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Data-driven simulation for fast prediction of pull-up process in bottom-up stereo-lithography[☆]

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ABSTRACT

Cohesive finite element simulation is a mechanics-based computational approach that can be used to model the pull-up process in bottom-up stereo-lithography (SLA) system to significantly increase the reliability and through-put of the bottom-up SLA process. This modeling relates the pull-up velocity and separation of the fabricated part during the pull-up process. However, finite element (FE) simulation of the pull-up process for the individual part is computationally very expensive, time-consuming, and not amenable to online monitoring. This paper outlines a computationally efficient data-driven scheme to predict the separation stress distribution in bottom-up SLA process. The proposed scheme relies on 2D shape context descriptor, neural network (NN), and a limited number of offline FE simulations. Towards this end, FE models and results for the cross-section of *n*-fold symmetric shapes form our databases. The 2D shape context descriptor represents different shapes through log-polar histograms in our database. A backpropagation (BP) neural network is trained using the log-polar histograms of the geometric shapes as inputs and the FE simulated stress distributions as outputs. The trained NN can then be used to predict the separation stress distribution of a new shape. The results demonstrate that the proposed data-driven method can drastically reduce computational costs and apply to any general databases. The comparison between the predicted results by the data-driven approach and the simulated FE results on new shapes verify the validity of the proposed method.

1. Introduction

Additive Manufacturing (AM), widely known as 3D printing, is a manufacturing technology that fabricates 3D solid objects directly from computer-aided design (CAD) data by adding materials layer upon layer. 3D printing technology allows manufacturers to make 3D shapes in sizes ranging from a 450 nm electronic kit to an average-sized building for many different applications [1,2]. However, regardless of all the significant advantages of AM technology, technical challenges, such as poor surface quality, high machine cost, low reliability and reproducibility, and limited compatible materials, still need to be addressed [1,3]. To improve the AM processes, researchers have examined different materials and parameters, combined different processes, and exploited a wide variety of post-processing techniques [3].

Among different AM technologies, the focus of this paper is on bottom-up image-projection-based Stereo-lithography (SLA). SLA is a photo-polymerization based process that achieves high accuracy and surface quality compared with other AM technologies [4,5]. In SLA process, the material filling mechanism is one of the most important factors that can significantly affect its reliability and through-put. Two material filling mechanisms are most widely used: *free-surface (top-down)* and *constrain-surface (bottom-up)*. Bottom-up SLA achieves better vertical resolution and higher material filling rate. Additionally, bottom-up SLA has several other advantages, such as less required amount of photopolymer resin and no exposure to oxygen during fabrication, over the top-down SLA process [6–11].

In spite of multiple advantages, parts fabricated by bottom-up SLA systems are subject to significant attachment forces, as they have to be separated from the bottom of the material container after each layer is cured. Large pull-up force creates a high risk of damage to the cured part. The separation between the cured part and the container is schematically shown in Fig. 1(1–4). The cured layer is formed between the previously formed layer and top of the Polydimethylsiloxane (PDMS) silicone film (a type of coating applied to the container so that the separation force is reduced [10,12]) as shown in Fig. 1(1). As the part is pulled up, the

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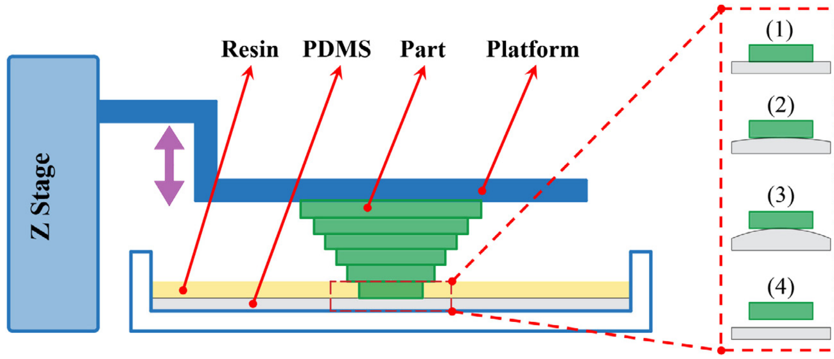

Fig. 1. Separation between the cured part and container during pull-up process.

PDMS silicone film starts to deform, and the separation of the part from the film starts from the boundary area as shown in Fig. 1(2). In Fig. 1(3), the separation area extends into the middle of the part while the platform continues moving up. The separation process is completed when the platform moves enough distance, as shown in Fig. 1(4).

