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Optimization simulated injection molding process for ultrahigh molecular weight polyethylene nanocomposite hip liner using response surface methodology and simulation of mechanical behavior

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ABSTRACT

In this study, injection molding process of ultrahigh molecular weight polyethylene (UHMWPE) reinforced with nano-hydroxyapatite (nHA) was simulated and optimized through minimizing the shrinkage and warpage of the hip liners as an essential part of a hip prosthesis. Fractional factorial design (FFD) was applied to the design of the experiment, modeling, and optimizing the shrinkage and warpage of UHMWPE/nHA composite liners. The Analysis of variance (ANOVA) was applied to find the importance of operative parameters and their effects. In this experiment, seven input parameters were surveyed, including mold temperature (A), melt temperature (B), injection time (C), packing time (D), packing pressure (E), coolant temperature (F), and type of liner (G). Two models were capable of predicting warpage and volumetric shrinkage (%) in different conditions with R^2 of 0.9949 and 0.9989, respectively. According to the models, the optimized values of warpage and volumetric shrinkage are 0.287222 mm and 13.6613%, respectively. Meanwhile, a finite element analysis (FE analysis) was also carried out to examine the stress distribution in liners under the force values of demanding and daily activities. The Von-Mises stress distribution showed that both of the liners can be applied to all activities with no failure. However, UHMWPE/nHA liner is more resistant to the highest loads than UHMWPE liner due to the effect of nHA in the nanocomposite. Finally, according to the results of injection molding simulations, optimization, structural analysis as well as the tensile strength and wear resistance, UHMWPE/nHA liner is recommended for the production of a hip prosthesis.

1. Introduction

Total hip replacement includes the substitution of a damaged hip joint with simulated prosthetic components (Clarke et al., 2015; Qurashi et al., 2018). After more than a half-century, from the first introduction of total hip replacement, ultra-high molecular weight polyethylene (UHMWPE) yet has been suggested as the main option in sustaining components, like a hip liner, for the replacements. This polymer has attracted the studies of many researchers and engineers due to an extreme stability of its non-oxidized state (Puppulin et al., 2016; Affatato et al., 2018). It is well-known the main cause of UHMWPE's failure is assigned to its oxidative degradation, subsequently declines its mechanical properties (Affatato et al., 2016). Meanwhile, the functioning period of a total hip replacement with a metal-on-polyethylene bearing may be restricted by the low wear resistance of polyethylene liner (Kuzyk et al., 2011). In fact, the contact of metal on conventional UHMWPE, hard-on-soft bearing, has shown low wear resistance in both clinical and laboratory experiments (Rajpura et al., 2014). However, it is well-known that the mechanical properties of UHMWPE composites can be enhanced by adding reinforced second phases of ceramics, like hydroxyapatite (HA) (Mirsalehi et al., 2016; Ommati et al., 2011; Azaman et al., 2013). HA is currently used as a common biomaterial for tissue engineering and bone repair because its chemical composition is similar to the bone mineral phase and it can

