Anusandhan - Rabindranath Tagore University Journal Vol. IX/ Issue XVIII March 2020 ISSN: 2278-4187

A Review on Fused Deposition Modeling of Additive Manufacturing Processes

Santosh Kumar Patel[1], **Dinesh Kumar Soni**[2]
[1]Research Scholar, Rabindranath Tagore University, Bhopal (M.P.) India.
[2]Rabindranath Tagore University, Bhopal (M.P.) India.

ABSTRACT

Fused Deposition modelling (FDM) is the most promising field of additive manufacturing technology. In fused deposition modelling method polymer filament is melted inside the extruder and extruded material were deposited one above another to manufacture product. In FDM process filament feed rate, heat sink fins, extrusion rate, nozzle diameter, pressure drop inside the extruder and temperature distribution are the parameters on which performance were depends. Here in this paper, it review the FDM process evolution and development in FDM process use as commercial 3D printing technique and also investigate the different process parameters on which the performance of 3D printer depends. This paper also reviews the dynamic analysis that is considered for the liquefier during working of FDM process.

Keywords-Fused deposition modeling, 3D printing, process parameters, Development, Dynamic analysis

I INTRODUCTION

Fused deposition modeling is the most prominent field of additive manufacturing. Thirty years into its research and development, additive manufacturing has become a mainstream manufacturing process. Through Fused deposition modeling additive manufacturing process different 3D components can be manufactured adding materials one over another layers with the help of computerized 3D solid model. It does not require any kind of predefined setup for manufacturing the product like jigs and fixtures or any other means. 3D printing as Fused Deposition Modelling (FDM) is one of commonly used additive manufacturing technology for various engineering and well as day to day life manufacturing product applications. StratasysInc was the first to introduce FDM process commercially in early 1990s in USA, during that time additive manufacturing is in its evolution period. In fused deposition modeling, a polymerfilament weather it is poly-lactic acid (PLA),Acrylonitrile butadiene styrene (ABS) or Nylon is feed into an extruder barrel through feed mechanism. Polymer gets melted into the heated block of liquefier where heat cartridge is used as a heat source above heat block, in liquefier heat sink is there to maintain temperature of polymer below melting point so that at the entrance of polymer filament in heat block it remain in the solid form so that it act as a plunger to extrude the melted polymer through nozzle. This enables to build complex 3D objects as the melted bead leaving the nozzle solidifies. The most common materials used in this type of process are amorphous thermoplastics, with acrylonitrile butadiene styrene (ABS), with poly lactic acid (PLA) being the most common. This paper provides more detailed information about the typical components of Fused Deposition Modeling and importantly, gives a review of the state of the art in process modeling and science for these processes.

(a) **Development and uses of FDM process** An FDM technology was first introduced in the 1990s, a growing number of applications are for end-use parts that must meet stringent functional design requirements for mechanical properties, thermal properties and dimensional tolerances. The market position and value of fused deposition modeling in today time is near abour $1.325 billion industry (2010 estimate) and it will reach to over $5 billion by 2020 (Wohlers, 2011[42]). Additive manufacturing products are used worldwide such as in industrial plants, homes/offices, service providers and academic institutions and government/military settings. Research and development in FDM from both government agencies and the private sector have grown rapidly in last decade for the improvement of product quality and ability to produce end product which do not required any kind of other processing(Scott *et al.*, 2012[27]), including the recent establishment of the National Additive Manufacturing Innovation Institute (NAMII, 2012[26]). Based on the report presented by Wohler in 2010[42], Stratasys' market share in the field of AM FDM systems is 3.5 times that of any other FDM system manufacturer near about 41.5 percent of all systems sold in 2010 (Wohlers, 2011[42]). Through report it is found thattill the end of 2010, there were 15,000 Stratasys FDM machines installed worldwide (Wohlers, 2011[42]). The current market of personal fabrication (Lipson and Kurman, 2010[21]) is also dominated by fused filament fabrication-type 3D printing systems, many of which are based on the open-source RepRap project (Jones *et al.*, 2011[14]). The growth and popularity of these systems have been increased remarkably due to the expiration of the initial Stratasys patents on the FDM process, as well as the low cost and easy of construction and handling of the systems. Regardless of the manufacturer, these small-scale machines sell for $1,500-5,000 and print parts from ABS and/or polylactic acid (PLA) polymers.

