Experimental Investigation into Fused Deposition Modelling of Acro-Nitrile Butadiene Styrene

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Abstract— Fused Deposition Modeling, a 3D printing technique is widely used in industrial applications because of its ability to manufacture complex objects in the stipulated time. However, the main concern in 3D printing technique is a judicious selection of input process parameters for optimized performance. In this paper, the performance measures like build time, model material consumption, support material consumption, surface roughness, hardness, and tensile strength of the part produced are analyzed by varying process parameters like layer thickness, support material, model interior, orientation. The design of experiments is based on Taguchi's orthogonal array L18 and the effect of each process parameter on performance measures is studied by ANOVA.

Keywords: Fused Deposition Modeling (FDM), Process Parameters, and Taguchi design of experiments

I. INTRODUCTION

Rapid manufacturing, also known as Additive Manufacturing is based on the criteria of product building layer-by-layer from the CAD file [1]. The CAD file is first sliced using corresponding software and each succeeding layer is built on the preceded layer until the total product is built [2]. The rapid manufacturing reduces manufacturing time and produces high quality parts with enhanced efficiency [3, 4]. Depending on the manufacturing styles and materials used; the rapid prototyping techniques are of different types like "fused deposition modeling (FDM), selective laser sintering (SLS), direct metal deposition (DMD), stereo-lithography (SLA), selective laser melting (SLM), digital light processing (DLP), electron beam melting (EBM), laminated object manufacture (LOM) and inkjet modeling (IJM)" [5].

The first methods for rapid prototyping became available in the late 1980s and were used to produce models and prototype parts. Today, they are used for a wide range of applications and are used to manufacture production-quality parts in relatively small numbers if desired without the typical unfavorable short-run economics. This economy has encouraged online service bureaus. Historical surveys of RP technology start with discussions of simulacra production techniques used by 19th-century sculptors. Some modern sculptors use the progeny technology to produce exhibitions. The ability to reproduce designs from a dataset has given rise to issues of rights, as it is now possible to interpolate volumetric data from one-dimensional images.

As with CNC subtractive methods, the computer-aided-design - computer-aided manufacturing CAD-CAM workflow in the traditional Rapid Prototyping process starts with the creation of geometric data, either as a 3D solid using a CAD workstation, or 2D slices using a scanning device. For RP this data must represent a valid geometric model; namely, one whose boundary surfaces enclose a finite volume, contain no holes exposing the interior and do not fold back on themselves. In other words, the object must have an "inside." The model is valid if for each point in 3D space the computer can determine uniquely whether that point lies inside, on, or outside the boundary surface of the model. CAD post-processors will approximate the application vendors' internal CAD geometric forms (e.g., B-splines) with a simplified mathematical form, which in turn is expressed in a specified data format which is a common feature in Additive Manufacturing: STL (stereo-lithography) a de facto standard for transferring solid geometric models to SFF machines. To obtain the necessary motion control trajectories to drive the actual SFF, Rapid Prototyping, 3D Printing or Additive Manufacturing mechanism, the prepared geometric model is typically sliced into layers, and the slices are scanned into lines [producing a "2D drawing" used to generate trajectory as in CNC`s tool path], mimicking in reverse the layer-to-layer physical building process.

A. *Fused Deposition Modeling (FDM)*

Fused deposition modeling (FDM) is an additive manufacturing technology commonly used for modeling, prototyping, and production applications. It is one of the techniques used for 3D printing.FDM works on an "additive" principle by laying down material in layers; a plastic filament or metal wire is unwound from a coil and supplies material to produce a part. The technology was developed by S. Scott Crump in the late 1980s and was commercialized in 1990. The term fused deposition modeling and its abbreviation to FDM are trademarked by Stratasys Inc. The exactly equivalent term, fused filament fabrication (FFF), was coined by the members of the Rep-Rap project to give a phrase that would be legally unconstrained in its use. It is also sometimes called Plastic Jet Printing (PJP).

Fused Deposition Modeling (FDM) is the extensively used Additive Manufacturing Technology. It fabricates parts by depositing semi-molten thermoplastic material in the form of thin layers on a platform that moves down a distance of thickness of one layer after depositing a layer for next layer to deposit [6,7]. In an FDM process, the part building occurs in a temperature controlled chamber. The platform is fixed and the heated nozzle moves in X-Y direction deposits model material. The nozzle deposits support material when required; therefore post processing has to be done to remove support material [8]. Manufacturers of commercial 3D printers mention how to set the input parameters like layer thickness, model interior, part orientation, support material, alignment etc. But finally, the product quality depends on the optimum settings of these input parameters [9].Fused deposition modeling (FDM) was developed by S. Scott Crump in the late 1980s and was commercialized in 1990 by Stratasys. With the expiration of the patent on this technology there is now a large open-source development community (called Rep-Rap), as well as commercial and DIY variants, which utilize this type of 3D printer. This has led to two orders of magnitude price drop since this technology's creation.

