Measurement 81 (2016) 174–196

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Optimization of fused deposition modeling process parameters for dimensional accuracy using I-optimality criterion

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ARTICLE INFO

Article history:
Received 12 March 2015
Received in revised form 2 December 2015
Accepted 14 December 2015
Available online 21 December 2015

Keywords:
Fused deposition modeling (FDM)
I-optimal design
Analysis of variance (ANOVA)
Optimization
Process parameters
Dimensional accuracy

ABSTRACT

Fused deposition modeling (FDM) is one of the widely used additive manufacturing technologies because it has flexibility and ability to build complex parts. The accuracy of parts fabricated by FDM is greatly influenced by various process parameters. FDM process has a complex mechanism in building parts and often poses difficulty in understanding adequately how conflicting FDM parameters will determine part quality and accuracy. Sectors such as medical implant, telecommunication, electronics and aerospace require increasingly higher levels of dimensional accuracy. Thus, traditional methods of ensuring quality do not effectively address global markets and customer's needs. This study proposes an I-optimality criterion for the optimization of FDM process parameters in order to address the limitations of the commonly used traditional designs. This study also aims to develop mathematical models in order to establish nonlinear relationship between process parameters and dimensional accuracy. The results show that I-optimality criterion is very promising technique in FDM process parameter optimization. Confirmation experiments show that the proposed method has great advantages in the aspect of both accuracy and efficiency compared with traditional methods proposed in previous studies.

1. Introduction

Fused deposition modeling (FDM), developed by Stratasys, belongs to the additive manufacturing technologies that allow for quick and clean development of prototypes and functional components. In this process, the layers are formed by extrusion of a plastic filament that is unwound from a coil and supplied to the liquefier head to produce a part. The semi-molten filament acts as a plunger to extrude the material via the nozzle [1]. The process behind this principle is that the materials are deposited in a configuration that preferably yields them layer by layer, and are hardened immediately following extrusion from the nozzle [2]. Further, this process relies on melting and selective deposition of thin filament of thermoplastic polymer in a cross-sectional design to form a layer of the whole part. The material spool used is mounted on the machine, and the FDM head is moved in horizontal *X* and *Y* planes so as to produce a layer in a raster movement [3–5]. The build platform moves vertically and shifts to a lower position upon completion of the part.

Additive manufacturing processes, including the FDM process, are required to deliver high-quality parts. The increasing demands on higher quality of fabricated parts by FDM in the modern manufacturing industry such as medical implant, telecommunication, electronics and aerospace require increasingly higher levels of dimensional accuracy. In such applications, maintaining dimensional accuracy with tight tolerances will ensure dimensional stability and repeatability of the manufactured part. The

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http://dx.doi.org/10.1016/j.measurement.2015.12.011
0263-2241/

quality of the final part fabricated by FDM depends greatly on the process parameters selected. Manufactured part by FDM process suffers from dimensional inaccuracy in comparison with other additive manufacturing processes such as SLS because of the variety of conflicting process parameters which affect the dimensional accuracy individually or collectively in interactions of several parameters [3]. This process has a complex mechanism in fabricating parts exhibiting much difficulty in understanding adequately of how parameters involved determine dimensional accuracy. Thus, establishing effective relationship between process parameters and dimensional accuracy and determination of final optimum parameter settings are vital for designers, equipment developers, and production engineers.

This paper is structured as follows: Section 2 reviews the previous research work. Section 3 introduces some useful information behind using computer generated optimal designs including I-optimality criterion. Section 4 presents the research methodology used. Section 5 presents an analysis of the data obtained from the experiment and developed mathematical models. Section 6 discusses the results. Section 7 presents optimization process. Section 8 presents conclusions.

2. Literature review

Some attempts have been made to improve dimensional accuracy of FDM fabricated parts through appropriate adjustments in the process parameters. Sood et al. [6] studied the influence of process parameters on the dimensional accuracy using Taguchi method and artificial neural networks (ANN). They pointed out the optimal process settings are different for each quality criteria, indicating that the optimal process settings cannot be obtained. For this reason, gray relational grade (GRG) was used to transform three responses into one response. The limitation of this work is that the optimum settings are restricted to the experimental values, where, in fact, the optimum settings are not exactly the same as the parameters' values used in experimental matrix. Thus final optimum parameter settings were not obtained using this approach. Nancharaiah et al. [7] carried out an experimental investigation on surface quality and dimensional accuracy by employing the Taguchi method and ANOVA technique. However, in this study, optimum settings of the parameters were not addressed. Zhang and Peng [8] investigated the relationship between process parameters and dimensional error and deformation. They reported that optimum process settings for dimensional error and deformation are varied. However, if the goal is to minimize both dimensional error and deformation together, the study could not provide a definite answer in terms of global solution to this problem. Sahu et al. [9] have applied Taguchi method to study the effect of process variables on part accuracy. However, the use of fuzzy inference system (FIS) requires developing rules. Therefore, it needs appropriate expertise knowledge and prior experience.

The above literature review shows that the quality of manufactured part by FDM is greatly influenced by various process parameters fixed at the time of pre-processing of the part. Although many experimental, theoretical, numerical and optimization studies have been proposed to improve dimensional accuracy for manufactured part in above literature, they have some common weaknesses and disadvantages summarized as follows. First, most of previous researchers have mainly studied dimensional accuracy of part manufactured by ABS; no work has been done of part manufactured by PC-ABS alloy. Second, traditional experimental design such as Taguchi and GRG were used extensively in previous studies to improve dimensional accuracy. However, traditional techniques are difficult to predict and build a functional relationship between process parameters and dimensional accuracy, for example, in traditional experimental techniques; two-factor interactions are confounded (aliased) with other main and higher interaction effects which produce biased estimates of main and interaction effects. This leads to misleading results in cases where many interactions of the factors have a significant influence on dimensional accuracy. Moreover, final optimal global solution cannot be determined because high-order empirical polynomial models cannot be developed by standard designs which is very important when the goal is optimization [3]. Next, there exists much literature, which employs Taguchi method combined with ANN or fuzzy comprehensive evaluation. This is because ANN and FIS do not provide enough information about factors and their interaction effects on the dimensional accuracy if further analyses using Taguchi and GRG have not been done. However, this approach has its disadvantages, as it increases the complexity of the computational process, requires large amount of data and high level of experience for the appropriate engineering judgment to interpret the results. Fourth, none of the literature considers all parameters with all possible levels affecting dimensional accuracy together and their interactions. This is extremely important in order to take advantage of achieving better accuracy and to obtain a functional relationship between parameters and dimensional accuracy. Finally, standard techniques of ensuring quality are not appropriate to solve complex problems and they do not effectively address global markets and customer's needs. This is because there are a large number of conflicting parameters in FDM process, nonlinear relationship, multi-factor interactions and restrictions (constraints) imposed on the levels of the experimental variables [3]; underscoring the need for this study.

In contrast to previous research, this study attempts to address the limitations of previous studies by developing a method that can improve dimensional accuracy efficiently and effectively. This paper proposes, for the first time, a methodology based on computer-generated optimal designs using I-optimality criterion that is efficient and reliable to solve the optimization problem involving large number of FDM parameters and levels with constraints (irregular experimental matrix) [10]. The proposed method provides better accuracy and performance than previous methods in several instances. In this study, a comprehensive relationship between parameters and dimensional accuracy of part fabricated by PC-ABS is established and mathematical models are also developed. This study provides a comprehensive investigation by considering all