A Study on Process Parameters of Fused Deposition Modelling Assisted Investment Casting

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Abstract

Now days, FDM process is widely applicable in many field of manufacturing. Materials used are consumable and can be formed into desired shapes for this reason; FDM process is assisting in investment casting (IC) process. FDM is suitable for making patterns for investment casting because of its capacity of producing very small and complex parts. Different process parameters are responsible for quality and accuracy of parts produces by rapid investment casting. Better quality products can be produced without additional cost of hard tooling by proper adjustment of process parameters. Machining economics and product value can be developed to great level by optimizations of machining parameters. This review paper is aimed to find out how different parameters of FDM process affect the accuracy and quality of part produced.
Keywords: Fused deposition modelling; Investment casting; casting patterns

1. Introduction

To produce complex and intricate parts investment casting is one of the suitable processes. However, in prototyping, design optimization, customized and specialized component productions and design iterations if the required numbers of pieces are less; use of the investment casting with high cost of tooling marks prohibitively costly. With the help of 3D printing, one can directly produce parts without necessity of costly tooling (Vyavahare et al. 2020). Without use of costly tools, RP technologies can produce patterns directly, so rapid investment casting is suitable for any type of low or higher grade of production (Rosochowski and Matuszak 2000). With FDM process, any complex shapes can be produced without wastage of material and with shorter time (Wang et al. 2018).

2. FDM working principle

In late 1980's, the FDM technology was established and numerous series of machines were developed (Bakar, Alkahari, and Boejang 2010). In FDM printer thermoplastic materials are used as raw material. In FDM working process, the raw material is extruded on the base of the printer in the form of layer through the heated nozzle. After one layer solidifies the next layer is extruded. In this way the object is built from bottom to up layer by layer. In some objects, there is need to give some support to build the part. There is provision in the 3D printer so that support structures are printed with the object. Later on these structures can be removed. Flow of material can be controlled through the nozzle which has a programmed mechanism to on and off or direct the flow of material (Kumar, Ahuja, and Singh 2012).

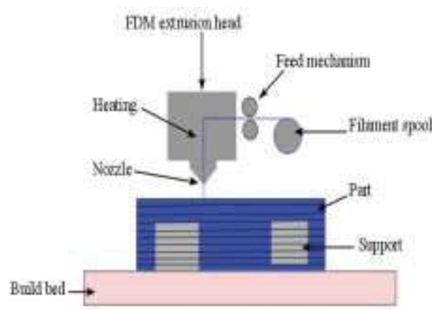

Fig. 1. Schematic of FDM (Alafaghani et al. 2017)

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3. Role of additive manufacturing in Investment casting

The additive manufacturing techniques are being used in the several fields of production. Rapid prototyping technologies can produce patterns without use of costly tooling (Grimm and Grimm 2002). In conventional IC, wax is poured into the metal die and patterns are prepared. Due to brittleness of the wax, patterns are damaged while transporting them to foundry. Also the cost of die is big issue for small production. In rapid investment casting the patterns are made from thermoplastic material so above problems are unraveled. The fused deposition modelling (FDM) is used in investment casting to make different patterns with different materials with different complex shapes (Bassoli et al. 2007; Sivadasan 2012).

Research was made on conversional casting and rapid investment casting, it was found that rapid casting is more suitable as sacrificial pattern comparing with casting (Dickens et al. 1995). The applications of Additive Manufacturing in the field of casting have reduced the time and cost of manufacturing by 50 %. If Additive Manufacturing technology applied to conventional investment casting, it is known as "rapid investment casting" (Kumar, Singh, and Ahuja 2013)

4. Proposed methodology for literature review on FDM

For the literature review author proposed methodology based on different criteria of FDM in casting is shown in Figure 2. Literature is categorized base on out parameters; input processing parameters, optimization methods used, and some new processes used for FDM process optimization. Finally this article focused on how different processing parameters distress on quality of part produced with FDM, which optimization methods can be used for the best output with combination of various input parameters.

