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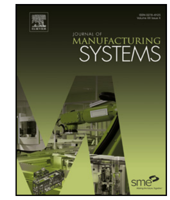

Technical Paper

A data mining approach in real-time measurement for polymer additive manufacturing process with exposure controlled projection lithography

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ABSTRACT

Real-time inspection and part dimensions determination during the manufacturing process can improve production of qualified parts. Exposure Controlled Projection Lithography (ECPL) is a bottom-up mask-projection additive manufacturing (AM) process, in which micro parts are fabricated from photopolymers on a stationary transparent substrate. An in-situ interferometric curing monitoring and measuring (ICM&M) system has been developed to infer the output of cured height. Successful ICM&M practice of data acquisition and analysis for retrieving useful information is central to the success of real-time measurement and control for the ECPL process. As the photopolymerization phenomena occur continuously over a range of space and time scales, the ICM&M data analysis is complicated with computation speed and cost. The large amount of video data, which is usually noisy and cumbersome, requires efficient data analysis methods to unleash the ICM&M capability. In this paper, we designed a pragmatic approach of ICM&M data mining to intelligently decipher part height across the cured part. As a data-driven measurement method, the ICM&M algorithms are strengthened by incorporating empirical values obtained from experimental observations to guarantee realistic solutions, and they are particularly useful in real time when limited resource is accessible for online computation. Experimental results indicate that the data-enabled ICM&M method could estimate the height profile of cured parts with accuracy and precision. The study exemplifies that data mining techniques can help realize the desired real time measurement for AM processes, and help unveil more insights about the process dynamics for advanced modeling and control.

1. Introduction

Additive Manufacturing (AM) techniques use a variety of approaches for direct joining materials to form physical objects. Manufacturers have been using these AM technologies in order to reduce development cycle times and get their products to the market quicker, more cost effectively, and with added values due to the incorporation of customizable features [1]. AM offers multiple advantages over traditional manufacturing techniques, including reduced material waste, lower energy intensity, reduced time to market, just-in-time production, and construction of structures not possible with traditional manufacturing processes. The numerous additive manufacturing processes could be classified based on materials or baseline technologies.

A number of technical issues must be addressed to achieve widespread use of additive processes for direct part production, and to realize the potential economic benefits. Among the issues are gaps in measurement methods, performance metrics, and standards needed to evaluate fundamental AM process characteristics, improve the performance of AM equipment, improve the accuracy of AM parts, and increase confidence in the mechanical properties of parts fabricated using these systems.

In 2012, an NIST workshop was held to understand and address the hurdles faced by the metal-based additive manufacturing community from the perspective of measurement science [2]. In 2016, another NIST workshop that focused on measurement science research needs for additive manufacturing of polymer-based materials took place to accelerate the commercialization and adoption of polymers-based AM [3]. The lack of real-time sensors in all the

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areas critical to process monitoring and control was identified as a major challenge.

To overcome the barriers in improving the accuracy and repeatability of an in-house built photopolymer additive manufacturing system – exposure controlled projection lithography (ECPL) [4], the authors' lab built an in-situ interferometric curing monitoring system [5,6]. Fig. 1 shows the overall physical system of the in-house designed additive manufacturing machine that includes the ECPL manufacturing system and ICM&M metrology system. The ECPL machine is a liquid vat stereolithography based system but projects the digital micromirror device (DMD) patterned ultraviolet (UV) light beam from beneath the stationary transparent substrate to cure a part with photopolymerizable resin material [7]. The ECPL system design shares the mask projection lithography's advantage in speed by curing a part cross section at one time, and features an immobilized vertical stage for fabricating micro optics and micro fluidics parts with smoother surface, that is, less staircase effect compared with traditional stacking stereolithography machines. The ICM&M system is based on a Mach-Zehnder interferometer [6]. The camera captures the intensity of incoming laser light from the resin chamber, and provides an interference pattern of intensity profile across the illuminated chamber area.

To upgrade the original primarily monitoring system into a real-time measurement equipment, the authors have created a sensor model based on interference optics to interpret the dynamic fringes in-situ automatically [8,9]. With the sensor model, for measuring the continuous growing surface of the part produced by the ECPL machine, online parameter estimation algorithms have been developed by adopting moving horizon exponentially weighted Fourier curve fitting and numerical integration to extract the phase change underlying the evolving interferograms [8,9]. The developed sensor model and measurement algorithms, together, establish a methodology of interferometric curing monitoring and measuring, and provide a feasible metrology system promising to enable real-time and full-field measurement of the photopolymer part dimensions.