During the pull-up process, the newly cured layer may not levitate together with the rest of the part and may stick to the bottom of the material container. Consequently, the part may break, leading to fabrication failure. One approach to address this problem is to increase the exposure time for over-curing the current layer so that its bonding force with the previous layer can be increased. However, the attachment force between the material container and the top fabricated layer is also increased simultaneously. Moreover, over-curing slows down the entire fabrication process and leads to poor surface quality and inaccurate dimensions. Another method to mitigate the attachment force is to apply a specific type of coatings to the material container. Appropriate coatings like Teflon and silicone films (PDMS being such an example as shown in Fig. 1) can help separate the built part from the material container [13,14]. However, even with the coatings, the required separation force is often considerable and may break the cured part. The objective of this work is to investigate this problem by relying on finite element (FE) simulation, the shape descriptor, and backpropagation (BP) neural network (NN) to substantially improve the through-put and reliability of the bottom-up projection-based additive manufacturing process. In this paper, a predictive model is developed to quickly determine the separation stresses during the pull-up separation process. The developed data-driven model can be useful for developing an *in-situ* feedback control system to alleviate the print failure issues in the bottom-up SLA process.

Overall, this paper makes following contributions:

(1) Developed an FE analysis (FEA) and NN based prediction model for quickly predicting separation stress distribution during the pull-up process of a bottom-up SLA system.
(2) Established a computationally efficient framework that is suited to develop *in-situ* feedback control system to mitigate the problem of fabricated part failure in bottom-up SLA.

In the next section, we review related works on pull-up process in bottom-up SLA systems, simulation of separation process, and FEA-NN based prediction models. A brief overview of the whole approach is given in Section 3. In Section 4, the creation of our shape database is described. Section 5 elaborates the creation of training data (input and output vectors) and provides details pertaining to FE simulation model of the separation process. Section 6 briefly describes the NN architecture underlying the prediction model. Numerical illustration is presented in Section 7. Finally, conclusion and future considerations are provided in Section 8.

2. Literature review

The techniques pertinent to pull-up process in bottom-up SLA process, simulation of the separation process, and FEA-NN based prediction models are briefly reviewed below.

Pull-up process in bottom-up system

Instead of simply over-curing the current layer to increase the bonding force, researchers have developed different methods to address the significant attachment force.

An alternative approach to solve the problem is to apply a specific type of coatings to the material container. Proper coatings such as Teflon and silicone films can help separate the part from the material container easily [13,14]. A coated Teflon glass has been used in the commercial machines of *Denken* and *EnvisionTec*. *Denken* has designed a digital light processing (DLP) system based on bottom-up technique. However, the attachment force was still very critical to breaking the built part [15]. Another bottom-up system called *E-DARTS* has been developed by *Autostrade* [16] as well. It performs similarly to the previous DLP system. The difference is a layer of silicone film was used as a medium between the built part and the resin container instead of Teflon. Huang and Jiang studied the attachment force through the coating of a super elastic silicone film [14]. They developed a direct mask photo-curing system using the super elastic and shear strength property to break the vacuum between the new curing layer and the resin container.

A two-channel system [9,10] and a two-way linear motion system [17,18] have also been proposed to reduce the pull-up separation force. In the two-channel system, Zhou et al. [10] used PDMS silicone film (the same film is used in our research as well) as an intermediate. Three effective factors related to the separation force were studied: exposure time, image area, and image shape. However, the experimental results still showed large separation force even with the PDMS film attached to the bottom of the resin container. That motivates the necessity of presenting a predictive methodology which is likely to be useful for *in-situ* feedback control system.

The authors have envisioned a predictive methodology and *in-situ* feedback control system in their previous works [7,8,19]. The goal of the proposed predictive scheme is to adaptively adjust the pull-up speed according to the predicted attachment stresses. To validate the proposed approach, we consider a bottom-up projection based system. In practice, a force sensor can be used in the system to monitor the force change dynamically and assist the prediction model to control the system. During the pull-up process, the sensor value would be dynamically compared to the predicted value and assist the model to compensate the errors introduced by linear approximation, coarse meshing, etc. If the maximum stress on the part is larger than a safety threshold, the speed of the motion would be reduced allowing for the separation to propagate.