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Effect of varying spatial orientations on build time requirements for FDM process: A case study

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ABSTRACT

In this research, effect of varying spatial orientations on the build time requirements for fused deposition modelling process is studied. Constructive solid geometry cylindrical primitive is taken as work piece and modeling is accomplished for it. Response surface methodology is used to design the experiments and obtain statistical models for build time requirements corresponding to different orientations of the given primitive in modeller build volume. Contour width, air gap, slice height, raster width, raster angle and angle of orientation are treated as process parameters. Percentage contribution of individual process parameter is found to change for build time corresponding to different spatial orientations. Also, the average of build time requirement changes with spatial orientation. This paper attempts to clearly discuss and describe the observations with an aim to develop a clear understanding of effect of spatial variations on the build time for Fused Deposition Modelling process. This work is an integral part of process layout optimization and these results can effectively aid designers specially while tackling nesting issues.

1. Introduction

Rapid Prototyping (RP)/Generative Manufacturing (GM) is around 3 decade old technology which enables quick transition from concept to physical models [1]. GM answers the need of manufacturing which is environment friendly with minimal wastage of material. Though material availability and data transfer techniques have hindered widespread use of GM as an end product technology in the past yet these have been dealt with effectively during recent times [2]. It has established itself as an efficient means for fast, easy and effective prototype production of intricate and complicated geometry parts [3]. GM applications extend from prototyping to end product manufacturing [4]. It is increasingly finding shining role in defence, aerospace, medical, polymer, and many other fields [5]. Especially, in defence support applications, GM proves itself a game changing landmark technology owing to its versatility and flexibility to produce custom engineered designs and products [6–8]. Busachi et al. [7] reported results of GM methodological studies carried out at various defence support systems in UK. Kalvala et al. [8] utilized friction assisted solid state lap seam welded joints with GM techniques and explained their probable utilization in defence applications. Several GM techniques like selective laser sintering [9], fused deposition modelling [10], three dimensional printing [11], laser engineered net shaping [12], etc. are in practice for fabrication of layered components directly from computer drawings of the part [5].

Fused Deposition Modelling (FDM) is one of GM techniques having unique advantage of variety of raw materials and modelers it offers [13]. It has the capability to produce intricate and complex shapes with reasonable time and cost requirements [5]. FDM has been widely used for various defence applications by different military manufacturers including EOIR technology, RLM industries, Sheppard air base, Tiberius arms, etc. [14]. These applications vary from prototypes, end products, guns, design modifications, etc. Several authors successfully fabricated various functional components using FDM by investigating the effect of various process parameters like raster width, air gap, slice height, etc. [15–17]. Srivastava et al. [15] experimentally investigated the effect of various process parameters upon responses with an aim to achieve layout optimization. Vasudevarao et al. [16] proposed an experimental design to determine significant factors and their interactions for optimal surface finish of parts fabricated via Fused

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Deposition Modelling process. Sood et al. [17] carried out parametric appraisal of the factors affecting the various mechanical properties of components fabricated by FDM process.

Majority of published research mainly focuses on the evaluation of effects of process parameters namely raster parameters, air gap; slice height, etc. on the build time and mechanical properties of fabricated components. In addition to these process parameters, spatial orientation significantly affects the build time which in turn affects the FDM layout process performance. Interestingly, investigations on effect of spatial orientation on build time for layout optimization of FDM process are almost untouched. Present work investigates effect of varying spatial orientation of components within the build volume in addition to other process parameters upon the build time (BT) requirements for FDM process.

2. Experimental procedure

2.1. Materials

Material used for current experimentation is Acrylonitrile Butadiene Styrene (ABS) having chemical formula (C8H8·C4H6·C3H3N)n. It is a thermoplastic used in making light weight, rigid, molded products like piping, musical instruments, golf club heads, automotive body parts, wheel covers, protective head gear, furniture buffer, air soft BBs, toys etc. An interesting application of an ABS variant has been reported in defence industry by Tiberius Arms, a group that produces different versions of their guns from cost effective ABS with the help of uPrint modeller which is an another high end FDM modeller [14]. It is a copolymer derived by polymerizing styrene and acrylonitrile in the presence of polybutadiene. Its composition varies from 15 to 35% acrylonitrile, 5–30% butadiene and 40–60% styrene which results in a long chain of polybutadiene crisscrossed with shorter chains of poly (styrene-co-acrylonitrile). Being polar, nitrile groups from neighboring chains attract each other and bind the chains together, making ABS stronger than pure polystyrene. ABS can be used in the temperature range of −25 °C to 60 °C. Model material and support material used for the current work are two variants of ABS namely ABS P430 and ABS SR30 respectively [18].