B. Organization of Thesis

The structure of the thesis is framed in a systematic way that:

- Chapter 1 presents Introduction in which the framework and the context of the study is highlighted.
- Chapter 2 presents the Literature Review in which work done by the up to current date by the researchers is briefed.
- Chapter 3 presents Experimental details and Methodology which presents the input and output parameters selected for the current study.
- Chapter 4 presents “Results and discussions” in which it mentions all the tables related to experimental calculations.
- Chapter5 presents “Conclusions and Recommendations” in which it mentions main conclusions of the entire work have been highlighted followed by the references.

II. LITERATURE REVIEW

A literature review is a text of a scholarly paper, which includes the current knowledge including substantive findings, as well as theoretical and methodological contributions to a particular topic. This section presents the recent developments in the field of FDM process considering different response parameters in different contexts such as Mohamed et al. [5] in their research used response surface methodology in designing the experimental matrix with 60 experimental runs. The study considered “layer thickness, air gap, raster angle, build orientation, road width, no of contours” as their input parameters and “build time, feedstock material consumption, and dynamic flexural modulus” as their output parameters. Further mathematical analysis has been conducted and the results showed that high layer thickness induced higher flexural strength in the part. Build time, material consumption and flexural modulus were mostly affected by layer thickness, air gap, no of contours and build direction. And also increase in “layer thickness and air gap” with decreasing number of contours reduces build time and feedstock material consumption significantly.

Gurrala et al. [7] in their research work performed 20 experimental runs using 3 Level Factorial Model with Face-Centered Central Composite Design. The study considered input parameters like “Model Interior, Horizontal Direction, and Vertical Direction” and considered “volumetric change” as the output parameter. Based on the volumetric change, the machine settings were corrected in order to correct the volumetric change. The study concluded that “horizontal and vertical directions” have more impact on “shrinkage and curl” when compared to the model interior.

Garg et al. [10] in their work unveiled the deformation behavior of the Fused Deposition Modeling specimens with individual raster’s of different layer thicknesses and lay at different directions under uni-axial tension. Finite element (FE) analysis has been carried out for FDM tensile specimens to simulate the elasto - plastic behavior and results have been validated with the experimental observations. FE analysis, experimental results have indicated that developed stress, strain at yield, elongation and tensile strength first decreases with layer thickness and then increases, number of layers along the loading direction were more in sample with less layer thickness so, more elongation and load bearing capacity whereas for more layer thickness, less number of air voids and higher intra-layer bonded region are the reasons for higher tensile strength of the specimen.

III. EXPERIMENTAL DETAILS AND METHODOLOGY

A. Set Up and Sample Preparation

In the present work, all the samples have been printed through fused deposition modeling machine manufactured by US Stratasys is shown in Fig. 3.1. The model material used for printing is Acro-Nitrile Butadiene Styrene(ABS) and the support material is 400R, the test samples have been prepared according to ASTM D790 standard of plastics which have dimensions as length 127mm, breadth 13mm, thickness 3mm as shown in Fig. 3.2.

Fig. 3.1

B. ABS Material:

The material used in the present study is Acro-nitrile butadiene styrene (ABS) which is a polymer. Acrylonitrile butadiene styrene (ABS) (chemical formula $(C_8H_8)_x\cdot(C_4H_6)_y\cdot(C_3H_3N)_z$) is a common thermoplastic polymer. Its glass transition temperature is approximately 105 °C (221 °F). ABS is amorphous and therefore has no true melting point.

ABSisa tera-polymer made by polymerizing styrene and acrylonitrile in the presence of poly butadiene. The proportions can vary from 15 to 35% acrylonitrile, 5 to 30% butadiene and 40 to 60% styrene. The result is a long chain of poly butadiene criss-crossed with shorter chains of poly(styrene-co-acrylonitrile). The nitrile groups from neighboring chains, being polar, attract each other and bind the chains together, making ABS stronger than pure polystyrene. The styrene gives the plastic a shiny, impervious surface. The poly butadiene, a rubbery substance, provides toughness even at low temperatures. For the majority of applications, ABS can be used between −20 and 80 °C (−4 and 176 °F) as its mechanical properties vary with temperature. The properties are created by rubber toughening, where fine particles of elastomer are distributed throughout the rigid matrix.

