Optics and Lasers in Engineering 107 (2018) 13–20

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Real-time laser focusing system for high-precision micromachining using diffractive beam sampler and advanced image sensor

Binh Xuan Cao [a,b], Phuong Le Hoang [c], Sanghoon Ahn [a], Jeng-o Kim [a], Heeshin Kang [a], Jiwhan Noh [a,b,*]

[a] Department of Laser and Electron Beam Applications, Korea Institute of Machinery & Materials (KIMM), Daejeon, South Korea
[b] Department of Nano-Mechatronics, Korea University of Science and Technology (UST), Daejeon, South Korea
[c] Department of Material Science and Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea

ARTICLE INFO

Keywords:
Focal-position detection
Laser micromachining
Diffractive beam samplers
Double-hole masks

ABSTRACT

In this manuscript, a system for the real-time detection of the focal position on a target sample's surface during laser micromachining is presented. This system utilizes the advantages of diffractive beam samplers, double-hole masks, and two laser sources, including a diode laser for detection and a high-powered laser for fabrication. Moreover, this system can simultaneously detect the focal position and examine the defocusing direction during fabrication. This ability gives it an advantage over conventional methods that can only conduct a single task. The off-axis detection beams generated by the diffractive beam sampler that are examined during the detection process create various configurations of the beam spots on the advanced image sensor that are enhanced to read the sizes and separation of the beam spots simultaneously. Furthermore, the analytical relationship between the beam spot spacing and the specimen–objective-lens distance is used to support the calibration process and compared with experimental results. According to the changes in the distance between beam spots, the focal point and defocusing direction can be identified with the highest precision, which is indicated by the similarity between the theory and the experimental results. In addition, images of microholes fabricated by a fabrication laser are shown as a test of the focal detection system that is consistent with theory. The resolution of the system is optimized to polish the images obtained by the image sensor. Therefore, it is demonstrated that this technique provides the most accurate focusing conditions with a high numerical aperture as well as inexpensive laser fabrication and processing.

1. Introduction

Recent enhancements in the laser micromachining capacity have drawn substantial interest from both scientists and engineers. The use of laser pulses has been demonstrated to be a crucial technique for the qualitative micropatterning of many types of matter, and it has the capability to change the properties of matter. This technique has promise for a wide variety of broad applications [1–8]. The realization of an optimal technique that allows a laser beam to be automatically focused on a sample having an unpredictably rough surface during fabrication is a considerable challenge. The main reasons are an inadequate effective laser power, unexpected permanent damage to the target sample and optical element, and the difficulties associated with simultaneous detection and fabrication [9–12]. Moreover, the high roughness of the sample's surface caused by the thermal interaction with the laser beam and pre-existing surface deformation is also considered a tremendous obstacle for focus detection as it approaches the processing distance of the laser beam. Therefore, it is difficult to mechanically manipulate samples that have curved surfaces without programming their roughness into the machining instructions in advance. One technique for overcoming these limitations is to investigate the surface of the sample accurately during mechanical manipulation and to tune the focus of the laser beam accordingly.

There exist some autofocus systems that operate according to the following mechanisms: maximizing the reflected light signal detected behind a pinhole followed by the confocal method, which basically employs two lenses aligned to focus at the same position, a pinhole where the light from focal plane is transmitted to the detector, and some other supportive apparatuses [13–17]; viewing/imaging the specimen in the same beam path as the laser [18–21]; and optical triangulation by means of a position-sensitive device [22]. In these methods, the confocal method with a divided aperture [15] provides significant advan-

* Corresponding author at: Department of Laser and Electron Beam Applications, Korea Institute of Machinery & Materials (KIMM), Daejeon, South Korea.
E-mail address: njw733@kimm.re.kr (J. Noh).

https://doi.org/10.1016/j.optlaseng.2018.03.002
Received 9 June 2017; Received in revised form 16 January 2018; Accepted 3 March 2018

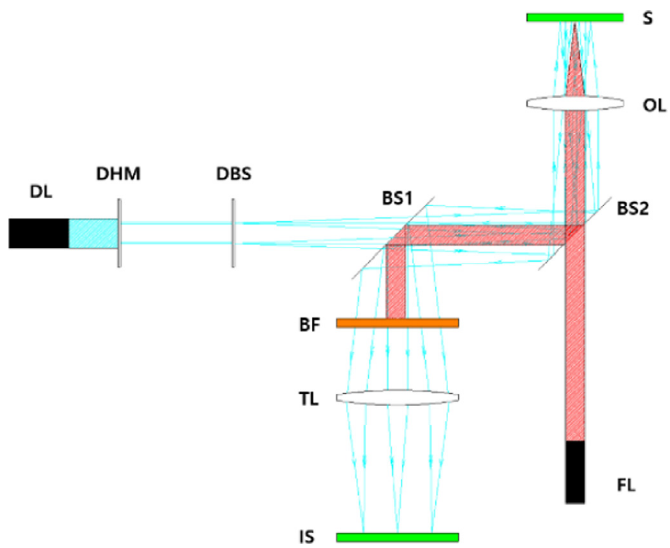

Fig. 1. Geometric schematic of the experimental principles. Light blue beams indicate the detection beams originating from a diode laser (DL), and the red beam indicates the fabrication beam originating from a high-powered fabrication laser (FL). The fabrication beam is directly projected and focused onto the specimen (S) through an objective lens (OL). The optical paths of the beams are directed by two beam splitters (BS1 and BS2). A beampass filter (BF) prevents the fabrication beam from passing through the tube lens (TL) and thus from damaging the image sensor (IS). The detection beam is first projected through the DHM and divided into two parallel beams. Next, the DBS divides the beam cluster generated from the DHM into three beam clusters at an angle of $\alpha = 2.07^{\circ}$ with respect to each other. The three beam clusters are then directed to the S through the OL and reflected to the IS through the TL and OL. The configuration of the beam clusters is depicted on the IS according to the relative position of the S with respect to the OL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