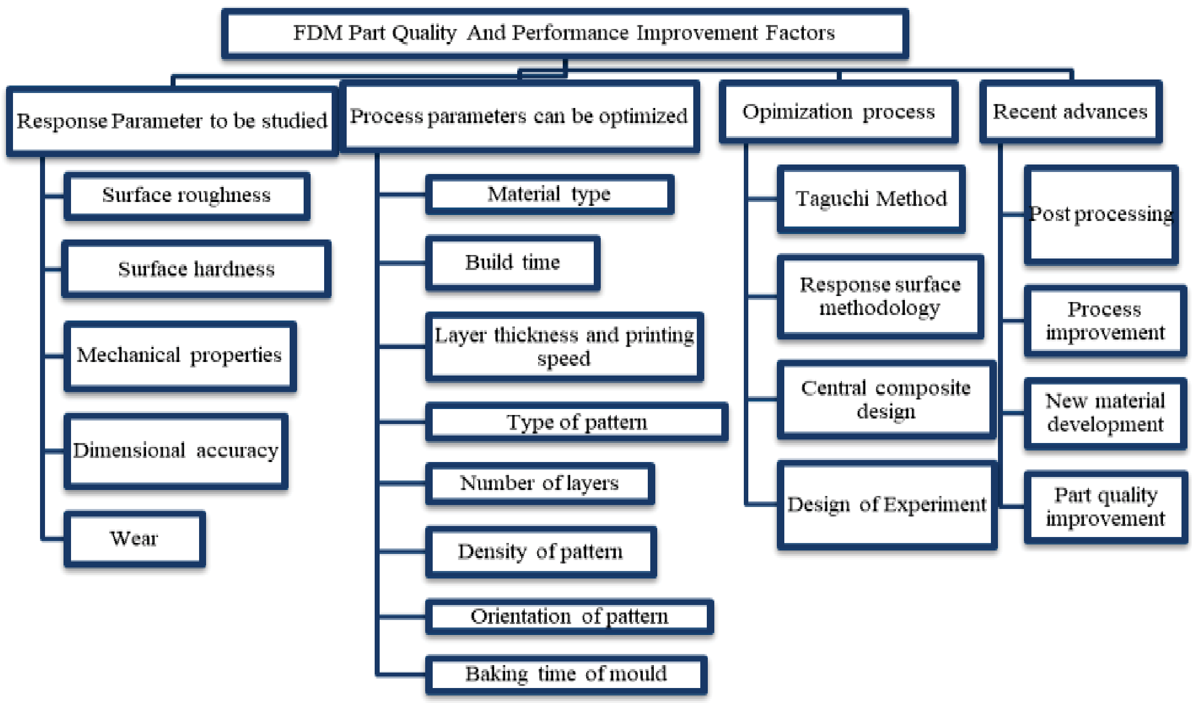

Fig. 2. Classification of literature review on fused deposition modeling and its application in investment casting

5. Parameters that are important in RIC

5.1 Dimensional accuracy of FDM printed patterns

In investment casting patterns dimensional accuracy is a big issue. Casting produce would be defective if the pattern is not correct. Research was made on finding methodology to compute volumetric error of the parts (Masood, Rattanawong, and Iovenitti 2000). Study developed mathematical technique to determine the optimum parameters to obtain dimensional accuracy by FDM. Result was confirmed with actual and experimental dimensions.

Shrinkage of the part found one of the effective parameter on the dimension. Study shows more shrinkage is found in length and width while in thickness direction positive eccentricity is there (Sood, Ohdar, and Mahapatra 2009). Many studies also found best setting of different parameters to increase the dimensional accuracy by using Taguchi's design method and other optimization methods (J. Singh, Singh, and Singh 2017). Orientation while preparing pattern on 3D printer is also effective parameter for dimensional accuracy. Accurate accuracy is found at 900 orientation (Garg, Singh, and Ips 2017).

5.2Surface roughness of FDM printed patterns

In moulding and parts assembly surface finish plays significant role. Surface condition of master patterns is replicated by the mould. To produce quality products, patterns must have proper finish to produce good castings. Surface finish of FDM part is influenced by various conflicting factors individually or interacting with others (Garg et al. 2017). Surface roughness can be reduced by chemical treatment or post processing treatment (Tiwary et al. 2019).

Construction of pattern both hollow and solid does not affect much on surface roughness. Percentage thickness of each layer affect the surface roughness of the side faces, while upper surface gives better quality as compared to bottom surface for both type of construction of patterns (Harun, Safian, and Idris 2009). Post processing treatment is significantly affective to reduce the surface roughness. Chemical treatment provides lower surface roughness (up to 0.30 µm) and better surface finish of FDM parts (Tiwary et al. 2019).

Many researchers worked on the surface defects and causes of it on FDM produced object. They also suggested different parameters optimum setting to reduce the errors (Kumar et al. 2012).

5.3Surface hardness

When there is surface contact between two moving parts, the surface hardness plays vital role in casting. For these kinds of engineering applications surface hardness must be acceptable to reduce wear of the parts. Some studies have been presented to show the effect of different parameters on the surface hardness. Several surface finishing methods like vapour smoothing, surface coating, nitrogen implantation, etc. found effective to increase the hardness of the components (Asgari et al. 2011, 2012; Carneiro et al. 2020; Ganesh et al. 2009). Cooling rate is one of the affecting parameter on surface hardness (Garg et al. 2017). V/A ratio is affecting parameter on hardness of the produced part. For better hardness smaller V/A ratio is preferable (Garg et al. 2017).