C. ABS Properties:

The most important mechanical properties of ABS are impact resistance and toughness. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. The impact resistance can be amplified by increasing the proportions of poly butadiene in relation to styrene and also acrylonitrile, although this causes changes in other properties. Impact resistance does not fall off rapidly at lower temperatures. Stability under load is excellent with limited loads. Thus, by changing the proportions of its components, ABS can be prepared in different grades. Two major categories could be ABS for extrusion and ABS for injection moulding, then high and medium impact resistance. Generally ABS would have useful characteristics within a temperature range from −20 to 80 °C (−4 to 176 °F).

The final properties will be influenced to some extent by the conditions under which the material is processed to the final product. For example, molding at a high temperature improves the gloss and heat resistance of the product whereas the highest impact resistance and strength are obtained by molding at low temperature. Fibers (usually glass fibers) and additives can be mixed in the resin pellets to make the final product strong and raise the operating range to as high as 80 °C (176 °F). Pigments can also be added, as the raw material original color is translucent ivory to white. The aging characteristics of the polymers are largely influenced by the poly butadiene content, and it is normal to include antioxidants in the composition. Other factors include exposure to ultraviolet radiation, for which additives are also available to protect against.

Even though ABS plastics are used largely for mechanical purposes, they also have electrical properties that are fairly constant over a wide range of frequencies. These properties are little affected by temperature and atmospheric humidity in the acceptable operating range of temperatures.

ABS is flammable when it is exposed to high temperatures, such as those of a wood fire. It will melt and then boil, at which point the vapors burst into intense, hot flames. Since pure ABS contains no halogens, its combustion does not typically produce any persistent organic pollutants, and the most toxic products of its combustion or pyrolysis are carbon monoxide and hydrogen cyanide. ABS is also damaged by sunlight. This caused one of the most widespread and expensive automobile recalls in US history due to the degradation of the seatbelt release buttons. ABS can be recycled, although it is not accepted by all recycling facilities.

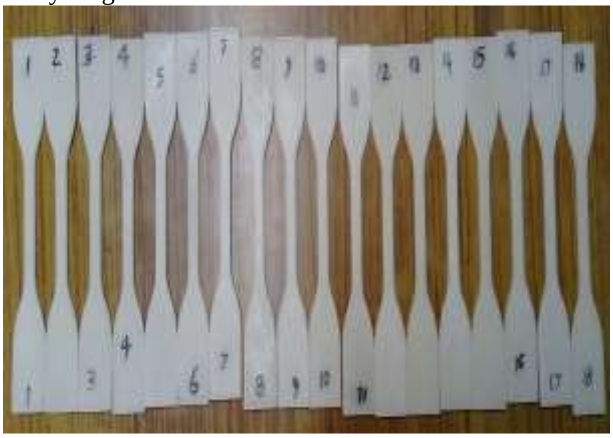


Fig. 3.2: Samples Prepared to Perform Tensile test

D. Design of Experiments (DOE)

In order to meet the customer needs and expectations the performance of the product or process need to improved. Thus purpose of experimentation is to understand how to reduce variation and subsequently getting to know which parameters are affecting the performance of the process or product.

1) Basis of Experimentation

The approach is based on use of orthogonal arrays to conduct experiments. The use of orthogonal arrays facilitates researchers to accommodate variety of situations in short number of experimental runs. The use of orthogonal arrays helps non-statistical oriented people in executing on practical basis. The designing of experiment involves strategic arrangement of three or more factors and their levels. The results are analysed after performing the experiments and next step is to determine the influential factors and further improvement is be done based on this to reduce variation in process or product development.

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The Taguchi method was developed by Genichi Taguchi. He developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect the product quality with a minimum amount of experimentation, thus saving time and resources. The Taguchi method is best used when there are an intermediate number of variables (3 to 50), few interactions between variables, and when only a few variables contribute significantly.

2) The DOE Process

The steps involved in an effective designed experiment are:[14]

1) State the concerned problem and select the objectives of experiment.
2) Select the type of quality characteristics and how to measure the outputs.
3) Select the factors that have more influence on output from the literature survey.
4) Identify control and noise factors and levels for each of the factors.
5) Select the appropriate orthogonal array (OA) and interactions that may influence the selected quality characteristics.
6) Assign factors to OA and locate interactions and conduct test described by trials in OA.
7) Analyse and interpret results of the experimental trials and conduct confirmation experiment.