II DESIGN OF FDM SYSTEM AND SCIENCE

Fused deposition modeling process includes different components which are extruder liquefier and print bed, gantry, filament feed mechanism, build surface, nozzle angle, nozzle diameter build environment, printed objected, and heat source. Fig.1 shows the different components of FDM 3D printer.

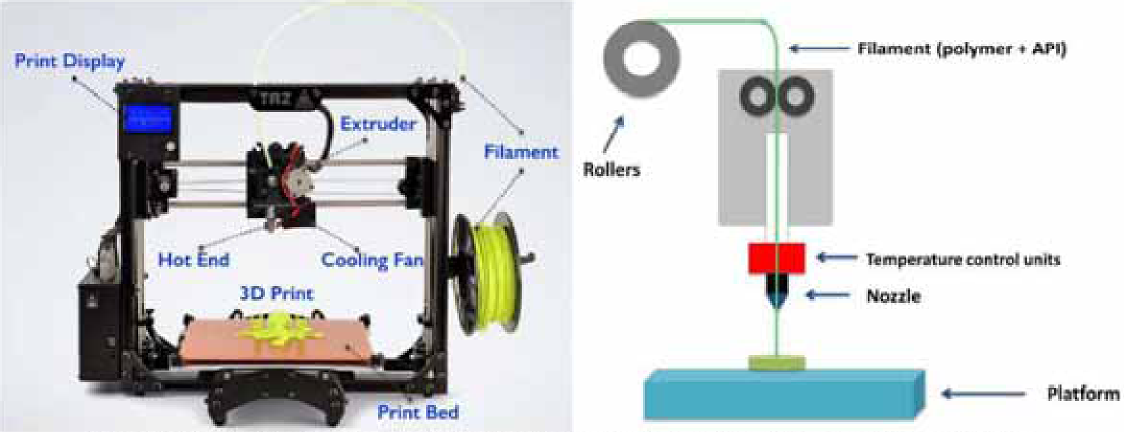

Fig No.1(a)FDM 3D printer (b) configuration diagram of fused deposition modeling

(a) **Material feed mechanism -** In FDM process filament feed materials are commonly thermoplastic polymer (PLA, ABS and Nylon)having diameter of near about 1.5-3 mm. In some small 3D printers systems filament feed material is provided as a loose coil where as in large systems it is provided in the form of reel to provide the filament to the system. In FDM process, feed filament is responsible to push the melted material through the extruder with the help of feed roller mechanism as shown in fig. 1(b). with the help of stepper motor which is connected to one of the rollers gives driving force in order to feed the filament in to the liquefier assembly. One of the rollers has a grooved or toothed surface like a gear to create sufficient friction for the roller to grab the feed filament and feed it to the liquefier inlet without slippage (Agarwala*et al.*, 1996[16]). Sufficient pressure were applied by the roller on the feed filament to smoothly feed inside the liquefier, extra feed force causes the bending of polymer filament.

(b) **Force required by feed mechanism -** During feeding filament is in tension above the feed rollers mechanism, which pull the filament from its reel (Bellini *et al.*, 2004[5]), whereas below the feed rollers it is in compression. The filament feed rate is controlled by the feed stepper motor so as to maintain a constant and consistent volumetric flow rate (Q) of melted polymer material from the nozzle exit. For a desired road width (*W*) and slice thickness (*H*), the linear filament feed velocity (*v*) can be approximated as (Agarwala*et al.*, 1996[16]; Bellini *et al.*, 2004[5]):

$$= \frac{}{} \tag{1}$$

While assuming no slipping in between the filament and rollers during feeding. The filament feed velocity can be simply related to feed roller velocity can be expressed as

$$= \tag{2}$$

Where is the angular velocity and is the radius of the rollers, respectively (Bellini *et al.*, 2004[5]; Agarwala*et al.*,1996[16]). The necessary force required to push the polymer melt through the liquefier can be determined if the pressure drop (Δ) inside the liquefier is known,

