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A Numerical Study on Warpage Deformation of Fused Deposition Modelling Built parts

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Abstract:
This research paper aims to describe and make a clear study about the warpage, also known as deformation causing errors in Rapid Prototyping (RP) processes. In most of the RP processes, warp deformation plays a vital role in narrating the part quality and durability. The mechanical strength, part and dimensional accuracy are severely affected by this undesirable effect produced during the fabrication process. Fused deposition modelling (FDM), one of the advanced technology among all RP technologies undergoes such type issues during part building. Since FDM follows the layer by layer build mechanism, hot semi-molten material is extruded over the bed to form the required layers. During the part building process, layers are subjected to forced convection inside the build chamber. The non-uniform cooling of build parts from the molten to the chamber temp leads to shrinkage and warp deformation in the build parts. Overcoming these issues can improve the part strength as well as part accuracy. The effect of FDM process parameters such as raster width, part orientation, part length and part width on part strength and accuracy of the FDM build parts are carried out using MATLAB R2017a software. The significance of each process parameters are checked and their effects are studied.

Keywords: Rapid Prototyping, Shrinkage, FDM, Warpage

Introduction:
Fused Deposition Modelling (FDM)comes under the group of Rapid Prototyping (RP). RP is a technique used for the quick manufacturing of 3D models. The word “Prototype" comes from the Latin words “proto” and “typus” which means “original” and “model”. Hence “Rapid Prototyping” (RP) means creating a prototype rapidly or quickly. It is done by using Computer-Aided Design (CAD) data software. Printing different parts and assembly of different parts are done through Additive Manufacturing. In the field of manufacturing, RP is used to create a 3D complex model from CAD data without any human intervention. Among all processes, FDM is the preferred one because of its popularity, adaptability and inexpensiveness. In this process, a thermoplastic material is used as a filament. The thermoplastic filament is given to the nozzle via an extruder head. The head then moves in three dimensions to deposit one layer over another to print the 3D model. FDM mainly uses ABS and PLA filament which is passed through a heated extruder and nozzle and then deposited in a layer by layer manner according to the CAD data to manufacture the complete part. Sometimes the printed part is not able to maintain the desired shape, geometry, dimension and accuracy as per the CAD data and it causes Warpage. This paper aims to take a look over the Warpage, otherwise known as deformation caused in FDM parts. Warpage or deformation is raised when the printed part becomes unable to maintain the desired dimensions, geometry and accuracy. In the FDM process, ABS is extruded from the nozzle in semi-molten hot form and deposited in a layer by layer manner to build the complete product. At that time the semi-molten deposited material starts cooling to get

solidified and there the issue of deformation or warpage may arise because of the non-uniform cooling of hot material. It is said that if the shrinkage throughout the part is uniform, then the molding will not deform or warp. Also achieving minimum shrinkage is a really difficult task. Over years some analyses were made to understand the warpage and deformation and the influence of parameters over it. As the FDM involve the processing of the material by thermal cycles which can also be the reason to create distortions or warpage in the built parts.

According to Wang et al. [1] the warp deformation is an important index to evaluate the quality, as well as the strength of the FDM build parts. This deformation is generally influenced by material characteristics, fabrication parameters and geometrical structure of CAD model and deposition path planning. A mathematical formula was proposed earlier, which can be utilized in controlling and adjusting the deformation.

The formula as, Inter layer Warp deformation of the Part

$$\delta = R\left(1 - \cos\frac{L}{2R}\right) = \frac{n^3 \Delta h}{6\alpha(T_g - T_e)(n-1)} \times \left\{1 - \cos\left[\frac{3\alpha L}{n\Delta h}(T_g - T_e)\frac{n-1}{n^2}\right]\right\}$$

Where,
R= Radius of Curvature,
L= Stacking Section length,
n= number of layer deposition,
Δh= Thickness of the Layer,
α= material linear shrinkage rate,
T_g= Glass transition temp and
T_e= Chamber Temperature.