3) Experimental and Testing Values

The procedure for measuring and detailed explanation of all the output parameters mentioned in tables 3.2 is explained in this section.

1) Build Time (BT): It is the time taken by the machine to build the entire part and it measured in minutes (min) [5]. It is measured directly from the software (CatalystEX) which is embedded with the FDM machine after inserting each array in the software and values are presented in the Table 4.1.
2) Surface Roughness (Ra): Surface roughness denotes the quality of the surface of the part. In typical applications it should always as low as possible and is measured in micro-meters (μm) [15]. It is measured using Taylor Hobson surface roughness tester and is shown in fig 3.2 and the measured values are presented in the Table 4.1.

Fig. 3.3: Surface Roughness Tester

3) Hardness (H): Hardness is the ability of the material to resist to indentation applied on it and is measured using Rockwell Hardness Tester on Scale-R [16]. The values of hardness number measured using the Rockwell scale Hardness is a measure of how resistant solid matter is to various kinds of permanent shape change when a compressive force is applied. Some materials (e.g. metals) are harder than others (e.g. plastics). Macroscopic hardness is generally characterized by strong intermolecular bonds, but the behavior of solid materials under force is complex; therefore, there are different measurements of hardness: scratch hardness, indentation hardness, and rebound hardness.
   There are three main types of hardness measurements: scratch, indentation, and rebound. Within each of these classes of measurement there are individual measurement scales.

a) Scratch hardness:

Scratch hardness is the measure of how resistant a sample is to fracture or permanent plastic deformation due to friction from a sharp object. The principle is that an object made of a harder material will scratch an object made of a softer material. When testing coatings, scratch hardness refers to the force necessary to cut through the film to the substrate. The most common test is Mohs scale, which is used in mineralogy. One tool to make this measurement is the sclerometer. Another tool used to make these tests is the pocket hardness tester. This tool consists of a scale arm with graduated markings attached to a four-wheeled carriage. A scratch tool with a sharp rim is mounted at a predetermined angle to the testing surface. In order to use it a weight of known mass is added to the scale arm at one of the graduated markings, the tool is then drawn across the test surface. The use of the weight and markings allows a known pressure to be applied without the need for complicated machinery.

b) Indentation hardness:

Indentation hardness measures the resistance of sample to material deformation due to a constant compression load from a sharp object; they are primarilyused in engineering and metallurgy fields. The tests work on the basic premise of measuring the critical dimensions of an indentation left by a specifically dimensioned and loaded indenter. Common indentation hardness scales are Rockwell, Vickers, Shore, and Brinell.

c) Rebound hardness:

Rebound hardness, also known as dynamic hardness, measures the height of the "bounce" of a diamond-tipped hammer dropped from a fixed height onto a material. This type of hardness is related to elasticity. The device used to take this measurement is known as a scleroscope. Two scales that measures rebound hardness are the Leeb rebound hardness test and Bennett hardness scale.

d) Tensile strength:

The part which is under tensile loading fails when the weakest fibre of all the fibres which are in tensile loading reaches its limit. In the tensile loading condition the load acts in axial direction, so the component fails due to pure tensile stress. TS is measured in units of Mega Pascal (MPa). And is measured using Universal Testing Machine under standard loading conditions.

IV. RESULTS AND DISCUSSION

In this chapter, the results and discussions related to study have been presented.

A. Results from Experimentation and Testing

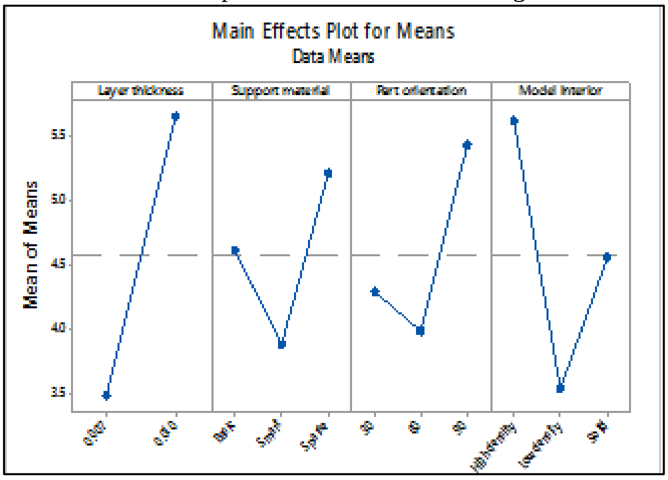
Table 4.1 presents all the output parameters which are considered in this study and are calculated as mentioned in section 3.3.

