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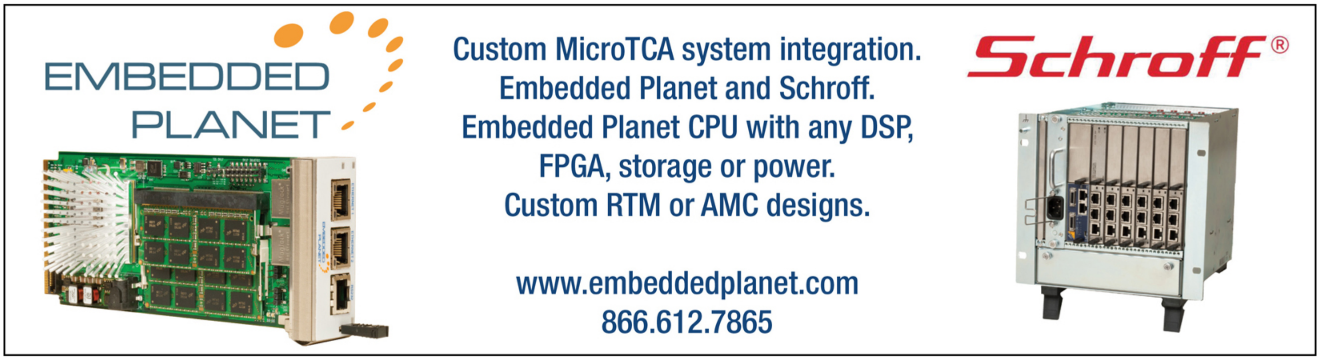

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Fabrication of microgrooves on a curved surface by the confocal measurement system using pulse laser and continuous laser

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In order to fabricate microgrooves on a curved surface, the curved surface was measured with a confocal system and then it was used for laser microprocessing. This paper proposes a new method of using a pulse laser for the confocal system to measure the curved surface. It also compares the conventional way of using a continuous laser and a new way of using the pulse laser with the confocal system. Using the data measured with the pulse laser for fabrication, microgrooves were fabricated on a curved surface. The width of the fabricated microgroove was 10 μm and the depth was 27 μm. The microgroove fabricated on a curved surface as a part of this study can be used in injection molding to manufacture a micropatterned plastic surface at a low cost. This plastic surface can be applied for a superhydrophobic surface, a self-cleaning surface, or a biochip. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3693702]

I. INTRODUCTION

Various processes to fabricate microgrooves on a surface are being studied. The leading processes include mechanical fabrication process using the mechanical tools, photolithography process,[1] and the laser process.[2–4]

The process using mechanical tools has a limitation in reducing the width of the groove because of a limitation in reducing the dimension of the mechanical tool. Although the photolithography process can reduce the width of the groove, it is used exclusively for the silicon wafer based process and cannot be used for other materials. Furthermore, a photolithography process requires a series of processes and thus is disadvantageous in terms of time and cost. In comparison, the laser process is relatively simpler and continues being advanced as the laser source technologies are being developed. Particularly, development of the ultrashort laser, whose pulse duration is in the femtosecond or picosecond domain, has enabled the fabrication of microgrooves with fewer parts being affected by heat in the case of metal.[5,6]

Another issue of fabricating microgrooves on a surface is to fabricate it on a curved surface. Fabricating microgrooves on a curved surface is required in most applications. Even when the microgroove is fabricated on a large area flat surface, it eventually becomes a curved surface because it is virtually impossible to manufacture a completely flat large area surface.

Wanner[7,8] fabricated microgrooves on a curved surface with a laser using the position sensing detector element. This paper proposes the fabrication of microgrooves on a curved surface using the confocal method, which is simpler and superior to the existing methods.