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develop a good bonding to the bone structure when implanted (Mirsalehi et al., 2016; Canillas et al., 2017). It was shown that using nanohydroxyapatite (nHA) as a reinforcement in the biopolymeric matrix may reduce the degradation rate of the biomaterial (Davachi et al., 2017, 2016a). Moreover, HA is a kind of bioactive material with an excellent biocompatibility, bioactivity, non-toxicity, non-inflammatory behavior and non-immunogenicity (Torabinejad et al., 2014). Because of those advantages, HA has been used as the promising reinforcement of UHMWPE nanocomposite by applying different mixing systems including mechanical ball mill, extruder as well as internal mixer (Mirsalehi et al., 2016; Kang et al., 2016; Fang et al., 2006, 2005). Kang et al. studied the effect of micro and nano HA on the mechanical properties of UHMWPE composites. Different percentage of micro and nano HA were mixed homogeneously with UHMWPE using dry mechanical ball mill. Results revealed that the mechanical properties of nano-HA/UHMWPE composites are much better than micro-HA/UHMWPE composites and pure UHMWPE. Moreover, the micro- and nano-HA/UHMWPE composites exhibit a low friction coefficient and good wear resistance at 15 wt% of micro-HA and 10 wt% of nano-HA (Kang et al., 2016). UHMWPE hip liner as a molded biomedical part can be affected by different conditions during the injection molding process. It is well known that controlling the process and optimization its parameters are challenging for manufacturers. The lack of knowledge about the material and process conditions leads to mold the part with some critical defects such as shrinkage and warpage. Non-uniform packing pressures in the mold cavities, non-uniform molding temperatures or cooling rates, non-uniform wall thicknesses, the molecular structure of materials (amorphous, crystalline) and fillers are some of the possible warpage reasons (Hakimian and Sulong, 2012). The shrinkage of the molded part is influenced by the cooling system, volumetric shrinkage, flow-induced residual stresses, flow-induced crystallization and orientation. The type of polymer and its structure can also affect the shrinkage, however, most of those factors are arisen from process conditions, such as injection time, packing time, melt temperature, mold surface temperature and packing pressure. The computer-aided engineering (CAE) programs such as Autodesk Moldflow have been widely used in injection molding industry for designing and optimizing (Oliaei et al., 2016). There are not many types of research for injection molding simulation of the medical and biomedical parts. Recently, injection molding of poly lactic acid (PLA) based antibacterial nanocomposite bone screws were simulated and optimized by minimizing the warpage and volumetric shrinkage of the bone screws (Heidari et al., 2017). The influence of process factors such as injection time, packing time, mold temperature, coolant temperature, melt temperature and packing pressure was studied using Autodesk Moldflow. The optimized material and process conditions were proposed as the best candidates for the injection molding of the screws on the basis of the injection molding simulations, structural analysis as well as optimization results obtained by design of experiment (DoE) method. In injection molding process, the molded-part quality depends on operating parameters and their interactions with different ranges of sensitivity. Therefore, it is necessary to use a systematic approach to figure out the function of different parameters and optimum conditions. In the traditional method, one parameter is varying and the other factors are kept constant. A large number of experiments results in consuming huge cost and time. Moreover, this method has not the capability of considering the effects of interactions between parameters. This problem could be solved by using a set of DoE methods. In recent years, DoE techniques have been used in several varieties of engineering applications (Masoudi et al., 2017; Sargolzaei et al., 2011; Yao et al., 2017; Younes et al., 2014). DoE provides several valuable benefits for researchers, including understanding necessary information in less number of experiments, recognizing the factors having significant effects on the outcome and examining more than one dependent variable using the same single set of experiments (Narayanan et al., 2014). Among the various methods of DoE, fractional factorial design (FFD) and response surface methodology (RSM) are the most powerful statistical techniques to explore the effects and significances of several controllable variables on a response of interest (Heidari et al., 2017; Gunst and Mason, 2009). FFD method uses the available properties of the design to decrease the number of experiments, while restrictively considers the loss of non-investigated critical information of all possible level combinations of the vital factors (Gunst and Mason, 2009). Although the optimization of injection molding simulation noticeably helps to improve the quality of the biomedical part, however, during the application of the medical part in the human body, its mechanical behavior should be considered as well as its production conditions. Thus, finite element (FE) analysis has been used to forecast the stress concentration point, stress distribution and subsequently, finding the failure site in the biomedical part during its application (Heidari et al., 2017). FE analysis is extremely used for premedical testing of orthopedic implants such as those used in hip replacement. It is a cost-effective procedure that can be applied to the various implants and analyze the effects of different conditions which are related to the behavior of the in-use implant (Caouette et al., 2015). The aim of the present study is a simulation of the injection molding process of UHMWPE and UHMWPE/nHA hip liners. Moreover, the influence of several injection molding parameters including mold temperature, melt temperature, coolant temperature, injection time, packing time and packing pressure on the shrinkage and warpage of two types of liners is investigated. This study consists of three major novelties in materials, the design of experiment and simulation of the liners using Moldflow and ANSYS Workbench. By the addition of nHA, the mechanical properties and biocompatibility of hip liner can be improved. The FFD method was selected for modeling and optimizing the conditions of injection processing, and the warpage and volumetric shrinkage were selected as the responses. Moreover, the hip prosthesis model is investigated by ANSYS Workbench to analyze the mechanical performance of hip liners in daily and demanding activities including cycling, walking, sit down, stairs down, stand up, stairs up and jogging.

2. Methodology and procedure

2.1. Material and characterization

A commercial grade of UHMWPE (Lumber L4000) was supplied from Mitsui Chemicals Company. Nano-HA (KF-HAP04) with a size ranging from 20 to 40 nm and 99% purity was purchased from Kinfon Pharma, China and all the nanoparticles information are reported elsewhere (Davachi et al., 2016a, b). Samples of UHMWPE/nHA composite with 10 wt% of HA, as well as pure UHMWPE, were prepared. The HA content in UHMWPE was chosen according to a previous study which was shown that UHMWPE/nHA composite with 10 wt% of nano-HA exhibits a low friction coefficient and good wear resistance (Kang et al., 2016). The UHMWPE nanocomposite was obtained by homogeneous mixing of 10 wt% of nano-HA with UHMWPE via dry mechanical ball mill. The mixing process totally took 4 h to complete in both clockwise and anti-clockwise direction. Then, the samples were heated and hot pressed at a temperature of 200 C under 15 MPa for 2 h. The pressure-volume-temperature (PVT) and rheological properties of nanocomposites are measured using SWO PVT 100 apparatus (China) and Anton Paar Physica MCR301 (Graz, Austria) with parallel-plate geometry, respectively. The measured characteristic data further were mathematically model fitted to be imported into Autodesk Moldflow® database as discussed in the previous works (Oliaei et al., 2016; Heidari et al., 2017). The PVT plots for the materials are shown in Fig. 1a,b and the Cross-WLF model of the rheological data for the materials are depicted in Fig. 1c,d. The mechanical properties of the samples are listed in Table 1 obtained by Gotech Universal AI-7000-LA (Taiwan) based on ASTM D638. The wear volume measured using Gotech GT-7012-DN for five samples and the average is reported in Table 1.