s. no	Layer thickness(mm)	Support material	Part orientation(deg)	Model interior	Build timemin	Ra(µm)	HMPa	TSMPa
1	0.01	Basic	30	Solid	20	3.3	65	31.9
2	0.01	Basic	60	High density	19	5.25	97	29.9
3	0.01	Basic	90	Low density	20	7.5	94	32.5
4	0.01	Sparse	30	Solid	20	8.95	60	25.9
5	0.01	Sparse	60	High density	19	7	70	28.6
6	0.01	Sparse	90	Low density	20	3.95	80	35.9
7	0.01	Smart	30	High density	19	7.55	63	27.9
8	0.01	Smart	60	Low density	20	4.1	61	35.6
9	0.01	Smart	90	Solid	20	3.35	82	30.6
10	0.007	Basic	30	Low density	37	1.9	80	28.6
11	0.007	Basic	60	Solid	37	3	78	35.8
12	0.007	Basic	90	High density	34	6.8	94	31.2
13	0.007	Sparse	30	High density	34	2.6	92	31.5
14	0.007	Sparse	60	Low density	32	2.3	80	40.0
15	0.007	Sparse	90	Solid	37	6.5	82	30.6
16	0.007	Smart	30	Low density	33	1.5	65	37.8
17	0.007	Smart	60	Solid	39	2.3	90	34.4
18	0.007	Smart	90	High density	36	4.55	80	31.5

Table 4.1: DOE Experimental Values

Level	Layer thickness	Support material	Part orientation	Model interior
1	3.494	4.625	4.300	5.625
2	5.661	3.892	3.992	3.542
3	-	5.217	5.442	4.567
Delta	2.167	1.325	1.450	2.083
Rank	1	4	3	2

Table 4.2: Response table foe Surface roughness



Main Effect Plots for Means

The above response tables for Ra are determined according to the mean of Layer thickness, SM, PO, MI values of S/N ratio or Mean at the particular levels. The ranks included based on delta statistics, which compares the relative magnitude of effects. The delta statistics is the highest average minus the lowest average for each factor. Minitab assigns ranks based on the delta values in descending order, the highest delta value has rank 1 and rank 2 is assigned to the second highest and rank 3 is assigned to the smallest among the delta values. The rank indicates the significant effect of each factor on the responses.

B. Conclusions from the plot:-

1) As Layer thickness increases it takes more time for the material to solidify there by strength and hardness are decreasing. So lesser value of layer thickness should be preferred.
2) In Basic type of support material, the nozzle moment is straight and material wastage is more. In Smart type the nozzle adjust its moment in such a way that only desired properties are obtained.
3) Part Orientation is one of the critical parameter so in my experimental analysis it is occurred at 60˚ part orientation. It is inline with the literature review.
4) In Solid type of material wastage is more. in Low Density type material consumption is less but strength and hardness are vary less. So High Density type is preferred in which both strength and hardness are High.

V. CONCLUSIONS AND FUTURE SCOPE

The experimental results were validated by producing parts with the obtained optimum process parameters. The proposed model tends to suggest that it is possible to produce parts with all the output parameters at optimum level using proposed model .The following conclusions are drawn based on the results obtained from this study:

1) Taguchi technique for design of experiments is apt for decreasing the number of experimental runs which uses the concept of orthogonal arrays for designing of experiments
2) ANOVA results showed that the output is mainly affected by layer thickness followed by model interior but least affected by support material type.
3) If layer thickness is increased then it takes less build time but it affects surface finish and strength.
4) Confirmation Experiments suggest that the developed models have successfully established relation between input and output parameters.

VI. FUTURE SCOPE

The Taguchi technique has been used for analysis of FDM in the current study which can also be applied for other rapid prototyping machines such as SLS, SLA. Other designing methods like response surface methodology, central composite design, etc. integrated with grey relational analysis and particle swarm optimization can be used for analysis in order to get optimum parameters. The study can be extended by printing a product with the optimum parameter set and the performance of the product can be analyzed using appropriate tools. A prototype of a real model can be prepared in a short time using this optimum parameter set and the performance of real model can be predicted which saves huge costs and time.

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