$$= \Delta \tag{3}$$

Where *A* is the cross-sectional area of the filament, which is assumed to be equal to the cross-sectional area of the liquefier (Bellini *et al.*, 2004[5]). This enables to calculate the torque ( ) required by the stepper motor

$$= \frac{}{2} \tag{4}$$

And also calculate the power required by the motor ( ) (Bellini *et al.*, 2004[5]):

$$= \tag{5}$$

(c) Liquefier dynamics - In FDM, liquefier is the most important component of 3D printer, where the solid polymer feed material get melted and pushed through a nozzle and extrude melted polymers. The dynamics of the FDM liquefier are critical and challenging in terms of modeling, the thermal properties of polymer melt inside the liquefier is a nonlinear function of temperature and shear rate. The behavior of different polymers during melting inside the liquefier is critical in describing the viscosity and variation of specific heat with respect to temperature. Polymers used during FDM process are generally shear thinning material and they are assumed as to follow a power-law viscosity model (Bellini *et al.*, 2004[5]; Mostafa*et al.*[25], 2009; Ramanath*et al.*, 2008[32]; Yardimci*et al.*, 1997[43]),

$$= (\;2c) \tag{6}$$

Where n is the viscosity, 2cthe shear rate and *K* and *n* are consistency and flow behavior index parameters. The change in viscosity with respect to temperature must also be considered because the material will be nonisothermal as it flows through the liquefier chamber. The change in viscosity with respect to temperature and shear rate-dependent terms, respectively (Bellini *et al.*, 2004[5]):

$$= (\;)_{0} (\;2c) \tag{7}$$

The viscosity depends on shear rate is simply the power-law expression with fit parameters evaluated at some reference temperature, $_0$. An Arrhenius model has been used for the variation of viscosity with respect to temperature,

$$(\;) = [\;(\quad \frac{1}{} - \frac{1}{}_{0}) [\tag{8}$$

Where is the activation energy (Bellini *et al.*, 2004[5]; Karis*et al.*, 1996[17]). Whereas *H(T)* is 1 at the reference temperature. Till now, only power-law viscosity models have been used in order to analyze the flow behavior of polymer melt inside the FDM liquefiers.

Some researchers have assumed that the heat capacity ( ) of melt is constant and it is not varying with the temperature (Bellini *et al.*, 2004[5]; Bellini, 2002[3]). However, is changing with respect to the glass transition temperature ( ) for amorphous polymers. The specific heat of melt varies with respect to temperature. If the temperature is below 300 K it follows the following relation

$$= 4.4 \;\; + 58 \tag{9}$$

Whereas if the temperature of the melt is increases above the 300 K, then it follows the relation,

$$= 1.05 \quad + 1668 \tag{10}$$

(d) Liquefier/nozzle geometry - The liquefier geometry has the greatest impact on the melt flow behavior in the liquefier. In most of the FDM system simple barrel tube of cylinder is used, where nozzle is connected with barrel at one end with the help of treads. In liquefier completely section is divided in to three sections as shown in fig. 2. Earlier systems of fused deposition modeling cylindrical barrel that bend 90° before get connecting to a feeder mechanism like that shown in Figure 1 (Ramanath*et al.*, 2008[32]; Mostafa*et al.*, 2009[25]). For easy analytical analysis and observation the liquefier is typically divided into sections, as shown in Figure3. Different design parameters include the liquefier length ($_1$), liquefier/filament diameter ($_1$), nozzle angle ( ), nozzle diameter ($_2$) and nozzle length ($_2$). Whereas the nozzle diameters are in the range of 0.2-0.5 mm with nozzle angles 120°(Yardimci*et al.*, 1997[43]).