5.4Mechanical Properties

The patterns must have adequate strength so that it should not get ruined during casting operation is to be carried out in the foundry. To improve strength of the FDM produced part many research works has been done and shown effect of different parameters (Rohde et al. 2018).

The air gap and raster orientation are greatly affected parameters on the tensile strength of an FDM part. Bead width, model temperature, and color are less affecting parameters (Lee et al. 2007). FDM produced parts measured anisotropic characteristics so the strength of the parts depends on the raster direction and it was not affected by build direction. Other studies shows that impact strength of FDM parts is greatly affected by pouring temperature and less affected by coating thickness (Bhati et al. 2020). Pouring temperature also affect the impact strength of the part. For Aluminum alloy pouring temperature is kept 7000 C to get maximum impact strength (Bhati et al. 2020).

Author has reviewed some research papers on the input parameters and its effect on response parameters of the FDM process and summarized main findings in the table1.

Table 1. Summary of research papers on FDM process parameters and main findings

Researcher	**Material**	**Process parameters**	**Response**	**Tool/Method used**	**Findings**
(Dickens et al. 1995)	Wax	3D Rapid processes	Accuracy, surface finish	Rapid processing applied to different foundries	RP can be applied in casting but wax can be used as FDM material but due to brittleness they should be handled with care.
(Masood et al. 2000)	Plastic	Different shapes of the part	Volumetric error	Mathematical model	Analytical and practical results show good agreements.
(Pandey, Reddy, and Dhande 2003)	ABS	Build orientation, layer thickness	Surface roughness	ANOVA	Prediction of model good agreements with experiments.

(Anthony 2004)	ABS	Layer thickness	Mechanical properties (thermal expansion, tensile strength, flexural strength)	Dynamic Mechanical Analysis(DMA), ANOVA	Layer thickness influences the tensile strength of FDM parts.
(Lee, Abdullah, and Khan 2005)	ABS	Air gap, Raster angle, Raster width, Layer thickness	Elastic performance	Taguchi method, signal-to-noise ratio, and analysis of variance	Layer thickness, raster angle and air gap significantly affect the part.
(Ahn et al. 2009)	ABS	Layer thickness, surfaces angle, c/s of filament	Roughness	Mathematical equation	Computed value and empirical values validate each other.
(Galantucci, Lavecchia, and Percoco 2009)	ABS	Tip dimension, raster width, slice height, chemical treatment	Surface finish	Contact and non-contact optical system	Effects of parameters are optimized and chemical treatment found to be useful in obtaining better surface finish.
(Galantucci, Lavecchia, and Percoco 2010)	ABS	Chemical treatment	Mechanical Properties, surface quality	Central Composite Designs (CCD)	Chemical treatments improve the surface finish of the part.
(Chhabra 2011)	Aluminum	Shell mould wall thickness, layer thickness, part orientation	Dimensional accuracy, surface roughness	Z-casting (pattern less casting)	Reducing shell mould wall thickness produced better quality parts
(Chang and Huang 2011)	ABS	Contour width, Contour depth, Part raster width, Raster angle	Profile error, extruding appearances	ANOVA	Contour width is significant factor for profile error.
(Kumar, Singh, and Ahuja 2015)	ABS	Layer thickness, type of support, model interior and scale	Dimensional deviation, surface roughness, micro hardness	Solid works design software	By assisting of FDM process in the investment casting, hybrid method of production was developed.
(Boschetto and Bottini 2015)	ABS	Layer thickness, deposition angle	Roughness	Mathematical formulation	Barrel finishing action deeply affects the profile of the parts.
(Belter and Dollar 2015)	ABS-P430	Print orientation	Part strength	Instron Testing system	Process of fill compositing made low value parts.
(Christiyan, Chandrasekhar, and Venkateswarlu 2016)	ABS + composite material	Layer thickness, printing speeds,	Tensile strength, flexural strength	Universal testing machine	To obtain better tensile and flexural strength there is need of low printing speed and low layer thickness.
(Boschetto and Bottini 2016)	ABS	Deposition angle, layer thickness	Dimensional accuracy	Mathematical formulation	Analytical result shows good agreement with practical.
(J. Singh et al. 2017)	ABS+	Drying time of coating, and thickness of the mould	Dimensional accuracy and surface finish	ANOVA	Significant factors for 4 different processes have been found.
(Garg et al. 2017)	ABS	Type of Pattern, Ratio of volume and area, Orientation of the Pattern, Pattern density, Thickness of the mould,	Dimensional accuracy, surface finish, and surface hardness	Taguchi design of experiments, ANOVA	Ratio of volume and area, Orientation of the Pattern, and thickness of the mould are influencing parameters.

