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Modeling of the chemical finishing process for polylactic acid parts in fused deposition modeling and investigation of its tensile properties

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ABSTRACT

Fused deposition modeling has become one of the most diffused rapid prototyping techniques, which is widely used to fabricate prototypes. However, further application of this technology is severely affected by poor surface roughness primarily due to staircase effect. It is necessary to adopt post-treatment operations to improve surface quality. Chemical finishing is typically employed to finish parts in fused deposition modeling. The purpose of this paper is to provide a universal finishing method or solution for FDM parts made up of PLA, and to represent the evolution of surface topography between adjacent layers during the chemical finishing operation by building a geometrical model of the deposited filament. Case study was used to validate the proposed model by an experimental observation using a 3D laser scanning microscope. The comparison between theoretical computed values and observed data shows a significant reliability by means of statistical analysis. Subsequently a number of specimens are tested to determine the changes in tensile properties of fused deposition modeling parts building in different orientations. The results show that the horizontal build directions have little influence on the tensile strength. And, untreated specimens of polylactic acid show brittle behavior due to the inherent material properties. Because of the thin transparent film formed on the appearance, the tensile mechanical properties of specimens after chemical finishing are obviously changed, with the result that the tensile strength reduces by 63% and elongations at break improve by 50%. This chemical finishing not only decreases the roughness of parts manufactured in fused deposition modeling significantly, but also improves the toughness of polylactic acid parts.

1. Introduction

Fused deposition modeling (FDM) is the most diffused rapid prototyping technique in the world (Wohlers, 2012). In comparison with traditional manufacture, it can rapidly fabricate prototypes with complex shapes using thermoplastic plastics, such as acrylonitrile butadiene styrene (ABS), polyethylene, polypropylene, polycarbonate and polylactic acid (PLA). Among the viable materials, PLA is one of the most potential polymers due to it is friendly to the environment, which can be produced through fermenting of renewable resources like corn and sugarcane. The primary characteristics of this technology include: low cost, toxic free materials, rapid response to the need of market and high utilization rate of raw materials. Hence, this technology has been widely applied in various fields, such as automotive, biomedical and customer product industry (Ivanova et al., 2013). However, further application of FDM parts is severely affected by poor surface roughness primarily due to staircase effect.

Issues related to poor surface roughness of FDM parts have been investigated through building several theoretical models by some researchers. Pandey et al. (2003) developed a semi-empirical model to predict surface roughness of FDM parts by assuming the layer profile as a sequence of parabola arcs. Using a simple material removal method namely hot cutter machining (HCM), they concluded that the model developed was able to predict surface roughness after HCM with more than 99% correlation and 97% confidence level in the direction of machining. Ahn et al. (2009a,b) proposed a model to represent the average roughness by assuming the filament profile as an elliptical curve. Attributes of cross-sectional shape, surface angle, layer thickness and overlap between adjacent layers were considered as the main factors affecting surface quality. By comparison between the measured data and computed values, the validity of the proposed model

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was proved. In Boschetto et al. (2012), a new model for theoretical representation of the roughness profile was proposed, which allowed to predict every roughness parameters in the range of deposition angle. Subsequently, a three-dimensional model for other roughness parameters considering the measurements direction was introduced in Boschetto et al. (2013).They studied the surface roughness of FDM samples using 3D profiler. The proposed approach is effective in investigated micro-geometrical features of FDM model.

Many attempts have been made to obtain better surface quality of FDM parts by optimizing fabrication parameters. A study conducted by Thrimurthulu et al. (2004) proposed a real coded genetic algorithm to obtain an optimum part deposition orientation for enhancing part surface finish and reducing build time. The predictions of the developed algorithm were validated using the results published earlier. Rianmora and Koomsap (2010) proposed an approach of adaptive slicing which applied the image processing technique to determine appropriate thickness and to recommend slicing positions upon a 3D model. Compared with other approaches, the adaptive slicing approach not only reduced build time but also maintained surface quality. Bakar et al. (2010) analyzed the effect of three parameters on FDM parts, such as layer thickness, contour width and internal raster. The study showed that these parameters contributed to improve the bonding quality between layers and to obtain a better surface finish. In order to determine the relationship between five input parameters, Mahapatra and Sood (2012) proposed an artificial neural network (ANN) model. Then Bayesian regularization was adopted for selection of optimum network architecture. The results showed that at the top surface raster width was the most important parameter to reduce surface roughness. And, part orientation and layer thickness were significant for improving surface finish at bottom and side surfaces, respectively.