II. EXPERIMENTAL DETAILS

The picosecond laser used in the paper was a diode pumped, mode-locked Nd:YVO$_4$ laser with a pulse width of 12 ps. The fundamental wavelength was 1064 nm. The laser was equipped with second- and third-harmonic generators to make laser wavelengths of 532 and 355 nm. In the experiments, a laser wavelength of 355 nm was used in the ultraviolet range because this allowed for a higher energy absorption into metal. Also, an ultraviolet laser beam could be focused onto the smaller beam spot. The beam spot diameter of the picosecond laser source is about 1 mm. M^2 of picosecond laser is 1.3. The effective focal length of objective lens is 20 mm. The calculated focus spot diameter is 12 μm. This picosecond pulse laser is used for fabricating and measuring in confocal system. For measurement in confocal system, the pulse energy of picosecond laser was reduced.

The confocal system was made in-house by the laboratory. The objective lens used by the confocal system and process system at the same time was the M PLAN APO NUV 20× (Mitutoyo). The processed sample was a mold material called NAK80. The fabricated surface morphology was investigated by scanning electron microscopy (SEM) with JEOL JSM-6300 and by optical microscopy with the NIKON ECLIPSE LV100.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. The Microgroove optical system on a surface using a confocal system

Figure 1 shows the optical layout of the laser processing system. Figure 1(a) is the optical layout of the conventional

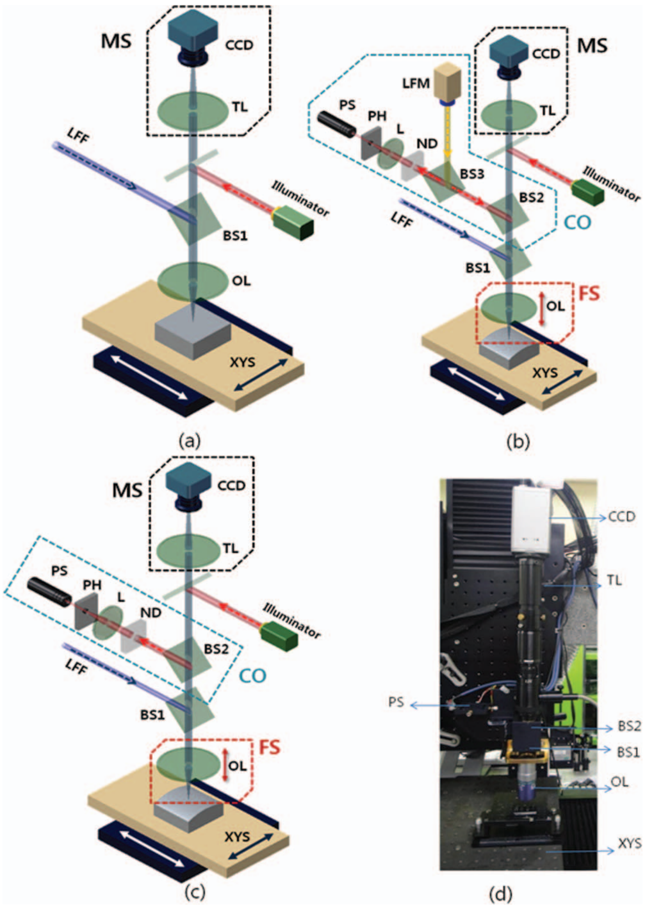

FIG. 1. Optical layout: (a) general optic layout for laser processing, (b) confocal optic layout using the measurements from a continuous laser, (c) confocal optic layout using the measurements from a pulse laser, and (d) photograph of the optical setup. LFF: Laser for fabrication (pulse laser), LFM: Laser for measurement (continuous laser), MS: Microscope system, TL: Tube lens, CO: Confocal system, BS: Beam splitter, ND: Neutral density filter, L: Lens, PH: Pinhole, PS: Photosensor, FS: Focusing stage, OL : Objective lens, and XYS: XY stage.