(Alsoufi and Elsayed 2017)	PLA	Angular direction, nozzle diameter, layer height, build time, print speed	Surface roughness	OriginLab® 2017 software	Nozzle diameter, layer height influence the most surface roughness
(Rohde et al. 2018)	ABS and polycarbonate	Raster angle, build orientations,	Anisotropic behavior	Universal testing machine	Anisotropic behavior was found with different values of parameters.
(Fernandes et al. 2018)	PLA	Infill Density, Extrusion Temperature, Raster Angle, Layer Thickness	Ultimate Tensile Strength, Yield Strength, Modulus of Elasticity	ANOVA	Optimum value of the parameters are found
(Dakshinamurthy and Gupta 2018)	ABS	Raster angle, slice height, raster width	Visco-elasticproperties	Taguchi Approach	Slice height and raster width are affecting parameters.
(Armillotta, Bellotti, and Cavallaro 2018)	ABS plus-P430 [60]	Layer thickness	Part dimensions	ANOVA	Increased layer thickness reduces the surface finish and has moderate effect on warpage of the part.
(Singh and Gupta 2019)	ABS	Part orientation, number of slurry coating layers, temperature	Hardness	ANOVA	Melting temperature plays significant role on hardness
(Bhati et al. 2020)	A-359 aluminumalloy	Pouring temperature, pouring time, coating thickness	Impact strength	Taguchi method	Pouring temperature plays significant role on strength.
(Kumar et al. 2021)	poly(ethylene glycol) di acrylate	Finite element formulation with stiffness regions	Topology optimization setting	ABAQUS analysis	Optimized results are validated with software.

6. Input Process parameters

6.1 Material

Light weight, low cost and high strength of polymer and its composites cause them on higher demand in all manufacturing industries. Research studies found parametric solution for different material compositions in FDM (Subramaniyan et al. 2020). Standard materials used in FDM are PLA, ABS Wax, polyethylene, polypropylene etc..

Some study shows ABS built pattern is suitable for rapid investment casting and it is having more quality advantages comparing with other additive manufacturing materials (Gouldsen 1998). Type of material also plays significant role on the hardness of the part.

Table 2. Categorization of reviewed literature related with optimization of process parameters on the base of materials

Material	**Researcher**
ABS	D. Ahn. 2009, S. H. Ahn 2002, Anthony 2004, Bakar 2010, Boschetto & Bottini 2016, Boschetto & Bottini 2015, Chang & Huang 2011, Coogan & Kazmer 2017, Dakshinamurthy & Gupta 2018, Galantucci 2010, Galantucci 2009, Garg. 2017, Gouldsen 1998, Harun. 2009, Kumar. 2015, B. H. Lee. 2005, C. S. Lee. 2007, Pandey. 2003, D. Singh 2020b, D. Singh 2020a, D. Singh, Singh, Boparai 2018, J. Singh 2020, Ranvir Singh 2019, Rupinder Singh & Gupta, 2019, Sood 2012
ABS+	Alsoufi & Elsayed, 2018, J. Singh 2017, J. Lee & Huang 2013
PLA	Alsoufi & Elsayed 2017, Fernandes 2018, Rajpurohit & Dave, 2018, Rajpurohit and Dave (2018b)
PC	A. Boschetto & Bottini, 2014, Salazar-Martín 2018, Tanikella 2017, Rohde 2018, Alsoufi & Elsayed, 2018, Singh 2018
ABS + hydrous magnesium silicate	Christiyan 2016
ABS, Nylon	Rupinder Singh 2016, Vishwas 2018
ABS, Polycarbonate	Rohde 2018
Wax	Dickens1995

6.2Build time

Building time for any object depends on the height of the object in Z direction. So, to reduce the build time designing of object with less overall built height is necessity. Build orientation, printing speed, part size, layers thickness also effect on the build time for a single component or an assembly (Abdulhameed et al. 2019). Some study found how build time affect the production time and developed intelligent approaches to reduce build time (Peng 2014). From the literature it is found that layer height and filling velocity are affecting parameters for build time.

6.3Layer thickness and printing speed

Study shows that strength of the FDM parts mainly depend on the printing speed and layer thickness. Better bonding happens between two successive layers at low printing speed with low layer thickness which revealed better tensile strength and flexural strength. With optimum printing speed of 30 mm/s, maximum tensile and flexural strength was observed (Christiyan et al. 2016). Many research studies found that the layer thickness is the most influencing parameter on the surface finish (Anthony 2004; Armillotta et al. 2018).

