Journal of Manufacturing Processes 20 (2015) 525–533

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Technical Paper

Investigations on dimensional accuracy of the components prepared by hybrid investment casting

Parlad Kumar [a], Rupinder Singh [b,*], I.P.S. Ahuja [a]

[a] Department of Mechanical Engineering, Punjabi University, Patiala, Punjab, India
[b] Department of Production Engineering, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India

ARTICLE INFO

Article history:
Received 12 February 2015
Received in revised form 15 July 2015
Accepted 15 July 2015
Available online 23 October 2015

Keywords:
Fused deposition modelling
Investment casting
Additive manufacturing
Rapid prototyping
Dimensional accuracy
Tolerance grades

ABSTRACT

The rapid prototyping technologies (RP) are very useful when a limited number of pieces are promptly required like: in making/testing prototypes, design iterations and design optimisations. The fused deposition modelling (FDM) is one of the RP technologies that can use thermoplastic for making sacrificial patterns used in investment casting (IC) applications. Investment casting, often known as precision casting process, is used to produce parts with controlled dimensional tolerances. In the present study, dimensional accuracy of hip joints prepared with FDM assisted IC process has been optimised using a design of experiments technique. The effect of process parameters on FDM assisted IC process has been evaluated and studied using ANOVA. The results of the present study indicated that hip joint castings are acceptable as per the international tolerance grades.

1. Introduction

In the recent past, rapid prototyping (RP) technologies have gained importance due to their various advantages [1,2]. Fused Deposition Modelling (FDM) is one of the major RP techniques. In this method, a three dimensional CAD model is prepared and given as an input to the FDM machine [3]. The FDM machine processes this file and makes the solid Acrylonitrile-butadiene-styrene (ABS) plastic model. The properties of this plastic model can be controlled by controlling FDM machine parameters [4]. This plastic model can be used to replace wax patterns in traditional investment casting (IC) process without any major modification in the process [5,6]. The plastic based sacrificial patterns benefit the IC process by eliminating the expensive tooling required for making wax patterns. Further, it enables the engineers to make design iterations, readily [7,8]. Therefore, this method is very time and cost effective when only limited number of pieces of a particular size are required, such as: in design iterations, missile parts, space craft parts, patient specific implants etc. The application of FDM based pattern in IC process to produce metal cast parts can be termed as rapid investment casting [9]. The FDM assisted IC process can be used to make functionally graded materials [10].

Dimensional accuracy of a component represents the degree of agreement between the manufactured dimension and its designed specification [11]. Dimensional accuracy is the most critical factor in IC and it is directly affected by the accuracy of the pattern. If the pattern is inaccurate, there are little chances of producing an accurate casting. But, the dimensional accuracy achieved with the FDM process is less as compared to conventional wax patterns [12]. The less accuracy of FDM is due to many factors such as: process parameters of the machine [13]; shrinkage of model during the transition from a semi-liquid state to solid and cooling at solid state [13,14]; and stair case effect on curved and taper surfaces [15]. The temperature and build speed during the build process also affects the accuracy of the parts [16]. Another main factor for dimensional inaccuracy is layer thickness [17]. In addition to this, there are some other factors which influence the dimensional accuracy of FDM independently or in interaction with others [18].

The review of literature reveals that a lot of work has been done by various researcher to improve the dimensional accuracy of FDM parts. Masood et al. [19] described a methodology for computing the volumetric error for any orientation. A mathematical technique was developed to determine the optimum part orientation of the parts built by the FDM. The technique was verified by comparing the results with the experimental measurements of the volumetric errors of the parts built at different orientations. Gregorian et al. [16] found an optimal shrinkage compensation factor for improving the accuracy of FDM models prepared by using FDM-1650 machine. A shrinkage compensation factor of 0.7% was

* Corresponding author. Tel.: +91 9872257575; fax: +91 1612490339.
E-mail addresses: pkgarg4050@gmail.com (P. Kumar), rupindersingh78@yahoo.com (R. Singh), ahujaips@yahoo.co.in (I.P.S. Ahuja).