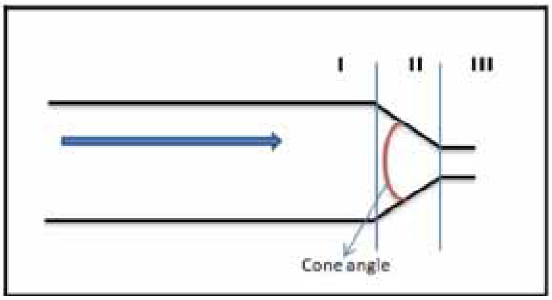

Fig No. 2 different sections of liquefier [5]

(e) Pressure drop estimation - While Polymer material moves inside the liquefier barrel there is some friction due to this some pressure drop inside the barrel taken place. Measure pressure drop taken place at second and third zone as mention in fig. 2, because in this region polymer is in melt form and due to high viscosity pressure drop during this section is high. Through the momentum balance equation inside the liquefier, it is able to predict the melt velocity profile, pressure drop and shear stress profile and with the help to energy balance equation temperature profile of polymer melt inside the liquefier can be predicted(Bellini *et al.*, 2004[5]; Bellini, 2002[3]) and others, done their work (Ramanath*et al.*, 2008[32]) used analytical solutions to the momentum balance equations developed for extruder liquefier (Michaeli, 2003[23]) for cylindrical barrels, conical and cylindrical shapes corresponding to section I, II and III, respectively, as shown in Figure 2 in conjunction with a power-law viscosity model with Arrhenius temperature dependence (equations 7 to 9) to model the liquefier. The assumptions that are consider during the dynamic analysis of melt is incompressible, a no-slip boundary condition applies at the walls of the liquefier and that the flow is fully developed, steady state and laminar (Michaeli, 2003[23]). The pressure drops inside the liquefier in each section are given respectively by:

$$\Delta_1 = 2 \quad {}_1 \left(\bar{\ }\right)^{1/} \int \left(\frac{+3}{{}_1 \quad +1}\right)^{1/} \left[\ \left(\quad \frac{1}{\ } - \frac{1}{\ }\right)\right] \tag{11}$$

$$(\ _2)$$

$$\Delta_2 = \left(\frac{2}{3 \quad (\ /2)}\right)\left(\frac{1}{3/_2} - \frac{1}{3/_1}\right)\times\left(\left(\frac{1}{2}\right)^{2} \quad (\ +3)2^{+3}\right)^{1/} \times \left[\ \left(\quad \frac{1}{\ } - \frac{1}{\ }\right)\right] \tag{12}$$

$$1/ \ (\ +2)(\ _1/2) \quad _2\ 1/ \qquad 1 \quad 1 \tag{13}$$

$$\Delta_{3} = 2_{3} \left(\frac{-}{\int} \right) \left(\frac{\overline{\qquad +3}}{(\ /2)_{2}} \right) \left[\left(\bar{\ } - \bar{\ } \right) \right]$$

Where the dimensions $_1$length of first section, $_3$ length of third section, $_1$and $_2$ correspond to the diameter of first and third section is the nozzle angle of the conical section of the liquefier, and *m* and ∫ are power-law fit parameters (Ramanath *et al.*, 2008[32]; Bellini *et al.*, 2004[5]; Bellini, 2002[3]; Michaeli, 2003[23]). The total pressure drop inside the liquefier is the sum of the pressure drops in different sections

$$\Delta \ = \Delta P_1 + \Delta_{\ 2} + \Delta_{\ 3} \tag{14}$$

III EXISTING RESEARCH EFFORT

The researcher have performed so much work in order to optimize the different input and output parameters of 3D printing in order to optimized it. They used different 3D printers, methods, optimization technique. All the work in the area of fused deposition modeling optimization is investigated and mention in the tabular form

Table No. 1
Existing research efforts

Name of Researchers	Year	Contribution	Working Material	Input Parameters	Output Parameters
Sebastian et.al.[50]	2008	Developed a new method for printer calibration and contour accuracy manufacturing with 3D – print technology	Plaster powder ZP130	Direction and position	–
Sun et.al.[51]	2008	Investigated the effect of processing conditions on the bonding quality of FDM polymer filament	ABS-P400	Liquefier temperature, envelope temperature, convective condition	Mesostructure, Bond strength b/w filaments
Saaidah et.al.[52]	2010	Analyzed fused deposition modeling performance	ABS-P400	Layer thickness, road width, air gap, built style or direction	Dimensional accuracy and surface roughness
Mohammad el.al.	2010	Investigated the effect of layer thickness and binder saturation level parameter on 3D printing process	Zp102 powder & Zb56 binder	Layer thickness, binder saturation level	Mechanical strength, integrity, surface quality,
		Experimentally		Layer	

