Laser scanning path generation considering photopolymer solidification in micro-stereolithography


Abstract It is essential to automate the scanning path generation process to effectively implement the micro-stereolithography. However, a scanning path that is generated based only on a 3D CAD model introduces dimensional inaccuracies. In micro-stereolithography, the photopolymer solidification is affected by fabrication conditions, such as the optical properties (laser power, laser scanning speed, laser scanning pitch focusing condition, etc.) and material properties of the photopolymer. Thus, the photopolymer solidification phenomena must be considered when generating a laser scanning path. In this paper, a scanning path generation algorithm that uses 3D CAD data and considers the photopolymer solidification phenomena is proposed to improve the dimensional accuracy in micro-stereolithography. Multi-line photopolymer solidification experiments were performed for various laser scanning conditions to examine the photopolymer solidification phenomena. From these experiments, linear relations between the solidification length (width) and scanning length (width) were acquired and stored in a database. Subsequently, these data were utilized to compensate the scanning path of the laser beam. In addition, experiments for determining the layer thickness in the z-direction were performed and these results were also used in the scanning path generation algorithm.

Keywords scanning path generation, photopolymer Solidification, Micro-stereolithography, UV laser beam

Nomenclature

- \( P_L \) Power of the laser beam
- \( \lambda \) Wavelength of the laser beam
- \( f \) Focal length of the focusing lens
- \( V_s \) Scanning speed of the laser beam
- \( D_p \) Penetration depth of the photopolymer
- \( E_c \) Critical exposure of the photopolymer
- \( W_0(z) \) Gaussian half-width of the laser beam
- \( y_{\text{length}} \), \( y_{\text{width}} \) Gaussian half-width of the laser beam
- \( a_{\text{length}} \), \( a_{\text{width}} \) Slope of the linear empirical compensation equations

1 Introduction

Micro-stereolithography is an emerging technology that uses a focused UV laser beam with a diameter of a few \( \mu \)m to fabricate 3D freeform microstructures. By scanning this laser beam over the surface of a UV-curable photopolymer, a cross-section of a 3D structure can be solidified. Once a layer is fabricated, a photopolymer filling process is started to ready the next layer for fabrication. These processes are then repeated. A 3D freeform microstructure is fabricated by stacking this series of solidified layers. In micro-stereolithography technology, fabrication conditions that are considered major process variables include laser-related parameters (power, scanning speed, scanning pitch, and focusing conditions) and material properties of the photopolymer (penetration depth and critical exposure).

Research into micro-stereolithography technology goes back to the early 1990s. Ikuta developed the IH (Integrated Harden polymer stereolithography) process [1] and the improved super IH process [2]. Bertsch et al. [3] developed a micro-stereolithography apparatus using a pattern generator. In this apparatus, a dynamic LCD pattern generator was used to generate the cross-sectional areas of a 3D structure. Zhang et al. developed a micro-stereolithography apparatus with insitu process monitoring using ceramic micro-stereolithography technology [4–5]. Lee et al. [6] developed a micro-lens using micro-stereolithography and fabricated a mold master using this technology. Kim et al. [7] proposed the virtual fabrication process.

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based on the internet environment. These studies were mainly concerned with the development of a micro-stereolithography apparatus or the fabrication of 3D microparts. Research concerning the dimensional accuracy of the scanning path generated to fabricate the 3D microstructures attracted little attention.

However, studies have been performed to improve the dimensional accuracy of conventional stereolithography technology. Most of these efforts have been focused on generating a scanning path that was simply based on 3D CAD information about the target product [8–10]. However, as these scanning paths are based solely on 3D CAD information, they do not guarantee dimensional accuracy in micro-stereolithography technology because the photopolymer solidification phenomena must also be considered.

In this study, cross-sections were generated with multiple scanning lines using micro-stereolithography. The effects of the scanning conditions on the accuracy of the 3D shape were studied experimentally. Multi-line solidification of the photopolymer was performed, and linear relations between the solidified length (width) and scanning length (width) were acquired. Based on these experimental results, a scanning path generation algorithm was proposed in which the experimental results were stored in a database and were then used to compensate for the photopolymer solidification effects in the scanning path generation process. In addition, experiments were performed to determine the layer thickness in the \( z \)-direction; these results were also applied to the scanning path generation algorithm.

2 Plane scanning path generation

2.1 Multi-line photopolymer solidification

In micro-stereolithography, a laser beam with a diameter of a few \( \mu \text{m} \) is used to solidify a very small area of a photopolymer. A focusing lens is used to generate the very small diameter laser beam. These thin single lines have to be overlapped and hatched (multi-line) with each other to fabricate the desired cross-sectional area. Therefore, single line solidification must be studied before investigating the multi-line phenomena.

A theoretical model of single-line photopolymer solidification has been proposed for conventional stereolithography [11]. However, this model is for an unfocused laser beam that does not reflect the solidified shape according to the variation of its Gaussian half-width along the laser beam axis.

Suppose that a continuous wave (CW) laser beam of wavelength \( \lambda \) and power \( P_L \) passes through a focusing lens of focal length \( f \), as shown in Fig. 1. The laser beam irradiates vertically and becomes focused on the surface \( (z = 0) \) of the photopolymer. Let the scanning speed of the laser beam be \( V_s \). Then, the solidified shape along the laser-moving axis can be expressed as follows [12]:

\[
y = \frac{2}{W_0(z)} \sqrt{\ln \left( \frac{2}{\pi W_0(z)^2 V_s E_c} \right)} - \frac{z}{D_p}
\]

where \( D_p \) is the penetration depth of the photopolymer and represents the depth at which the irradiance becomes 1/e times that at the surface, \( E_c \) is the critical exposure of the photopolymer and represents the energy level as the photopolymer changes from liquid to solid, \( D_p \) and \( E_c \) are properties of the photopolymer and can be evaluated through experiments, and \( W_0(z) \) is the Gaussian half-width of the laser beam which varies along the optical axis due to the focusing lens.

Using this analytical model, the solidified depth and width can be calculated for given laser exposure conditions and material properties of the photopolymer. In actual micro-stereolithography, however, many UV laser scanning lines are overlapped to fabricate a given cross-sectional area; these cross-sections are stacked in a layer-by-layer manner to form the desired 3D shape. In this case, the width and length of the solidified area are not coincident with the geometry of the scanning width and length. From preliminary experiments of photopolymer solidification, the authors found that the solidified width and length of the cured photopolymer depended largely on the scanning conditions of the laser beam. For example, the scanning pitch, laser power, scanning speed, and scanning width of the laser beam markedly affected the

Fig. 1. Scanning using a lens to focus a laser beam on the surface of a photopolymer

Fig. 2. Schematic drawing of the experimental setup