This study continues the authors' research initiative in seeking for real-time measurement method for the dimensions, primarily the vertical height, of additively manufactured photopolymer parts made by the ECPL process. With the ICM&M sensor model and algorithms established in previous work [8], the main practical aspects, data processing and effects of algorithms and algorithm parameters, which are critical for effective implementation of the ICM&M method, remain unresolved. Based on the developed ICM&M method resultant from previous research on sensor modeling and algorithms [8,9], this study is aimed at the potential of harnessing the rich but usually noisy data from video of interferograms with data mining techniques to realize a real-time metrology of cured part height for advanced process control [10].

To start, Section 2 of this paper introduces briefly the prior research result of the developed sensor model and algorithms that formulate the ICM&M method. Section 2 will also identify the research issues raised by the real and rich data in physical implementation of the ICM&M. Section 3 is focused on addressing the practical issues from the data perspective with the aid of a data mining approach to fulfill the ICM&M's role as a reliable metrology for the ECPL process. The developed ICM&M data analysis algorithms are summarized in Section 4 followed by conclusions in Section 5.

2. The ICM&M method from data perspective

2.1. Data analytics in manufacturing

Enormous literature is available in the area of data analysis techniques, and solution approaches are often adjusted or rediscovered for the specific application domain such as manufacturing processes and materials development. Data analysis is pervasive in scientific simulations, experiments and observations with the aim of finding useful information [11], and is used extensively to improve the performance of manufacturing systems at different levels. The focus of the research so far is on data mining techniques as well as on the stages before and after data mining, including data collection, processing, cleaning, transformation and decision making based on data [12]. Developing data enabled sensing and control techniques is an emerging research line for advanced manufacturing with higher efficiency and lower cost [12].

2.2. The conceptualized ICM&M method

To achieve the full power of data mining, one needs both a well-formulated objective, a well-articulated statement of assumptions and some empirical data coming from experiments or observations and expert knowledge [13]. In the authors' previous published work [8,9], a fundamental framework of the ICM&M method was already conceptualized, which provides a well-established model for the material implementation of ICM&M with realistic datasets.

Firstly, the ICM&M sensor model for computing the cured height has been created as shown in Eq. (1) [8,9].

$$Z = \frac{\lambda}{2\left(n_m - n_l\right)} \sum_i T_i f_i \qquad (1)$$

where Z is cured height (μm), λ is the ICM&M system's laser wavelength 0.532 μm, nm and nl are mean cured and liquid part refractive index; Ti is the time step of integration, fi is the instantaneous frequency in the *i*th run of parameter estimation.

In Eq. (1), the refractive index difference term $\Delta n = (n_m - n_l)$ requires calibration with ex-situ microscope measurements of cured height. A value of $\Delta n = 0.0222$, derived from calibration experiment which cured square blocks under UV exposure of 22% iris level for 12 s [8], was used in this study. It is noted that the cumulative sum term $\sum_i T_i f_i$ is essentially the total phase angle that has changed during the curing process with a unit referred as cycle (one cycle is 2π rad).

Secondly, the ICM&M algorithms of moving horizon exponentially weighted curve fitting with "fourier1" model, simply referred as "rolling fit" later, has been developed to estimate online the instantaneous frequency in the sensor model [8,9].

2.3. To materialize the ICM&M method with data techniques

The ICM&M method, consisting of sensor model and algorithms, is by nature a data-driven measurement method, developed to gain insights for the ECPL curing process and to infer with confidence about the final height of the cured product. In practice, the conceptual level of the ICM&M sensor models and algorithms should be embedded into the context of real data environment during data acquisition, algorithms implementation, model evaluation, and final decision making. Employing the data science process [14], a diagram as shown in Fig. 2 illustrates from the data perspective the implementation level of the ICM&M method with yellow highlights (1)–(4) identifying the nodes where substantial data analysis may be performed.

Firstly, during image acquisition, the video often has missing frames. Worse still, the images may be of low quality, for instance, interferograms are low contrast and noisy due to camera electronics issues [15]. Preprocessing and classification (yellow highlight (1) in Fig. 2) could help obtain a clean dataset for ICM&M analysis.

Furthermore, the ECPL process parameters and the ICM&M algorithm parameters will affect the accuracy and robustness of the ICM&M method for ECPL cured part measurement. The ECPL pro-