Parametric Study to Predict the Bond Formation in FDM Process

Deep Vinodbhai Bhalodi, Karan Satishbhai Zalavadiya, and Pavan Kumar Gurrala

***Abstract*—Additive manufacturing techniques are prominently being used presently in the day-to-day manufacturing of products. FDM process, one of the widely used additive manufacturing technique, involves the semi molten filament of plastic that is extruded from heated nozzle and deposited over print table where it gets cooled and solidified by transferring the heat to surrounding which is maintained at relatively very low temperature. Simultaneously deposited filament forms bond with adjacent filament. Heat transfer from the filament occurs in the form of conduction and convection. Therefore, the effect of convection coefficient on bond formation is studied. Also the methodology for prediction of bond dimensions with respect to convection coefficient for the given set of parameters is presented. The procedure to achieve the desired time required for the bond formation is also been attempted.**

***Index Terms*—Additive manufacturing, fused deposition modelling, bond formation, convection heat transfer coefficient.**

I. Introduction

In FDM process, the molten material gets deposited in a predefined path. The filament gradually cools down by transferring heat to the surrounding which is maintained at comparatively low temperature. Cooling leads to solidification of the deposited polymer material which results in bonding between the filaments. Various models have been developed by different researchers to study the neck formation process. In one such model the balance of work done by two counteracting forces namely the surface tension and viscous forces was considered by Frenkel [1], modified Frenkel's model was reported considering bonding between two spherical particles [2]. Also, bonding between two cylindrical filaments was considered and the relation between dimensionless neck growth and dimensionless time was achieved [3]. In FDM a void is formed between four neighboring filaments. The effect of dimensions of this void on strength was studied [4]. Furthermore it was established that the direction of filament deposition between consecutive layers, called raster angle, affect the strength of the part [5]. Many researchers focused over the effect of temperature on the neck growth. As the surrounding temperature is very less compared to temperature at the interface between the bonding filaments, the existence cooling profile was established. In order to acquire the desired profile, definite parametric study is essential and hence the effect of specific parameters like extrusion temperature and surrounding temperature were also presented [6], [7]. Furthermore, it was found that for a part produced by FDM, the layers at the bottom shows quantitatively larger neck growth compared to layer at the top. This is because of the conduction heat transfer that takes place from the subsequently deposited layer above bottom layers, and hence higher temperature is maintained at bottom layers for longer time. In addition to this, it was understood that in FDM the bond formation stops well above the glass transition temperature [8]. Additionally, it was established that Biot number affect temperature field isotropically (in axial direction) and Parcet number affect the temperature anistropically (in radial direction) [9]. In the recent period of time, particular analysis and simulation softwares are being used for thermal modelling. Finite element analysis of extruded filament in FDM is being simulated [10].

From the study, it has been observed that understanding the bond formation is very important in studying the part and its strength. From literature, very little work has been reported on parametric study on heat transfer which is critical for the quality of bond formed in FDM process. Hence, it is essential to understand the characteristics of bond formed and also to evaluate the dynamics bond formation which is termed as neck growth. In the present work, the effect of convection heat transfer coefficient on neck growth process in FDM has been studied. Also it is understood that prior to any manufacturing process, it is essential to evaluate the set of parameters required for the desired results which can certainly be achieved through parametric study. Thus, the variation in neck size has also to be evaluated by varying convection coefficient of heat transfer.

II. Mathematical Model for Parametric Study

From literature, it was observed that strength of FDM produced part is dependent on the dimensions of the neck. Hence, in order to achieve the desired strength, it is essential to get the desired neck size. There are numerous parameters in FDM namely extrusion temperature, surrounding temperature, convection coefficient, diameter of extruded filament, velocity of nozzle head, etc that affect the extent to which bond formation takes place. In the literature, it was established that extrusion temperature has more significant effect over bond formation than ambient temperature and with an effect of convection coefficient on neck growth [4]. For getting a relation between neck growth and convection coefficient, the following properties namely thermal conductivity (k=0.177 W/mK), specific heat (C_p=2080 J/kgK), density (ρ=1050 kg/m^3), glass transition temperature (T_g=94^{o}C), surface tension (Γ=0.029 N/m), viscosity (η=5100

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Ns/m^2) are considered [8]. Since it is very difficult to monitor surface tension and viscosity during entire neck growth process, they are assumed to be constant with temperature and their values are described at 240°C temperature.

A mathematical model was presented assuming the bond formation between spherical polymer particles that relates dimensionless neck growth and dimensionless time as shown in (1) [2].

$$\frac{d\theta}{dt} = \frac{\Gamma}{r_0\eta}\left[\frac{2^{-5/3}\cos\theta\sin\theta(2-\cos\theta)^{1/3}}{(1-\cos\theta)(1+\cos\theta)^{1/3}}\right] \quad (1)$$

The initial radius of extruded filament (r_0) is taken as 0.235 mm [4]. Equation (1), when solved using numerical methods, a graph relating dimensionless neck growth and time is obtained as shown in Fig. 1.