http://dx.doi.org/10.1016/j.jmapro.2015.07.008
1526-6125/

suggested. Tong et al. [20] suggested an approach of software error compensation to improve the accuracy of a FDM machine by considering correction of both STL and SSL file formats. The STL file compensation method was applied to the FDM-3000 machine and it reduced the average volumetric error by around 30%. Sood et al. [21] conducted a study for improving dimensional accuracy of FDM built parts. It is found that the shrinkage of the FDM parts adversely affect the dimensions. Optimum parameters setting was found out using Taguchi's parameter design in order to minimise percentage change in length, width and thickness of standard test specimen. Bakar et al. [22] showed that FDM is less accurate when making circular shape. The researchers recommended that for making small parts with a good accuracy and appearance, appropriate values of contour width and internal raster should be applied, besides applying thin layer. Percoco et al. [23] found that shrinkage compensation factor gives correct results with solid parts but poor results for hollow and sparse parts. Galantucci et al. [13] verified the adequateness of the shrinkage compensation factor for shafts and holes. It was found that shrinkage compensation factor gives better results on shafts as compared to holes. Noriega et al. [24] proposed a method for increasing accuracy of the distance between parallel faces on FDM manufactured prismatic parts by replacing the theoretical values of CAD model dimensions by new optimised values. A reduction in manufacturing error up to 50% was reported. Guo and Zhou [25] discussed about possible errors like machine error, STL model error and shrinkage error during FDM pattern making and silicone mould casting. The authors identified various process parameters influencing these errors and suggested that CAD model compensation and process improvement should be used to eliminate the errors. Gurrala and Regalla [26] conducted experiments for multi-objective optimisation of FDM machine parameters for optimum strength and volumetric shrinkage. It was found that the strength of the part has to be compromised in order to obtain better dimensional stability. Boschetto and Bottini [27] tried to predict the obtainable accuracy of the FDM parts and reported that the dimensional deviations of FDM parts strongly depend upon the deposition angle. Volpato et al. [28] found that the dimensional accuracy in the *Z* direction of an FDM part can be increased by improving the surface quality of the support base. It was reported that reductions in *Z*-axis error of up to 50% can be achieved. However, the manufacturing time and volume of support material required are adversely affected with the proposed configurations. Singh et al. [29] tried to improve the dimensional accuracy of the FDM assisted castings by changing the shell moulding process. It was proposed to add some fibrous material in the slurry material during shell making in the IC process.

The different methods suggested by various researchers for improving the dimensional accuracy are mainly focused on error correction by software and parametric optimisation of FDM machine. These methods have been proved to be successful for improving the dimensional accuracy of FDM models. But for IC applications the dimensional accuracy can be further increased by the hybridisation of conventional wax pattern based investment casting with the modern plastic pattern based investment casting. In this method, instead of using only wax or plastic pattern, a wax coated plastic pattern can be used in investment casting process and this process can be termed as hybrid investment casting.

In this paper, it is proposed that a thin layer of wax on plastic pattern will reduce inaccuracy due to staircase effect and shrinkage. The effect of some other casting process parameters like: volume to area ratio of the casting; orientation of the part during pattern making; density of the pattern; mould wall thickness; and grade of material has also been analysed on the dimensional accuracy of the castings. In order to get the best dimensional accuracy, the optimisation of process parameters has also been done and it has been checked that whether international tolerance (IT) grades of the components produced by using hybrid investment casting process are consistent with the permissible range of tolerance grades as per ISO standards.

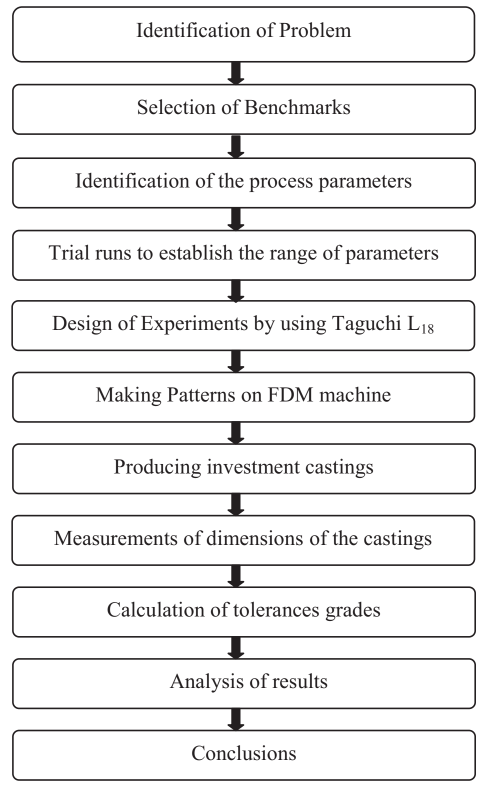

Fig. 1. Methodology of the study.

2. Methodology

The various steps of the study are represented in Fig. 1 in the form of a flow chart.

2.1. Selection of benchmarks

Three different parts of practical importance and having different volume to surface area ratios have been selected as shown in Fig. 1. These parts are the different types of prosthetic biomedical implants that are used in total hip replacement joint of human body. Three different grades of stainless steel have been used to make these parts by hybrid investment casting process. The drawings of these parts have been shown in Fig. 2(a–c).

2.2. Identification of process parameters

The various input factors that may influence the dimensional accuracy have been identified. These factors are: type of pattern, volume to area ratio of the casting, orientation of pattern in FDM machine, density of the pattern, mould thickness and grade of the material. For experimentation, two or three levels have been selected for each input factor. The factors and their levels have been decided on the basis of preliminary study and pilot experiments. The list of various input factors along with their levels is given in Table 1.

A brief description of these input factors has been given below:

(i) *Type of pattern:* Two types of patterns have been selected. The first pattern is made of ABS plastic and coated with a thin layer of wax whereas the second is uncoated ABS plastic pattern.