laser process. A fabricating laser is reflected off a beam splitter and is focused on the sample through the objective lens. When the intensity of the focused laser beam exceeds the ablation threshold intensity of the sample, the ablation is occurred. In our experiment, the focused laser radius is about 6 μm. A repetition rate of laser source is 400 kHz. The average power with which laser ablation begins on the NAK80 is about 20 MW. The pulse energy is the 0.05 μJ. Therefore, the ablation threshold fluence is 0.0442 J/cm^2. The microscope system is usually mounted to observe the condition of the sample. The infinite beam generated by the objective lens passes through the beam splitter and is focused with the tube lens. This sample image is delivered to the CCD to observe the sample condition. Although it is not shown in the figure, the white light source for the CCD is irradiated as the axis for the infinite beam. Figure 1(b) shows the confocal optical layout using a continuous laser measurement. Fabrication of microgrooves on a curved surface using the confocal system consists of two steps. The first step is to measure the curved surface using the confocal optical system. The next step is to move the objective lens by using the measurement data and to fabricate the microgroove on a curved surface. The laser beam for measurement irradiated by the continuous laser in Figure 1(b) passes through a beam splitter 3 (BS3) and BS2 and is focused by an objective lens. The objective lens then moves to ensure that this beam is focused in the curved sample and pinhole. In other words, the objective moves so that the beam reflected from the curved sample passes through BS1, BS2, and BS3 and then focused in the pinhole. The distance of the objective lens movement is recorded, and the other side of the curved sample is irradiated to the XY stage (XYS) by the laser. Since the sample is curved, the focal position is changed. Then the objective lens moves so that the beam is focused in both the curved sample and pinhole. The moved distance is recorded again, and the curvature data will be measured through the repeated processes. After the measurement is completed, it will proceed to the fabrication step. In the second step, the continuous laser for measurement is turned off and the pulse laser for fabrication begins to be activated. The pulse laser beam passes through BS1 and is focused on the objective lens. Then this pulse laser begins irradiation to the sample. The processing begins when the intensity of the laser for fabrication is greater than the ablation threshold value and the sample moves by the XYS. The objective lens knows how much it should move according to the distance the sample moved using the curved surface measurement data. The objective lens moves according to the curved surface data to continue maintaining the focus on the curved surface. The process allows for the fabrication of microgrooves on a curved surface.

Figure 1(c) does not use the continuous laser, which is for measurement. Instead, it uses the pulse laser with reduced laser power. In the first step of measurement, the intensity of the pulse laser is adjusted to be lower than the ablation threshold intensity of the sample. That way, the sample is not processed by the pulse laser. Under the condition, the objective lens then moves so that the reflected beam of the pulse laser passes through BS1 and BS2 and is focused in the pinhole by the lens. Since the movement distance of the objective lens is the curved surface data of the sample, the movement distances are measured. The curve surface of the other side is measured in the same process. After the curved surface is measured, the process proceeds to the fabrication step. This time, the intensity of the pulse laser for fabrication is set to be greater than the ablation threshold value of the sample. The sample is moved by the XYS, and the objective lens moves according to the movement of the sample and the microgroove is fabricated.

B. Comparison of using the pulse laser and using the continuous wave laser for measurement with the confocal system

Figure 1(b) shows the use of the continuous laser for measuring the curved surface while Figure 1(c) shows the use of the pulse laser for measurement. During the measurement, the power of the pulse laser is lowered. These two methods have strengths and weaknesses as described as follows: Using the continuous laser for measurement requires one more laser than the pulse laser for measurement system. Therefore, it is

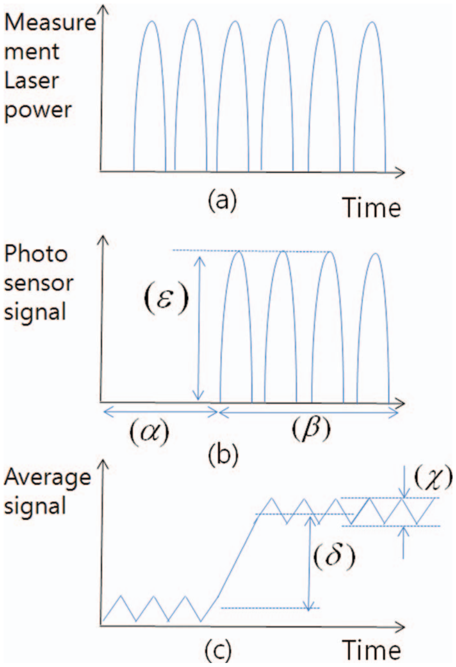

FIG. 2. Simplified signal of a confocal system. (a) Signal from the measurement laser power, (b) signal of the photosensor, and (c) average signal of the photosensor.