The warp deformation increases with an increase in raster length and shrinkage rate and decreases with an increase in layer numbers. In order to get minimum deformation of the build parts, the chamber temperature (T_e) should be maintained same as the glass transition temperature (T_g) of the build material.

Alsoufi et al [2] studied the effect of printing speed and nozzle temperature on the warpage deformation and concluded that with suitable selection of process parameters can reduce the warpage deformation significantly. Nazan et al [3] adopted DOE with four process parameters such as layer temperature, infilled density, 1st layer height and other layer height and examined 16 samples to verify its effect on warpage deformation. A coating layer of synthetic polymer called Polyvinylpyrrolidone (PVP) is used over the platform bed to reduce the deformation of the 1st layer. They proposed a formula to find out the warpage deformation numerically.

Fig-1 Warping deformation

Warping Deformation = y= $y_1 - y_2$

Where,

y_1= printed height,

y_2= height after warping

Out of four process parameters, temperature and 1st layer height has significance influence over the deformation. Panda et al. [4] used MEM-300 3D printer and considered exceptional parameters like line width compensation, extrusion velocity, filling velocity, layer thickness, and nozzle diameter to check its effect on deformation. Internal stress generated due to the contraction of layers affects the part accuracy by producing deformation including warp & inner delamination or cracking. The non-uniform distribution of temperature inside the build chamber, lack of pre-heating of the base plate and improper control of process parameters are responsible for warp deformation. There is a high non-linear interaction effect between the dimensional errors, warp deformation and Genetic Programming.

Mahapatra and Panda [5] concluded that, during part building, the deposited layers contracts and results in inner stresses, which affect the part size by creating deformation, shrinkage, including warp and inner-layer delaminating or cracking. Guerrero-de-Mier et al [6] investigated the effect of process parameters along with the chamber as well as material temp on the warp deformation. The stacking section lengths, thermal shrinkage co-efficient of material and chamber temperature are the key factors to affect the warp deformation. They developed a method to reduce the warpage through limiting stacking section length, splitting model in bricks spatially locked with configurable gaps between them by adopting dispersion- accumulation mechanism.

Wang et al [7] used the FDM technology to print JJY tablets, where they tried to reduce the warping deformation by using the combination of 75% ethanol and Hydroxypropyl methylcellulose (HPMC) 9%, which acts as an adhesive on the bed. They considered the best parameters as drying at room temperature, filling density 40%, and 3mm model height, 2 numbers of outer rings and 15mm /s print speed.

Kuo et al [8] conducted an experimental study by designing and fabricating a closed chamber to maintain the chamber temperature and increase the modeling space up to 2.75 times for the FDM machine. The bed temperature and chamber temperature has significant effect on the warpage. Taguchi method was adopted to reduce the warpage of parts printed with ABS, which is used widely to determine optimal process parameters. Optimal process parameters recommended are nozzle, bed and chamber temperature 230^0C, 93^0C and 43^0C respectively at a print speed of 60mm/sec.

According to Kunal Singh [9] said that, solution of warping is divided in to 3 categories as:

a) Treating the bed with chemical solution
b) Providing an enclosure
c) Modifying internal structure of the model.

Fitzharris et al [10] adopted process simulation model using Polyphenylene Sulfide (PPS) as the build material found that crystallization process occurs during the cooling of layers leads to warpage of the fabricated parts. Material Coefficient of thermal expansion (CTE), thermal conductivity, heat capacity and Young's Modulus were considered to establish the relationship between material parameters and warpage values. Decreasing the coefficient of thermal expansion results in decrease in the FDM part warpage.

Antonio et al. [11] found that distortion for rectangular plate depends on maximum dimension on the horizontal plane as a beam deflection. Due to the involvement of repetitive thermal cycle leads to distortion and warpage. Vyavahare et al [12] conducted experimental study using ABS to build Pyramidal & Conical parts to check the influence of 5 parameters such as: layer thickness, wall print speed, build orientation, and wall thickness and extrusion temperature on warpage. Various researchers have worked on warpage deformation and surface roughness generated due to part distortions [13-14].