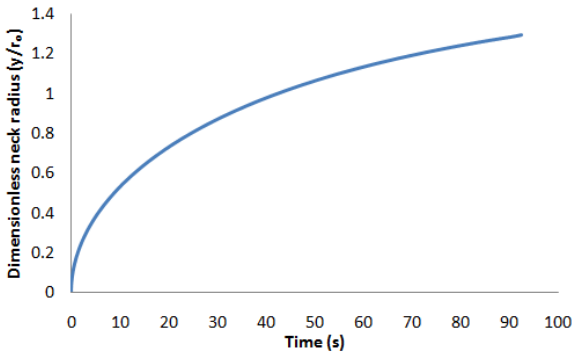

Fig. 1. Variation in dimensionless neck radius with time.

From the graph obtained it is easy to determine the dimensionless neck growth (y/r_0) value corresponding to absolute time (t), where y is absolute neck size. The interface temperature varies continuously with time. Hence, the interface temperature can be described as a function of time as shown in (2) [6].

$$T = T_\infty + (T_o - T_\infty)e^{-mx} \quad (2)$$

where $m = \frac{\sqrt{1+4\alpha\beta}-1}{2\alpha}$, $\alpha = \frac{k}{\rho Cv}$ and $\beta = \frac{hP}{\rho CAv}$ (3)

A = Cross section area,

P = Perimeter of the cross section

v = Velocity of extrusion head

As the distance travelled by FDM nozzle in time (t) is the product of velocity of FDM head (v) and time require to cover the distance (t), (2) can be modified as (4).

$$T = T_\infty + (T_o - T_\infty)e^{-mvt} \quad (4)$$

Therefore, $m = \frac{1}{vt}\ln\left(\frac{T_0 - T_\infty}{T - T_\infty}\right)$ (5)

Further, in Equation (3) when β is made as subject, and represented in terms of m and α, it results in (6).

$$\beta = m(m\alpha + 1) \quad (6)$$

In order to acquire the relationship between convection coefficient and time, the value of m from (5) along with the value of β have to be substituted into in (6), resulting in (7). On further simplification, Equation (8) can be obtained that establishes relation among convection coefficient (h), time (t) and temperature (T).

$$\frac{hP}{\rho ACv} = \left(\frac{1}{vt}\ln\left(\frac{T_0 - T_\infty}{T - T_\infty}\right)\right)\times\left(\frac{\alpha}{vt}\ln\left(\frac{T_0 - T_\infty}{T - T_\infty}\right)+1\right) \quad (7)$$

$$h = \left(\frac{\rho ACv}{P}\right)\left(\frac{1}{vt}\ln\left(\frac{T_0 - T_\infty}{T - T_\infty}\right)\right)\left(\frac{\alpha}{vt}\ln\left(\frac{T_0 - T_\infty}{T - T_\infty}\right)+1\right) \quad (8)$$

The control parameters like extrusion temperature, surrounding temperature and velocity of extrusion head are 270°C, 70°C and 25.4 mm/s respectively [6], [11].

III. Results and Discussions

It has been discussed in the literature that as the interface temperature decreases from extrusion temperature to surrounding temperature, the neck growth stops well before the glass transition temperature. Accordingly, it has been considered that the neck growth stops at 110°C temperature, termed here as "limiting sintering temperature". Fig. 2 is obtained considering the convection coefficient has 75 W/m^2K when substituted in (5). It can be observed from the graph that there is an exponential decrease in the interface temperature with time. The reason behind such a behavior because of larger temperature difference (200°C) between interface and surrounding resulting in higher rate of convection heat transfer. Eventually, due to heat transfer, the temperature at the interface decreases which results into comparatively less temperature difference between interface and surrounding at the later stage. Hence, with the increase in time lapse this decreasing temperature difference results in exponential behavior of temperature with time. It is observed that the cooling profile obtained is for a particular value of convection heat transfer coefficient. This reflects that as the convection coefficient is changed, a new cooling profile will be generated. It means that the time required to achieve the limiting sintering temperature at the interface will also change. Hence it can be established that the time required to achieve the limiting sintering temperature depends entirely over convection coefficient.