Compared to other additive manufacture, some similar methods could be adopted to model the printing process. Garg et al. (2015a) developed an artificial intelligence approach of multi-gene genetic programming (MGGP) to model the selective laser melting (SLM) process. The result revealed the hidden relationships between surface characteristics and the laser power, which could be used to optimize the SLM process. Garg et al. (2015b) proposed two variants of the evolutionary approach using genetic programming (GP) in the formulation of a functional expression between the density of fabricated parts and seven inputs of the SLM process. A major contribution of the study was that the optimum values of the inputs could be selected to curtail the energy usage from the SLM process. Further study was conducted by Garg et al. (2015c), and a new computational intelligence (CI) approach (ensemble-based MGGP (ENMGGP)) that made use of statistical and classification strategies for improving its generalization. The proposed EN-MGGP model outperformed the standardized model and was proven to capture the dynamics of the SLS process by unveiling dominant input process parameters and the hidden non-linear relationships.

Whereas, roughness on the vertical orientation caused by staircase effect cannot be completely avoided through building theoretical models or optimizing fabrication parameters, especially when the surface quality of the FDM part is required to a high level. Therefore, post-treatment operations to improve surface quality are needed.

At present, two primary approaches are used to achieve smooth surfaces on parts: chemical and mechanical smoothing. In Galantucci et al. (2009,2010), a chemical post-treatment of ABS prototypes was adopted after studying the influence of FDM machining parameters on surface quality, yielding a significant improvement in surface finish. Then tensile and bending mechanical properties were investigated by designing and performing experiments with the result that a general improvement of the flexural strength was obtained. A more in-depth knowledge to explore the effect on the compressive strength after chemical treatment of ABS was investigated by Percoco et al. (2012). The results revealed that mechanical properties of treated parts in some cases were better than those of non-treated parts. By design of experiments, Rao et al. (2012) analyzed the various parameters of a chemical treatment process of ABS parts. The authors found that concentration and initial roughness were the most significant parameters on the condition of using acetone solution. And the parts obtained have a glossy look compared to plastic molded parts. Garg et al. (2016) studied the effect of acetone vapour treatment on surface roughness and dimensional accuracy of simple primitives and flat surfaces of FDM samples. The optical microscopic was used to assess the surface roughness of the samples. Boschetto and Bottini (2015) proposed a geometrical model of the profile to predict the surface morphology achieved by barrel finishing (BF). The profilometer and dimensional measurements were used to assess the output of the coupled technologies in terms of surface roughness and accuracy. The authors found that the deposition angle strongly affected the BF removal speed and altered nominal dimensions of part. Application of surface coatings was another approach to achieving a desired surface finish, in addition to adding strength to a finished part (Turner et al., 2014).

Literature survey reveals that few studies have been investigated on the chemical finishing of PLA parts quantitatively, not to mention a more in-depth understanding of the chemical finishing processing of treated parts made up of this material. The purpose of this paper is to represent the evolution of surface topography between adjacent layers during the chemical finishing operation by building a geometrical model of the deposited filament. Furthermore, the aim of the experimental activity is to investigate the influence of the chemical finishing on the tensile strength of PLA parts in FDM.

In this work, a theoretical model of transformation of the surface topography between adjacent layers during chemical treatment has been proposed. The formulation begins from an analysis of the chemical treated process and ends to provide a method to calculate the thickness of the thin transparent film formed due to chemical finishing. Before and after chemical finishing, the surface topography is observed by a 3D laser scanning microscope to verify the model built. Subsequently, a more in-depth knowledge to analyze and compare the tensile properties of finished and non-finished FDM parts building in different orientations is investigated by design of an experiment.

2. Modeling of the process of the chemical finishing

For FDM parts, there exists a range of corrugated structures on the surface due to the staircase effect, which can be erased by vapor polishing using easy volatile solvents. In this paper, the filament feed stock is PLA, which dissolves easily in some organic solvent, such as dichloromethane. The process of dissolution and flow on the profile of PLA part in FDM is shown in Fig. 1. Appear on model surface, peaks and valleys become droplets through absorbing the volatile solvent. Then, under the effects of liquid surface tension and gravity, these two kinds of droplets blend continually, resulting in lower peaks and filled valleys. As it goes on, a dynamic balance will be achieved. Finally, a smoother surface can be obtained until vapor evaporated. Furthermore, a thin transparent film forms on the surface of parts which can be observed by the naked eye. Laser Raman spectra shows that there exists no dichloromethane in the dried product, and it has been volatilized completely after chemical treatment processing (Kasuga et al., 1999). This indicates that the dissolved molecules keep attach to the model surface during the progress. Based on the analysis above, the mass and volume of parts before and after chemical finishing can be supposed to maintain