more advantageous to use the pulse laser in terms of simplicity for measurement. Also, from the optical alignment aspect it is better to use the pulse laser. That is because using the continuous laser requires the optical path of the continuous laser to exactly match that of the pulse laser. It is very difficult to exactly align the optical paths of different lasers. The position of the measuring laser focus and that of the fabricating laser focus differs when using the measuring laser and fabricating laser separately. Therefore, an offset value must be set to the curved surface data obtained from the measurement for correcting the measured value. Obtaining the exact offset value is difficult during the experiment and fabricating by using the value is also difficult.

However, there is a problem of noise for the average signal of the photosensors when using the pulse laser for measurement. Figure 2 shows the simplified signal of each part of a confocal system. Figure 2(a) depicts the measurement laser power signal according to time. Since it uses the pulse laser, a pulse laser is generated. Figure 2(b) shows the signal of the photosensor. (α) in Figure 2 is a section in which the beam is not focused in the pinhole of the photosensor. In this section, the objective lens moves until it finds the area in which the beam is focused in the pinhole of the photosensor. (β) in Figure 2 is the section in which the photosensor generates the signal as the beam is focused in the pinhole. In other words, it is the section in which the objective lens finds the confocal location. Since the measurement laser power is in the pulse form in the (β) section, the photosensor signal will also be the pulse form. (ε) in Figure 2(b) is the amplitude of the photosensor signal. If this amplitude is large, it means that the light intensity of the beam entering the photosensor is large. If it is small, it means that the light intensity of the beam entering the photosensor is small. The signals in Figure 2(b) are averaged to find the confocal location in a confocal system. The averaged signal is shown in Figure 2(c). While the averaged signal has 0 V in the (α) section, the averaged photosignal is generated in the (β) section. As shown in Figure 2(c), the (δ) signal is generated as the signal moves from the (α) section to the (β) section. This (δ) volt signal is used to determine if the location of the objective lens is the confocal location. Since this is an electronic circuit, there will always be the noise component. If (χ) is smaller than (δ), the confocal signal can be exactly obtained. However, if (δ) is so small that (χ) is larger than (δ), it will not be possible to obtain the exact confocal signal. When using the pulse laser for measurement, (δ) value in Figure 2 will be relatively smaller than using the continuous laser, since the pulse signals are averaged. Although (δ) can be increased by raising the measurement laser power, it is still limited. If the peak pulse power in picosecond laser is very high, (δ) of picosecond laser is high enough to detect. However, if we use the high peak power in picosecond laser for measurement, the NAK80 is damaged because the fluence of picosecond laser is higher than the ablation threshold fluence of NAK80. Therefore, we use the peak power that is less than the ablation threshold fluence of NAK80. (δ) can be increased by increasing the pulse duration (the time for which the laser is activated) of the measurement laser or by increasing the repetition rate of the measurement laser. However, the current trend in laser fabrication is to reduce the pulse duration.[9–12] Reducing the pulse duration can improve the fabrication precision and to fabricate a smaller microgroove as the area affected by heat decreases. The ultrashort pulse laser with the pulse duration from 100 fs to 10 ps has been developed and is currently used in laser fabrication. For this paper, a 12-ps laser is used to improve the fabrication quality. If a 12-ps pulse laser with the repetition rate of 400 kHz is used, the laser will be activated in only 12 ps out of 2 500 000 ps, and the remaining 2 499 988 ps will have no pulse laser. That will reduce the (δ) value as shown in Figure 2(c). Although the (δ) value can be increased by raising the repetition rate of the pulse laser, that will cause a problem in the fabrication process. To increase the repetition rate of a pulse laser, the scan speed of the laser beam must be increased and that will degrade the location precision. It is also difficult to develop a laser source with high repetition rate and pulse energy.

