiments the temperature was ramped from 190 to 240^{o}C at heating rates of 5, 10 and 15^{o}C/min. The selection of sintering temperatures was based on previous observations made with ABS P400 [8]. Previous results showed to the neck growth for ABS P400 is negligible at temperature below 200^{o}C. Moreover, it was found that degradation of the material would occurs rapidly occur at temperature above that of 240^{o}C.

Figure 5 shows a typical coalescence evolution for ABS P400 cylindrical particles. The projected area of the particles and the diameter of the neck formed between them were measured using the image analysis software ImagePro®. It can be seen in Figure 5 that after relatively long exposure to high temperature the particles' contour become irregular which may be attribute to some thermo-oxidative degradation of the polymer.



a) b) c) d) e) f)

Figure 5: Neck growth evolution for ABS P400 at constant temperature (200^{o}C) a) 0 s, b) 120 s, c) 240 s, d) 390 s, e) 570 s, f) 840 s

4. Prediction of the Bond Formation

4.1 Approach

Quantitative predictions of the degree of bonding achieved during the filament deposition process were made based on experimental data used in conjunction with heat transfer and sintering models. In the FDM process, the initial temperature of the polymer filament is well above its glass transition temperature. The temperature of the filaments then rapidly decreases while a neck is formed between adjacent filaments. This sequence of events is difficult to reproduced while collecting accurate measurements of the dynamic of the neck growth between polymer filaments. The approach used in this work consists in carrying out sintering experiments (neck growth between filaments) under controlled conditions. The sintering experimental data were then used to obtain an estimate of the polymer surface tension. This information was incorporated into a sintering model used in conjunction with the heat transfer model for the FDM process to generate predictions of the neck growth between filaments in the FDM process.

The polymer's surface tension was determined by fitting the experimental data for the sintering neck growth to a Newtonian sintering model proposed by Pokluda and co-workers[8].

$$\frac{d\theta}{dt} = \frac{\Gamma}{a_o \mu} \frac{2^{-5/3} \cos\theta \sin\theta (2-\cos\theta)^{1/3}}{(1-\cos\theta)(1+\cos\theta)^{1/3}} \tag{5}$$

with $\theta = \sin^{-1} y/a$ and where a_o is the initial particle radius. Details on the mathematical development and assessment of the model have been discussed elsewhere[9][10].

Figure 6 compares the dimensionless neck growth profile predicted by the Newtonian sintering model and the sintering experimental results obtained under isothermal conditions. As seen in the figure, there is a relatively good agreement between the experimental data and the model predictions. Based on all the results obtained under non-isothermal conditions, the surface tension of ABS P400 was set to be *0.029* at *240^{o}C* with a temperature dependence $\Delta\Gamma/\Delta T$ = *-0.00345 N/m/K*.

4.2 Model Predictions

The neck growth evolution between polymer filaments in the FDM process is predicted by combining predictions from the heat transfer model (Equations 2, 3 and 4) and a Newtonian polymer sintering model (Equation 5). The temperature dependence of the material properties, namely viscosity, surface tension, heat capacitance, thermal conductivity, and density, is

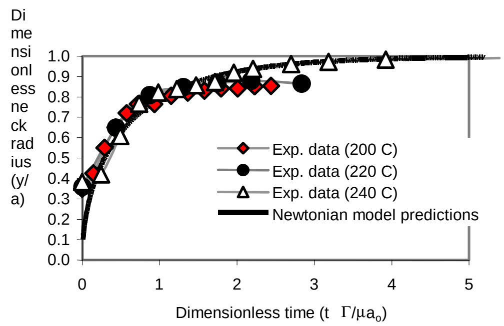


Figure 6: Dimensionless neck growth profiles for ABS P400 at 200°C (Γ=0.054 N/m), 220°C (Γ=0.047 N/m), and 240°C (Γ=0.029 N/m) – Constant temperature sintering experiment.

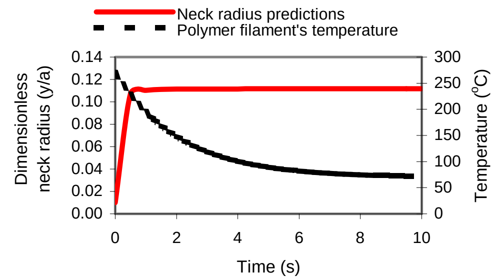


Figure 7: Model predictions for the dimensionless neck growth profile for ABS P400 under conditions outlined in Table Y.

considered in both models. Figure 7 presents the model predictions for the neck growth between polymer filaments in the FDM process. The cooling temperature profile in the figure is the same as that in Table 1. The model predictions are found to be in general agreement with experimental data[8]. It can be seen that most of the neck growth between the polymer filaments occurs within seconds following the extrusion of the polymer on the foundation. The rate and level of wetting that can be achieved between polymer filaments are highly dependent on the extrusion temperature, envelope temperature and convection conditions.

5. Concluding Remarks

In this paper, thermal process during the FDM extrusion was analyzed and the cooling temperature profile of the extruded filament was obtained. Sintering experiments were carried out to evaluate qualitatively the dynamics of bond formation between polymer filaments. Based on sintering experimental data and the results of heat transfer analysis, the degree of bonding achieved during the filament deposition process was predicted quantitatively using the polymer sintering models.

It can be concluded that the filament will not be maintained above glass transition T_g long enough for perfect bonding to occur. As a result, it is expected that the bonding properties are not same as those of ABS material. The bond strength is weaker than that of ABS filament. The FDM prototypes can be viewed as composites of partially bonded ABS filaments and voids. Because of imperfect bonding, the existing methods of calculating the elastic constants of solid with voids are not adequate. Even though the higher values of T_o and T_∞ would help in obtaining better bonding among filaments, which would in turn result in better part integrity, they may not be practical for the process. This is because higher temperatures would affect the dimension accuracy and surface quality of the final part.

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