tages such as a high sensitivity, a long working distance, an improved signal-to-noise ratio, rapid imaging, and a high axial resolution. However, this method has some limitations such as difficult alignment and phototoxicity of the high-intensity laser. Moreover, all of the mentioned approaches employ auxiliary lasers in addition to working lasers with comparatively low-numerical-aperture optics. Furthermore, these procedures must be completed before the fabrication process. Therefore, the focusing conditions are relatively tolerant. In manufacturing applications [23–26], a displacement measurement sensor setup is used to achieve real-time measurement. In addition to its high cost and complexity, the use of a sensor for receiving feedback from the expected beam has some restrictions. One, the precise form of the reflection relies on the surface topology. When a laser beam strikes a rough or granular surface, it is scattered in all directions owing to the microscopic irregularities of the interface. Accordingly, the feedback results contain diffuse deflection. Another method uses a beam splitter and charge-coupled device (CCD) camera to explore the focal position. However, a plasma may be created during fabrication owing to the high-powered laser, which commonly causes reflection problems and the destruction of the sensor in the CCD camera; therefore, the corresponding results will not be exact. Given these issues, real-time measurement presents enormous challenges that require new techniques to handle them.

Previous publications introduced the new concept of a focal position detection system using a diffractive beam splitter that allows the laser beam to be focused on a sample surface with an unpredictably rough morphology [27]. The method is based on (1) low-intensity fractional beams that indicate the distance shifted from the focal position of the target sample and (2) a high-intensity main beam that handles focus detection and fabrication. This system has been thoroughly evaluated and found to be low in price, flexible, accurate, and simple to use in the laser micromachining industry. Nevertheless, this method can only detect the focal point and identify the defocusing displacement separately. Moreover, this method cannot simultaneously carry out the focusing step and fabrication, creating doubt about the practical applications of real-time focal position detection.

In this paper, a new machine-tool–workpiece system for the real-time exploration of a sample's focal position is presented to reduce or eliminate the disadvantages of traditional methods. The focal position was stringently and controllably detected by examining the defocusing direction at a very high resolution and numerical aperture using the highly divergent angle of the sampled beam clusters induced by the integration of the diffractive beam sampler (DBS) and double-hole metal mask. The new generation of image sensors with ultrasmall pixel sizes and rapid responses contributes to the high-precision reading of the beam spot spacing. Furthermore, the focusing and processing steps conducted simultaneously with usage of two laser sources allows for the massive production of three-dimensional (3D) laser micropatterning. As a result, a plethora of new techniques employed for extremely high-intensity lasers based on the proposed functionality with a low price, multiple capabilities, and simplicity can be created as an ideal way to fabricate 3D nano- and micro-optical elements.

The paper is organized as follows. First, we state the experimental principles of focus detection and a list of devices and optical elements used in the experiments. Second, we determine an analytical expression for the relationship between the beam spot spacing and the distance between the objective lens and the specimen on the basis of an analogous optical model. Third, we mention the significance of finding the working distance and calibration steps for focus determination. Next, the experimental results for the calibration steps and a discussion are presented. Finally, we present our conclusions about the method and its potential for use in both science and industry.

2. Experimental methods

2.1. Experimental conditions and apparatus

The experimental principles involve directing the detection beam from a laser diode through a DBS (Holo/or SA-022-I-Y-A) [28] and double-hole mask (DHM) simultaneously. The DBS divides the laser beam into three fractional beams with different intensity distributions and a propagation angle of 2.07°. The main beam has the highest intensity of approximately 97%, and the two fractional beams have a smaller intensity of 1.5% [27]. The DHM converts the main beam into two parallel beams that also propagate through the DBS. The beam clusters reflect off the specimen, which is a silicon wafer, and are directed to create beam spot images on an image sensor. The technique first uses the specimen to obtain the focal point of the processing laser and to optimize the positions of the optical elements in the setup. Later, the specimen will be replaced by a real target sample to conduct laser fabrication. Currently, we do not need to use the focus detection specimen again for additional target samples. The images obtained on the image sensor provide information about the defocusing direction and displacement according to the positions, shapes, and sizes of the beam spots on the image sensor. After the target sample is properly located at the focus, the fabrication beam from a high-powered laser source is projected onto the specimen through the objective lens to produce the patterns. Both the detection and fabrication lasers operate simultaneously to guarantee that the fabrication process remains in focus.

Our optical system is shown in Fig. 1. The detection beam was directed through the DHM and then transmitted through the DBS. The DBS split the beam cluster from the DHM into three beam clusters, where each cluster contains two parallel beams with different intensity distributions, as described above. The main cluster—or central cluster—has the highest power, whereas the two fractional clusters—or side clusters—have a much lower intensity. In principle, when the sample (silicon wafer) was gradually moved around the focal position, the on-axis