Another reason the (δ) value is small is because of the inclination of the measurement surface. As the inclination increases, the light intensity of the beam entering the photosensor decreases because the reflected amount decreases if the sample is included when the beam reflecting from the sample enters the photosensor. Therefore, it is more advantageous to use the continuous laser instead of the pulse one for measurement if the sample is stiffly inclined. In the experiment, the pulse laser with a 12 ps pulse duration and 400 kHz repetition rate can be measured only at the inclination of 15° or less. In other words, (δ)becomes less than (χ)in Figure 2(c). However, even if the measurement was made using the continuous laser when the inclination of the curved sample is greater than 15°, there is a problem of laser fabrication as there will be too high of an amount of beams reflected from the sample and that will make the fabrication difficult. Therefore, if the inclination of the sample is greater than 15°, it is recommended to

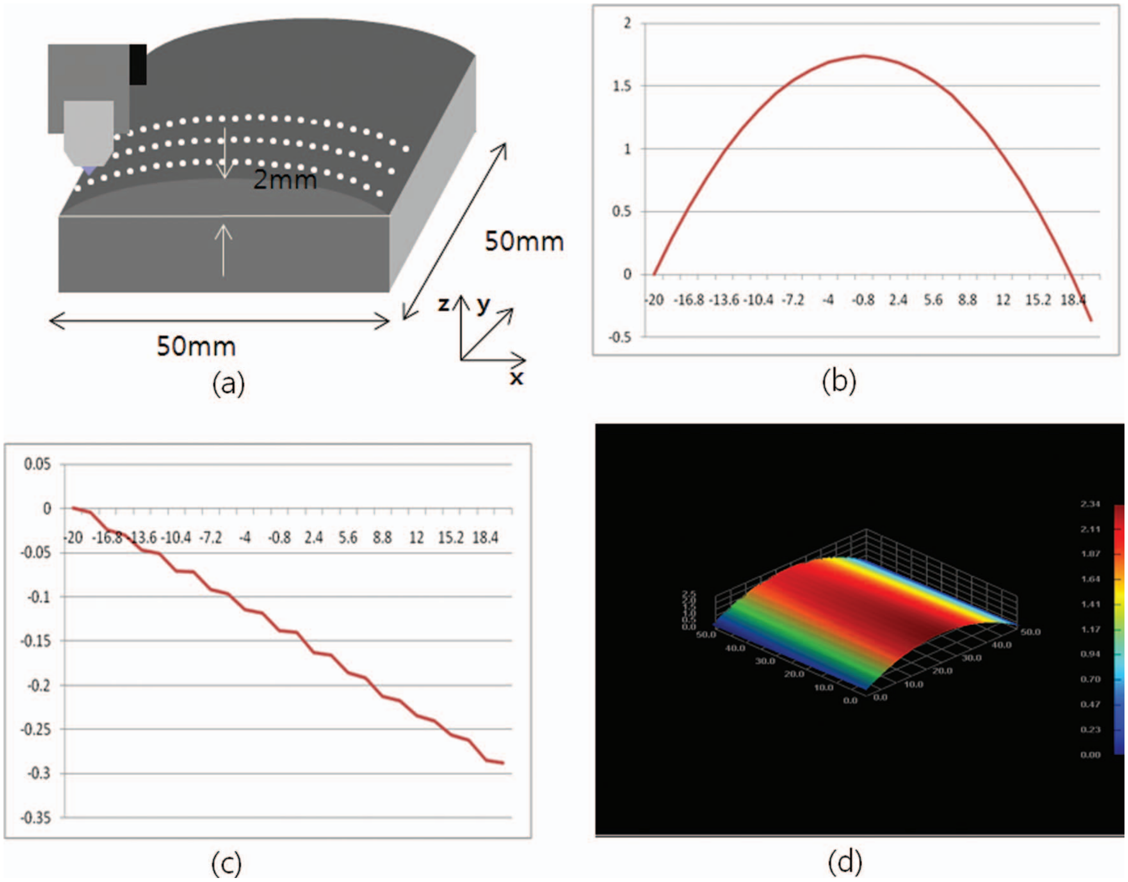

FIG. 3. The measurement result of curved surface using a confocal system. (a) Measurement method, (b) measurement result when "y" is 20 mm, (c) measurement result when x = 0, and (d) measurement result of a curved surface.

irradiate the laser with the multi-axis stage to rotate and move the sample for fabrication.