Nancharaiah et.al.[54]	2010	investigated the surface quality and dimensional accuracy of FDM components	ABS	thickness , road width , raster angle, air gap	Surface quality and dimensional accuracy
Masood et.al.[55]	2010	Evaluated the tensile property of processed FDM polycarbonate material	PC	Build styles, raster angle, raster width	Tensile strength
Arivazhagen et.al.[56]	2011	Performed Dynamic mechanical analysis of FDM rapid processed polycarbonate material	PC	Build style, raster angle, raster width	Storage modulus, complex viscosity, loss modulus
Zhang et.al.[57]	2012	Optimized process parameters for fused deposition modeling	ABS	Wire Width compensation, extrusion velocity, filling velocity, layer thickness	Dimensional error, warpage deformation
Nannan et.al.[58]	2013	Presented a study on Additive manufacturing technology, application and research needs	ABS	–	–
Ismail et. al.[59]	2013	Performed experimental investigation of FDM process for improvement of mechanical properties and production cost	ABSplus-P430	Raster angle, part orientation	Surface roughness, manufacturing time, maintenance cost

Sahu et. al.[60]	2013	Performed a study on dimensional accuracy of fused deposition modeling	ABS	–	–
Villalpando et. al. [61]	2014	Proposed an optimization approach for components build by fused deposition modeling with parametric internal structure	ABS	Deposited layer, raster orientation	Mechanical property, build time, material utilized
Galantucci et. al.[62]	2014	Analyzed the dimensional performance for a 3D open source printer based on fused deposition modeling technique	ABS (3 mm dia)	Change in length, width and height	Dimensional accuracy
Baschetto et. al.[63]	2014	Predicted accuracy in fused deposition modeling	ABS	Layer thickness, deposition angle	Dimension deviation
Yangyang et. al.[64]	2015	Executed 3D printing of shape memory polymer for functional part fabrication	Shape memory polymer	Extruder temperature, scanning speed	Part density, dimensional accuracy and Surface roughness
Isalam et. al.[65]	2015	Performed an experimental investigation in to the dimensional error of powder binder three dimensional printing	Z150 (plaster of Paris) & binder Zb63	_	Base flatness
Singamneni et. al. [69]	2015	Performed Modeling and evaluation of curved layer fused deposition	Fabproxy, ABS polymer	Curved laver thickness	Compressive load

IV CONCLUSION

Fused deposition modeling is a prime method of additive manufacturing and also the most cheapest and easy useable method. Here in this paper it focuses on different parameters on which the performance of FDM 3D printer depends. From the study it has been understood that the parameters like orientation, layer thickness, raster width, feed speed, temperature distribution and model build temperature directly affects the quality of the part. There are various approaches for parameter optimization of FDM process and different techniques for improving the quality of the part.

REFERENCES

[1] Ahn, S.H., Montero, M., Odell, D., Roundy, S. and Wright, P.K. (2002), "Anisotropic material properties of fused deposition modeling ABS", Rapid Prototyping Journal, Vol. 8, pp. 248-257.

[2] Bellehumeur, C., Li, L., Sun, Q. and Gu, P. (2004), "Modeling of bond formation between polymer filaments in the fused deposition modeling process", Journal ofManufacturing Processes, Vol. 6, pp. 170-178.

[3] Bellini, A. (2002), "Fused deposition of ceramics: a comprehensive experimental, analytical and computational study of material behavior, fabrication process and equipment design", PhD dissertation, Drexel University, Philadelphia, PA.

[4] Bellini, A. and Guceri, S. (2003), "Mechanical characterization of parts fabricated using fused deposition modeling", Rapid Prototyping Journal, Vol. 9, pp. 252-264.

[5] Bellini, A., Güçeri, S. and Bertoldi, M. (2004), "Liquefier dynamics in fused deposition", Journal of ManufacturingScience and Engineering, Transactions of the ASME, Vol. 126, pp.237-246.