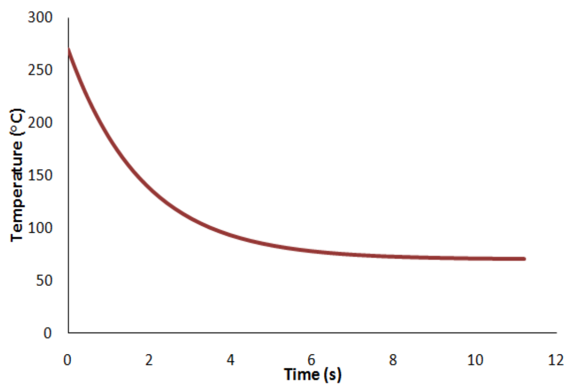

Fig. 2. Cooling profile at the interface between two filaments at h=75 W/m^2K.

In order to understand the effect of convection coefficient, Equation (8) needs to be solved with T=110°C. This helps us understanding the relation between convection coefficient and the time required to achieve limiting sintering temperature. Fig. 3 relates change in convection coefficient with varying time. It is clear from the graph that for larger values of convection coefficient, heat transfer rate will be higher. Therefore less time is required to achieve limiting sintering temperature. While for smaller values of convection coefficient, heat transfer will be at slower rate.

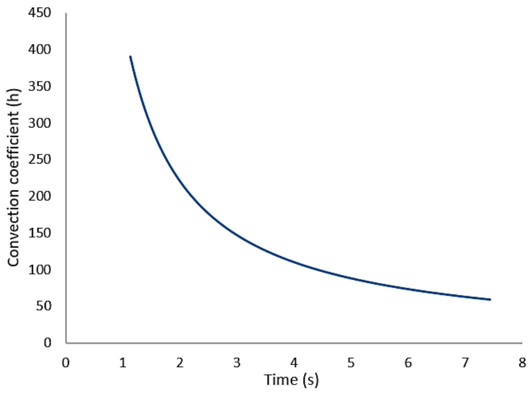

Fig. 3. Convection Coefficient (*h*) v/s Time (*t*).

This results in more time required to achieve limiting sintering temperature. Therefore, based on the design requirements of the end product, the convection coefficient can be set. Depending on the applications, there may arise situations where the time required for solidification need to be accurate enough to obtain the desired properties of solidified filament. Moreover, the time required for solidification that is also the time required for acquiring desired neck growth can be determined from Fig. 1. Having obtained the solidification time, the value of convection coefficient (*h*) can appropriately be set with the help of graph in Fig. 3.

Benchmarking this value of convection coefficient (*h*), required thermal conductivity of gas in the chamber can be found with the help of (9). Therefore, the gases corresponding to this derived thermal conductivity should be selected as the surrounding environment to achieve the predicted result. It is to be noted that Nusselt number (*Nu*) depends on the product of Prandtl number (*Pr*) and Grashoff number (*Gr*) which can be found easily from standard Data Handbook on heat transfer [12], [13]. It is the shape of the filament and the surrounding conditions that decides the value of Nusselt number. With k_f= thermal conductivity of surrounding atmosphere (W/mK), L_c the characteristic length ($4A_c/P$), P and A_c are perimeter and the area of the filament cross-section respectively

$$Nu = \frac{hL_c}{k_f} \tag{9}$$

For a given convection coefficient (*h*), the time required to terminate the bond formation can be obtained with the help of graph shown in Fig. 3. Simultaneously, for the corresponding time (*t*), neck growth can be estimated from Fig. 1.

From the above two cases, the relation between the convection coefficient and the time serves the essential purpose of prediction of the neck growth successfully. However, there exist boundaries in setting the values of convection coefficient. Thus an optimized set of values need to be selected in order to lower the cost of production along with maintaining the quality of the end product. Further, this work helps in optimizing the value of convection coefficient in FDM process. Moreover, the present study also serves as the fundamental work for experimental validation of the effect of convection coefficient in FDM produced parts.

IV. Conclusion

Additive manufacturing is considered as prominent among various advanced manufacturing process. In advanced manufacturing process, prediction of the results helps the manufacturer to achieve higher quality products. Moreover the productivity can be increased considerably. Like any other advanced manufacturing process, successful prediction in FDM can be achieved by performing parametric study. Bonding occurs between two adjacent filaments in FDM process, which is the most prominent part of additive manufacturing. In the present work, the parametric study of convection heat transfer coefficient that influence sintering or bond formation phenomenon has been performed. Also the calculations involved have been discussed in detail, so that in future it will be easy to predict for different set of parameters. Following conclusions are derived from the present work:

1) Graphical results as well as mathematical model have been derived which relates convection heat transfer coefficient with the time required for termination of sintering process.
2) Estimation of convection coefficient of heat transfer with respect to desired neck dimensions between the filaments have been achieved. Hence with this results, suitable surrounding atmosphere may be selected such that its thermal conductivity equals the estimated value.
3) For a given value of the convection coefficient, the process is described which helps to comment over the extent of sintering prior to manufacturing. Limiting sintering temperature is the deciding parameter for prediction.

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