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Repeatability of linear and radial dimension of ABS replicas fabricated by fused deposition modelling and chemical vapor smoothing process: A case study

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ABSTRACT

In this research work, an effort has been made to study the influence of fused deposition modelling (FDM) and chemical vapor smoothing (CVS) process parameters on the selected linear and radial dimension as well as on repeatability of acrylonitrile butadiene styrene (ABS) replicas as a case study. The study highlights that orientation of parts on FDM build platform, part density (part interior style) and interaction between these two parameters significantly affect the accuracy of selected dimensions. Shrinkage has been observed in the selected radial dimension of the prototypes, but there is a positive deviation in the linear dimension from the desired value. The CVS process reduces both the dimensions slightly due to reflow of the material. Optimum parameter settings that were different for both linear and radial dimensions have been investigated using Taguchi's L18 orthogonal array. The IT grades of ABS replicas prepared by this combined process were found to be consistent with the permissible range of tolerance grades as per ISO standard UNI EN 20286-I (1995) and DIN 16901 for plastic materials. Finally, optimum level of process parameters that simultaneously minimizes the deviation in both the dimensions have been found out using response optimization module of Minitab 17 software and the results obtained have been verified by performing the confirmation experiments.

1. Introduction

In today's scenario, the production of prototypes and specialized or customized products such as implants using conventional production technologies has become very expensive and time-consuming. But the demand of these tailor made implants is increasing at high rates all around the world. Also, these implants must have excellent surface quality and dimensional accuracy [1]. Development of such implants using an appropriate route so that they can satisfy the above requirements is the need of today's world. Investment casting (IC) also known as 'precision casting' is the most widely used process for producing complex and intricate shaped metallic components that require good surface finish and dimensional accuracy [2]. However, IC is considered economical only for mass production [3]. If the volume is low like in prototyping, during manufacturing of specialized component or during design iterations, the high cost of wax pattern tooling makes the IC process expensive [3,4].

In such cases, rapid prototyping (RP) becomes one of the feasible solutions used widely in which manufacturing facilities are being utilized for specialized, low volume and customized products [5,6]. FDM is one of the commercially used RP process to construct prototypes and parts that can be used directly as finished products [7,8]. In the process of FDM, the materials like ABS, polycarbonate or wax has been fed into the FDM extrusion head, where they are heated to a semi-liquid state [9]. The head then deposits the material in thin layers and each layer bonds to the previous layer by particular material fabrication technology until the 3D physical model is built [10,11]. Although, FDM process has been implemented successfully to reduce the product build time for complex shape objects, but the surface finish of the FDM prototypes having curved or angled surfaces suffers badly due to stair-step effect [12]. So, for effective use of RP technology, improvement in surface quality, dimensional accuracy and part strength are the key issues that have to be addressed [13,14].

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Many researchers have directed their effort to improve the surface finish and dimensional accuracy of FDM prototypes by adjusting the process parameters. Bharath et al. [15] investigated the effect of five process parameters, namely build orientation, layer thickness, road width, air gap and model temperature on the surface finish of parts fabricated by FDM 1650 and concluded that layer thickness and part orientation have a significant effect on the surface finish. Layer thickness of 0.007″ and part orientation of 70° resulted in the best surface finish in his work. The author also suggests to develop any suitable post-processing techniques and advancements in the FDM hardware for further improvement in surface finish. Thrimurthulu et al. [16] developed a model to improve surface finish and to reduce build time by optimizing part deposition orientation using adaptive slicing scheme for the FDM process. Surface finish and build time are the most important concerns and these two generally contradict with each other. A coded genetic algorithm was used to obtain the optimal solution. Chakraborty et al. [17] described a method for the FDM process, in which the layers are deposited along curved paths instead of horizontal paths and concluded that this method called curved layer fused deposition modelling (CLFDM), has the potential to increase the strength of parts and to reduce the stair-step effect, number of layers and ultimately build time.

Galantucci et al. [18] employed a post-processing technique to improve the surface finish of FDM fabricated ABS parts by immersing them in a dimethyl-ketone and water solution (ratio 9:1) and concluded that by this treatment flexural strength as well as surface finish of the components has improved significantly along with small variations in prototype dimensions. Nuñez et al. [19] examined the effect of part density and layer thickness on dimensional accuracy, flatness, and surface texture obtained in FDM with ABS-plus as the model material and concluded that minimum dimensional deviation was obtained with layer thickness of 0.254 mm and with solid density. The *Z* axis exhibited the worst dimensional behavior and density of model interior fill was found to be the parameter affecting most dimensional precision even more than the layer thickness on the *Z* axis.