Among all process parameters raster angle, raster width and chamber temp have significant effect on the warpage and deformation [15-19]. This part warpage and deformation leads to part failure and dimensional inaccuracy. However, warpage and deformation can be minimized up to certain extent by selecting proper FDM process parameters. Adopting various artificial algorithms, better parameter setting can be suggested to improve the part quality and accuracy. A number of research works are carried out to check the significance of process parameters on warp defamation, but very less research works are done numerically.

<u>Methods and Analysis:</u>

Our research work is focused to minimize the warpage deformation and to check the influence of process parameters over it numerically.

For the numerical analysis of warpage deformation of FDM build parts, MATLAB R2017a software is used. The design of experiment (DOE) approach is adopted which deals about concerning the minimum number of experiments necessary to develop an empirical model of a research problem and a methodology for setting up the necessary experiments. Hence we have adopted the same. Response surface methodology (RSM) technique has the ideology to manage the experiments in a chronological manner to get optimal response and validation. RSM technique with face centered central composite design is selected for the experimental purpose and in our case it suggests 13 settings for experimental runs, which includes 08 axial points and 05 center points. All numerical data are gathered using MATLAB for each run order taken from DOE and listed in the table below.

Table1: Numerical data

Serial Number	Raster Width in mm	Raster Angle in degree	Number of Lines in magnitude	Raster Length in mm
1	0.2	30	304	60
2	0.4	30	152	63
3	0.2	60	378	34
4	0.4	60	189	35
5	0.2	45	353	45
6	0.4	45	176	43
7	0.3	30	203	60
8	0.3	60	252	34
9	0.3	45	176	42
10	0.3	45	177	41
11	0.3	45	176	41
12	0.3	45	177	42
13	0.3	45	174	45

MATLAB software is to analyse the effect of raster angle and raster width on the warpage through the number of lines and the raster length. Deformation starts from the 1st layer and increase with increase in part height. This warpage deformation leads to inaccuarcy and part distoration. The deforamtion along the part and length can be observed from the figure 1 & 2.

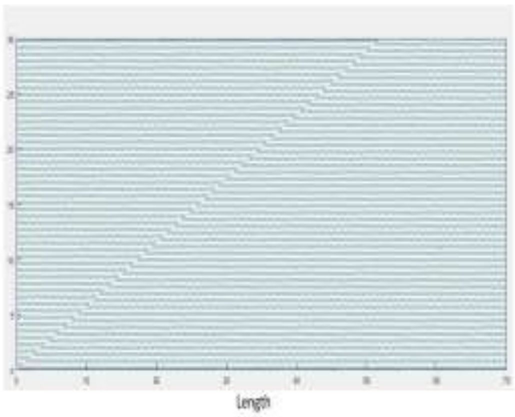

Figure 1: Deformation along the part

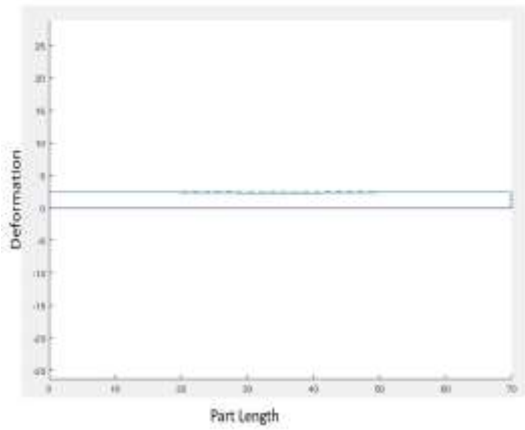

Figure 2: Deformation along the length of part

From the regressioon analysis quadraic regression equations are generated for the predicitoin of number of lines count and length of the raster.