[6] Bourell, D.L., Leu, M.C. and Rosen, D.W. (Eds) (2009), Roadmap for Additive Manufacturing: Identifying the Future ofFreeform Processing, The University of Texas at Austin Laboratory for Freeform Fabrication Advanced Manufacturing Series, Austin, TX.

[7] Crockett, R.S. (1997), "The liquid-to-solid transition in stereo deposition techniques", PhD thesis, University of Arizona.

[8] Crockett, R.S. and Calvert, P.D. (1996), "The liquid-to-solid transition in stereo deposition techniques", in Bourell, D.L.

[9] Beaman, J.J., Marcus, H.L., Crawford, R.H. and Barlow, J.W. (Eds), Solid Freeform Fabrication Proceedings, University of Texas at Austin, Austin, TX, pp. 257-264.

[10] Frenkel, J. (1945), "Viscous flow of crystalline bodies under the action of surface tension",

[11] Gibson, I., Rosen, D.W. and Stucker, B. (2010), Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing, Springer, New York, NY.

[12] Halidi, S.N.A.M. and Abdullah, J. (2012), "Moisture effects on the ABS used for fused deposition modeling rapid prototyping machine", IEEE Symposium on Humanities,Science and Engineering Research, Kuala Lumpur, pp. 839-843.

[13] Ji, L.B. and Zhou, T.R. (2010), "Finite element simulation of temperature field in fused deposition modeling", Manufacturing Science and Engineering,, Vols. 97/101, pp. 2585-2588.

[14] Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C. and Bowyer, A. (2011), "RepRap – the replicating rapid prototyper", Robotica, Vol. 29, pp. 177-191.

[15] Duineveld, P.C. (2003), "The stability of ink-jet printed lines of liquid with zero receding contact angle on a homogeneous substrate", Journal of Fluid Mechanics, Vol. 477, p. 26.

[16] Agarwala, M.K., Jamalabad, V.R., Langrana, N.A., Safari, A., Whalen, P.J. and Danforth, S.C. (1996), "Structural quality of parts processed by fused deposition", Rapid PrototypingJournal, Vol. 2, pp. 4-19.

[17] Karis, T.E., Dawson, D.J., Davis, C.R., Kono, R.N., Kim, G., Jhon, M.S. and Kim, S.J. (1996), "Rapidprototyping materials rheology", Journal of Imaging Scienceand Technology, Vol.40, pp. 147-154.

[18] Liang, J.Z. (1995), "Effect of the die angle on the extrusion swell of rubber compound", Journal of Materials ProcessingTechnology, Vol. 52, pp. 207-212.

[19] Liang, J.Z. and Ness, J.N. (1997), "Effect of die angle on flow behavior for high impact polystyrene melt", Polymer Testing, Vol. 16, pp. 403-412.

[20] Liang, J.Z., Chan, J.S.F. and Wong, E.T.T. (2001), "Effects of operation conditions and die angles on the pressure losses in capillary flow of polystyrene melt", Journal of MaterialsProcessing Technology, Vol. 114, pp. 118-121.

[21] Lipson, H. and Kurman, M. (2010), "Factory@Home: the emerging economy of personal manufacturing", occasional papers in science and technology policy, US Office of Science and Technology Policy, Washington, DC.

[22] Mao, T., Kuhn, D.C.S. and Tran, H. (1997), "Spread and rebound of liquid droplets upon impact on flat surfaces", AIChE Journal, Vol. 43, p. 11.

[23] Michaeli, W. (2003), Extrusion Dies for Plastics and Rubber:Design and Engineering Computations, HanserVerlag, Munchen.

[24] Middleman, S. (1995), Modeling Axisymmetric Flows Dynamics of Films, Jets, and Drops, Academic Press, San Diego, CA.

[25] Mostafa, N., Syed, H.M., Igor, S. and Andrew, G. (2009), "A study of melt flow analysis of an ABS-iron composite in fused deposition modeling process", Tsinghua Science andTechnology, Vol. 14, pp. 29-37.

[26] Namii (2012), "Namii website", available at: http://namii.org/ (accessed 28 December 2012).

[27] Scott, J., Gupta, N., Weber, C., Newsome, S., Wohlers, T. and Caffrey, T. (2012), Additive Manufacturing: Status andOpportunities, Institute for Defense Analysis: Science and Technology Policy Institute, Washington, DC.