Pennington et al. [20] investigated the dimensional accuracy of parts produced by the FDM technique of RP and concluded that part size, location in the work envelope and envelope temperature had a significant effect on the dimensional accuracy of ABS parts. Rattanawong et al. [21] developed a part build orientation system based on a primitive volume approach for RP by considering the volumetric error (VE) generated during the process. The developed system graphically displays the VE at different orientation and recommended the best orientation for minimum VE. Based on the results, the recommended build orientation in case of cylinder and cube was 0° and 90° because VE was minimum at these orientations.

Sood et al. [22] examined the effect of five parameters (layer thickness, part build orientation, raster angle, air gap and raster width) on the dimensional accuracy of length, width and thickness of FDM-made ABS parts using the Taguchi method. The results indicated that optimum parameter that minimizes the variation in all the responses were different. So, the common factor settings that simultaneously show the minimum deviation in all the responses had been obtained using grey Taguchi method. Mohamed et al. [23] tried to study the influence of six FDM process parameters (layer thickness, air gap, raster angle, build orientation, road width and number of contours) on the percentage change in length, width and thickness using I-optimality criterion. The optimum parameter settings for all the three responses were different and the best solution was achieved by I-optimality criterion. The main advantage of I-optimality criterion is that the optimum settings were not restricted to the experimental values as in the case of grey Taguchi method, so true optimum settings were achieved using this approach. Katatny et al. [24] made investigations regarding the errors generated during the fabrication of two anatomical parts (skull or mandible) for different human sizes (infant, female or male) using FDM3000 system by comparing the dimensions with actual models and concluded that high level of accuracy has been achieved by the FDM process in comparison with other RP techniques.

Further, in order to improve the surface finish of plastic replicas, chemical vapor smoothing (CVS) process has been established recently in which ABS or similar plastic materials are exposed to chemical vapors generally of acetone [25,26]. These chemical vapors enhance the surface finish of the ABS replicas by softening the external layer as the acetone breaks the secondary bonds between the ABS polymer chains. This permits the chains to slide past one another and stream to more stable positions.

The literature review reveals that orientation, layer thickness and part density (part interior style) are the main factors that affect the dimensional accuracy of FDM prototypes [19,22,23] and lot of research work has been done to improve the surface finish and dimensional accuracy of by employing various techniques such as by optimizing the input parameters, by utilizing the optimum slicing strategy, or by optimizing part build orientations. Also, some work has been reported that reveals that the surface finish of ABS replicas improved significantly by exposing them to suitable chemicals at the expense of dimensional accuracy [18]. But still a lot of scope has been observed to determine the effect of combined process of FDM and CVS on the dimensional accuracy as well as on the repeatability of fabricated replicas. So, in this research work the author tried to study the influence of FDM and CVS process parameters on the linear and radial dimensions as well as on the repeatability of dimensions. The optimization of process parameters has been done to obtain the optimum parameter settings and it has been also checked that whether the tolerance of the fabricated components is consistent with the permissible range of tolerance grades as per ISO standards. The main aim of this research work is to predict the feasibility as well as repeatability of combined process of FDM and CVS to fabricate the selected components with required properties, so that they can be utilized in the IC process as a sacrificial pattern for the production of specialized or tailor made products in small to medium quantity.

2. Methododlogy and experimentation

In this work, a component of biomedical application (hip joint) as shown in Fig. 1 has been selected as the benchmark. The hip joint is basically a ball-and-socket joint. The socket is made of bone and cartilage, and the ball is the head of the thigh bone (femoral head). During the hip replacement surgery, the damaged hip joint is replaced with metal, plastic or ceramic components. Generally, the ball (femoral head) is removed and replaced with new and durable artificial synthetic part. The CAD model of the selected component has been made using SolidWorks software and then converted into .STL format which serves as input to the FDM machine. Fabrication of the 3-D model has been done layer by layer by FDM machine, followed by a CVS process to enhance its surface finish.

Although, CVS is a surface treatment process utilized to improve the surface finish of plastic components but variations in part dimensions due to this process has been observed by some of the researchers [18,25]. Also, literature review reveals that variation in part dimension due to the CVS is of the order to be easily measured with equipment having least count of 0.01 mm [18,25]. So in this work, deviation of the two critical dimensions as shown in Fig. 1 after the CVS process has been measured by digital vernier