6.4Number of layers (mould thickness)

Mould shell wall thickness is the most influencing parameters on the dimensional accuracy of the castings. To increase the cooling rate mould thickness should be kept lower which increases the hardness of the part produced (Garg et al. 2017). Many studies recommended the appropriate shell wall mould thickness of the cavity, for the determined accuracy of the parts. Experiments with different mould thicknesses has been performed and suggested value of mould thickness for higher dimensional accuracy has been found (Singh and Singh 2016b). By reducing the mould thickness surface hardness can be increased (J. Singh, Singh, and Singh 2020). In general number of layers affects the dimensional accuracy significantly (R. Singh et al. 2017). By increasing number of layers, the strength of part could be increased. Temperature gradient develops at the bottom of the part due to which diffusion occurs, which strengthen the part

6.5Density of the pattern

In case of conventional investment casting dewaxing is important step, similarly during burning of the patterns density is important parameter in FDM. Many studies suggested that density of pattern does not mark on all responses. But some study suggested to use low density pattern to minimize cracking of shell. Keeping low density of pattern would produce little ash in the mould and cost effective too. Number of layer and density of patterns are influencing parameters for surface hardness of the parts (Singh and Singh 2016b).

6.6Orientation of pattern

Surface roughness of the parts is affected by the orientation at which the part is built. The orientation of the part also affects the dimensional accuracy as well as surface finish of the patterns produced on FDM machine (Garg et al. 2017). With proper orientation, support structure required would be less due to which cost of material required will decrease. Ultimately there will be savings of fabrication time and materials. Studies suggested optimum level of orientation to improve quality and time of product.

Deposition angle (raster angle) plays a very significant role on the dimensional accuracy of the parts. Patterns produced at 90^0 orientation gives better surface finish (Pandey et al. 2003; D. Singh, Singh, and Boparai 2020). (Masood 2000) developed system with complex geometry with different layer thickness with part orientation. Generic algorithm was developed to find best orientation in order to minimize volumetric error in the component.

6.7Baking time of mould

In the process of investment casting, mould baking time is important parameter. During baking time pattern is burnt out from the mould. Proper baking time may cause good surface finish in FDM parts. Baking time of mould is significant parameter for hardness. Optimum value was kept 40 min as baking time for proper burn out of the pattern (D. Singh et al. 2020). Surface finish is affected by drying time of primary coating. To improve the surface finish drying time of primary coating is increased (J. Singh et al. 2017)

From the literature survey various process parametric effects on the out parameter of the FDM part is found and summarized in the table3.

Table 3. Main finding parameters on quality of FDM parts reviewed from research papers

Quality measures	Main finding parameters from review
Dimensional accuracy	Layer thickness, Raster angle, air gap
Surface Roughness	Pre and Post-processing processes, Layer thickness
Mechanical properties (Strength)	Printing speed, Layer thickness
Surface Hardness	Mould thickness, Baking time, density of mould,

7. FDM process parameters optimization

In manufacturing field quality products with low cost and shorter time periods are on demand. So to fulfill these needs, process parameters must be optimized in particular machine application (Patel, Patel, and Patel 2012). In research papers different methods for optimization of process parameters are found, which are response surface methodology, Taguchi method, factorial design, Central Composite Design, etc. Optimization of processing parameters provides the correct amendments of different parameters which lead to improve the quality and strength of the parts. Many researchers found the effects of various parameters on the quality characteristics for the FDM process and suggested best setting of input factors for the proposed response parameters (Chang 2011; Garg. 2017; Singh and Singh 2016a). Many researchers found ANOVA and Taguchi method as much suitable technique to optimize process parameters on FDM.

8. Conclusion

From the literature review following conclusions are found:

- ABS is more suitable material for producing the patterns in rapid investment casting. Complex geometries could be produced with ABS material in FDM which in turn useful for investment casting.
- To produce better quality products, dimensional accuracy and surface finish of the FDM patterns should be kept higher. Process parameters which affect the dimensional accuracy and surface finish are: orientation, layer thickness, raster angle, raster width, density of pattern, air gap. With optimization techniques these process parameters can be optimized.
- There is necessity to discover the influence of various input factors like density of pattern, backing time, orientation of the work piece, layer thickness, number of layers, printing speed, etc. on the dimensional accuracy, surface finish, surface hardness and mechanical properties of the part produced. Few studies have been found on the experimental studies of various parameters optimization in rapid investment casting.

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