[28] Shofner, M.L., Lozano, K., Rodríguez-Macías, F.J. and Barrera, E.V. (2003), "Nano fiber-reinforced polymers prepared by fused deposition modeling", Journal of Applied Polymer Science, Vol. 89, pp. 3081-3090.

[29] Sun, Q., Rizvi, G.M., Bellehumeur, C.T. and Gu, P. (2008), "Effect of processing conditions on the bonding quality of FDM polymer filaments", Rapid Prototyping Journal, Vol. 14, pp. 72-80.

[30] Osswald, T.A. and Menges, G. (2003), Materials Science of Polymers for Engineers, Carl HanserVerlag, Kempten.

[31] Park, H., Carr, W.W., Zhu, J. and Morris, J.F. (2003), "Single drop impaction on a solid surface", AICHE Journal, Vol. 49, p. 11.

[32] Ramanath, H.S., Chua, C.K., Leong, K.F. and Shah, K.D. (2008), "Melt flow behaviour of poly-epsilon-caprolactone in fused deposition modeling", Journal of MaterialsScience-Materials in Medicine, Vol. 19, pp. 2541-2550.

[33] Rosenzweig, N. and Narkis, M. (1981), "Sintering rheology of amorphous polymers", Polymer Engineering and Science, Vol. 21, pp. 1167-1170.

[34] Thomas, J.P. and Rodriguez, J.F. (2000), "Modeling the fracture strength between fused depositions extruded roads", Solid freeform Fabrication Proceedings, University of Texas at Austin, Austin, TX, pp. 16-23.

[35] Venkataraman, N., Rangarajan, S., Harper, B., Matthewson, M.J., Safari, A. and Danforth, S.C. (2000a), "Processproperty- performance relationship for fused deposition of ceramics (FDC) feedstock materials", in Danforth, S.C.,

[36] DIMOS, D. and Prinz, F.B. (Eds), Solid Freeform and Additive Fabrication, San Francisco, CA, pp. 203-210.

[37] Venkataraman, N., Rangarajan, S., Matthewson, M.J., Harper, B., Safari, A., Danforth, S.C., Wu, G.,

[38] Langrana, N., Guceri, S. and Yardimci, A. (2000b), "Feedstock material property-process relationships in fused deposition of ceramics (FDC)", Rapid Prototyping Journal, Vol. 6, pp. 244-252.

[39] Venkataraman, N., Rangarajan, S., Matthewson, M.J., Safari, A., Danforth, S.C. and Yardimci, A. (1999), "Mechanical and rheological properties of feedstock material for fused deposition of ceramics and metals (FDC and FDMet) and their relationship to process performance", in

[40] Bourell, D.L., Beaman, J.J., Crawford, R.H., Marcus, H.L. and Barlow, J.W. (Eds), Solid Freeform Fabrication Proceedings, University of Texas at Austin, Austin, TX.

[41] Wang, T.M., Xi, J.T. and Jin, Y. (2007), "A model research for prototype warp deformation in the FDM process", International Journal of Advanced Manufacturing Technology, Vol. 33, pp. 1087-1096.

[42] Wohlers, T.T. (2011), Wohlers Report 2011, Report 2010: AdditiveManufacturing and 3D Printing State of the Industry AnnualWorldwide Progress Report, Wohlers Associates, Inc., Fort Collins, CO.

[43] Yardimci, M.A., Hattori, T., Guceri, S.I. and Danforth, S.C. (1997), "Thermal analysis of fused deposition", in

[44] Bourell, D.L., Beaman, J.J., Crawford, R.H., Marcus, H.L. and Barlow, J.W. (Eds), Solid Freeform Fabrication Proceedings, University of Texas at Austin, Austin, TX.