Number of Lines = 1024.12931 - 4054.91379 **x** Raster Width - 6.21054 x Raster Angle + 5.16667 x Raster Width x Raster Angle x 5120.68966 x Raster Width^2 + 0.063142 x Raster Angle^2 (1)

Raster Length = 174.09483 - 410.60345 x Raster Width - 2.95958 x Raster Angle + 2.50000 x Raster Width x Raster Angle + 605.17241 x Raster Width^2 + 0.018008 x Raster Angle^2 (2)

The graph shows the influence of each process parameters on the warpage. The warpage deformation directly depends upon the number lines required and raster length on a single layer.

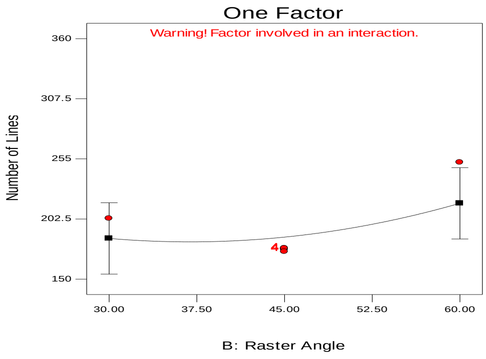

Figure 3. Effect of raster angle on number of lines

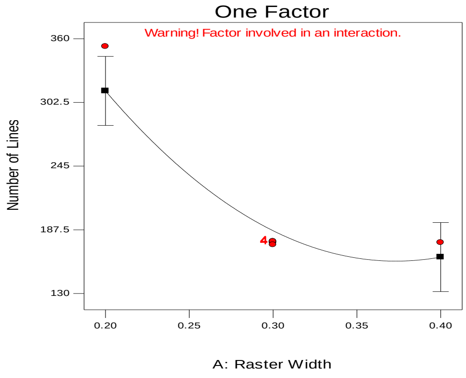

Figure 4. Effect of raster width on number of lines

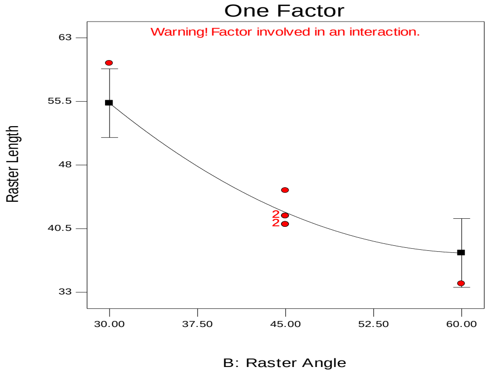

Figure 5. Effect of raster angle on raster length

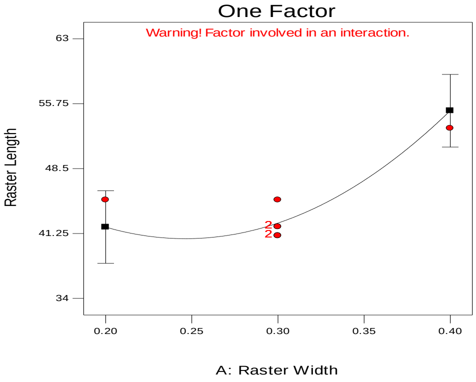

Figure 6. Effect of raster width on raster length

From figure 3 & 4 it can be seen that the number of lines increases with increase in raster angle and decreases with increase in raster width. Again from figure 5 & 6 it can be noted that the raster length decreases with increase in raster angle and increases with increase in raster width. The raster length is directly proportional to the raster width and inversely proportional to the raster angle.

Conclusion:

Warp deformation and part distortion are two major draw backs of RP that affect part quality and accuracy. Non-uniform shrinkage in the printed part can cause the warpage deformation or we can say a differential shrinkage value is the reason of warpage. The deformation starts from the 1st layer and increases with an increase in layer numbers. Fully elimination of warpage is a quiet difficult task. The bed temperature and chamber temperature has some effect on the part distortion. From the above work it can be noted that by selecting suitable raster angle and raster width the deformation can be minimized up to some extent. By maintaining the glass transition temp near to that chamber temp also have a significant effect on the part.

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