In order to arrive upon definite and meaningful design principles, components chosen are cylindrical primitives of constructive solid geometry (CSG) [19]. There are seven basic primitives of CSG namely cylindrical, conical, spherical, pyramidal, prismatic, cubical and cuboidal. It is a matter of general understanding of CAD that all the rest of shapes can be obtained by performing Boolean operations on these primitives and thus the design principles proposed for them can be thought of as generally applicable. Though the design principles for cylindrical workpiece are established in current case study, this work can similarly be extended for six remaining primitives also. In the present work, experiments are carried out for cylindrical primitives having.stl size $X = 20$ mm, $Y = 69.999$ mm, $Z = 20$ mm. Five different spatial orientations in the given build volume are considered for cylindrical primitives to arrive upon best orientation. These are absolute rotation about *x*-axis, absolute rotation about *y*-axis, absolute rotation about *z*-axis, rotation about *x*-axis keeping minimum *z* height and rotation about *y*-axis keeping minimum *z*-height. Fig. 1 presents the different spatial orientations of cylindrical primitives at varying angles.

Modeller used in the current experimentation is Fortus 250mc which is one of the most advanced and versatile Stratasys systems that offers cost effective printing of FDM parts with appreciable efficiency [20]. It pairs fine layer resolution with a larger build envelope which imparts power to fine-tune most aspects of prototype production. It is an office friendly high end FDM system which optimizes parts for strength, print time and aesthetics [21]. It is based on FDM technology. There are five basic steps involved in the FDM process which include [22]:

- Step 1 Formulation computer aided design (CAD) model from the component drawing
- Step 2 Converting CAD model of the drawing into.stl format, i.e., tessellated to enable it to be used as an input in to insight software
- Step 3 Dividing the tessellated.stl file into thin layers, i.e., slicing
- Step 4 Constructing layers for actual physical model generation
- Step 5 Cleaning and finishing model

Its working is explained as follows: A plastic filament is uncoiled from a roll and supplies material to an extrusion nozzle which can be used depending on requirement. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by an automated computational mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The model or part is produced by extrusion of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle [23]. The technical specifications of this modeller are tabulated in Table 1.

2.2. Selection of process parameters

There are four classes of parameters which are found to affect the FDM process. These are operation specific, modeller specific, geometry specific and material specific parameters [24]. Operation specific parameters include slice thickness, road width, head speed, raster angle, temperature of extruding material, envelope temperature, contour width, raster width, single/multi fill contours and air gap. Modeller specific parameters include nozzle diameter, filament feed rate, roller speed, flow rate and filament diameter. Geometry specific parameters include fill vector length, support structures and orientation. Material specific properties include physical properties, binder, viscosity, chemical composition and flexibility [2,25].

Previous experimentations, trial experiments and literature survey reflect that BT requirement of FDM modeler is mainly affected by six process parameters namely contour width (CW), slice height (SH), orientation (O), raster angle (RA), raster width (RW) and air gap (AG). These parameters are therefore selected as process parameters owing to their larger effect on BT as compared to others.

2.3. Response Surface Methodology (RSM) based experimentation

RSM technique is an extremely powerful statistical tool adopted for experimental design and building of empirical models in order to reduce experimental runs. This work utilizes central composite RSM design which has several advantages over other RSM designs. One of the biggest advantages of CCD is tremendous reduction in the number of runs as compared to full factorial designs [26]. Six process parameters namely SH, O, CW, RA, RW, and AG at three levels each were chosen for experimentation. Their details are summarized in Table 2.

Based on previous research work, rests of the parameters are kept constant throughout the experimentation primarily due to their lesser effect on the output as compared to chosen process parameters [5]. The constant parameters and their values are listed in Table 3.

Build time (BT) is a critical factor for optimization of any GM technique and is taken as the response for current experimentation. Though build-time is frequently used as a measure of process time/process speed, yet these two terms are not the same. Process time