[45] Anitha R, Arunachalam S, Radhakrishnan P(2001) Critical parameters influencing the quality of prototypes in fused deposition modeling. J Mater Process Technology 118(1–3):385– 388

[46] Thrimurthulu K, Pandey PM, Reddy NV(2004) Optimum part deposition orientation in fused deposition modeling. Int J Mach Tools Manufacturing 44(6):585–594

[47] Lee B, Abdullah J, Khan Z(2005) Optimization of rapid proto- typing parameters for production of flexible ABS object. J Mater Process Technology 169(1):54–61

[48] Ang KC, Leong KF, Chua CK(2006) Investigation of the mechanical properties and porosity relationships in fused deposition modeling-fabricated porous structures. Rapid Prototype J 12(2):100–105

[49] Wang CC, Lin TW, Hu SS(2007)"Optimizing the rapid proto- typing process by integrating the Taguchi method with the gray relational analysis". Rapid Prototype J 13(5):304–315

[50] Sebastian Stopp, Thomas Wolff, Franz Irlinger and Tim Lueth(2008) "A new method for printer calibration and contour accuracy manufacturing with 3D-print technology".Rapid Prototyping Journal 14/3 (2008) 167–172.

[51] Q. Sun, G.M. Rizvi, C.T. Bellehumeur, P. Gu, (2008),"Effect of processing conditions on the bonding quality of FDM polymer filaments", Rapid Prototyping Journal, Vol. 14 Iss 2 pp. 72–80

[52] Nur Saaidah Abu Bakar, Mohd Rizal Alkahari, Hambali Boejang(2010)"Analysis on fused deposition modeling performance".Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)ISSN 1673-565X (Print); ISSN 1862-1775

[53] Mohammad Vaezi & Chee Kai Chua(2010)"Effects of layer thickness and binder saturation level parameters on 3D printing process" Int J Advance Manufacturing Technology 53:275–284

[54] Nancharaiah T, Raju DR, Raju VR(2010)"An experimental investigation on surface quality and dimensional accuracy of FDM components". Int J Emerging Technology 1(2):106–111

[55] S. H. Masood, W. Rattanawong and P. Iovenitti(2000)" Part Build Orientations Based on Volumetric Error in Fused Deposition Modeling".Int J Advance Manufacturing Technology (2000) 16:162–168

[56] Arivazhagan A, Masood SH, Sbarski I (2011)"Dynamic mechanical analysis of FDM rapid prototyping processed polycarbonate material".In: Proceedings of the 69th annual technical conference of the society of plastics engineers 2011 (ANTEC 2011), vol 1. Boston, Massachusetts, United States, 1–5 May 2011, pp 950–955

[57] Zhang JW, Peng AH(2012)"Process-parameter optimization for fused deposition modeling based on Taguchi method". Advance Mater Res 538:444–447

[58] Nannan GUO, Ming C. LEU(2013)"Additive manufacturing: technology, applications and research needs " Front. Mech. Eng. 2013, 8(3): 215–243

[59] Ismail Durgun, Rukiye Ertan(2014),"Experimental investigation of FDM process for improvement of mechanical properties and production cost", Rapid Prototyping Journal, Vol. 20 Iss 3 pp. 228 – 235

[60] Sahu RK, Mahapatra S, Sood AK(2013)"A study on dimensional accuracy of fused deposition modelling (FDM) processed parts using fuzzy logic". J Manufacturing Science Prod 13(3):183–197

[61] L. Villalpandoa, H. Eiliata, R. J. Urbanicb(2014)"An optimization approach for components built by fused deposition modeling with parametric internal structures"CIRP17(2014)800– 805

[62] L.M. Galantuccia, I. Bodib, J. Kacanib, F. Lavecchiaa (2015)"Analysis of dimensional performance for a 3D open-source printer based on fused deposition modeling technique" CIRP 28 (2015) 82 – 87

[63] A. Boschetto & L. Bottini(2014)" Accuracy prediction in fused deposition modelling" Int J Advance Manufacturing Technology (2014) 73:913–928

[64] Yang Yang1, Yonghua Chen1,Ying Wei1 & Yingtian Li 1(2015)"3D printing of shape memory polymer for functional part fabrication "Int J Advance Manufacturing Technology DOI 10.1007/s00170-015-7843-2

[65] M. N. Islam1 & Samuel Sacks1(2015)" An experimental investigation into the dimensional error of powder-binder three-dimensional printing". Int J Advance Manufacturing Technology (2016) 82:1371–1380