Another problem of using the pulse laser for measurement is the loss of the laser power by BS1. When using a 355 nm wavelength for the fabrication laser, BS1 will have to use the beam splitter to reflect half and will then have to transmit the other half of the 355 nm wavelength because the 355 nm beam must penetrate through the BS1 so that the beam reflected from the sample must reach the photosensor for measurement. This means that the laser power will be lost in BS1 during fabrication. That will force the use of higher laser power and will thus result in increased laser costs.

C. Results of measuring a curved surface using a confocal system

Figure 3(a) shows the measurement method of the curved sample. The sample is a 50 mm × 50 mm square with a curved top. The curve is shaped like a cylinder having a height of 2 mm. The radius of curvature is 105.5 mm. The top of the curved sample was polished. Twenty six points in the x axis direction and 26 points in the y axis direction were measured. For each point, it took 2.1 s for the measurement. Figure 3(b) shows the result of the x direction measurement while y was fixed at 20 mm. As expected, circular measurement data were obtained. The horizontal axis in Figure 3(b) means the x direction coordinate, while the vertical axis means the z direction measurement. The unit is "mm" for both axes. Figure 3(c) shows the y direction measurement result at x = 0. The horizontal axis means the y direction coordinate while the vertical axis means the z direction measurement. Since the y direction is a flat surface, there must be no change in the measured value. However, it shows that z = 0 when y = −20 mm and z = −300 μm when y = 20 mm. That means that the sample is slightly inclined in the y direction or that the sample was fabricated to be slightly inclined in the y direction. These measured values show why a fabricated surface must be measured and the measurements that are to be used for microfabrication. If the laser focus is set to the surface at y = −20 mm for fabrication, it will not be properly fabricated at y = 20 mm. It is because, assuming that the laser wavelength is 355 nm, the focal length of the focus lens is 10 mm, the laser beam diameter is 1 mm, and the laser M^2 is 1.3; the diameter of the focused beam is around 6 μm and depth of focus is 318 μm. In laser fabrication, the precision is degraded when there is the error of depth of focus on the fabricated surface. Figure 3(d) shows the z measurement values in color of 26 measurement points in the x direction and 26 measurement points in the y direction. As expected, the measurement values are in the form of a cylinder.

D. Results of curved surface fabrication using a confocal system

Figure 4(a) is a picture of a sample with the microgroove having been fabricated by using the measurement data in

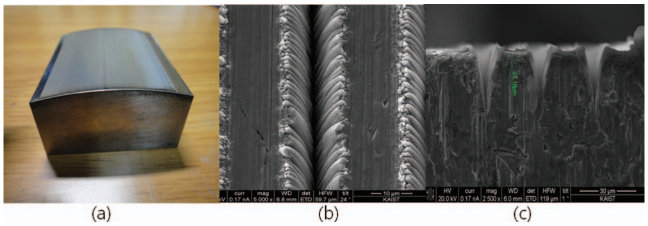

FIG. 4. (a) The fabrication result of a microgroove on the curved surface. (b) SEM image of a microgroove (top view). (c) SEM image of a microgroove (cross section).

Figure 3(d) on an actual curved surface. The fabrication laser had the power of 100 MW, a repetition rate of 400 kHz, a wavelength of 355 nm, a sample transport speed of 100 mm/s, and a fabrication repeat count of 25. The processing direction is y direction. Under such fabrication conditions, we fabricated 2500 microgrooves on an area of 50 mm × 50 mm. Figure 4(b) shows the magnified SEM picture of the microgrooves shown in Figure 4(a). Figure 4(c) shows the picture of a cross section of the fabricated microgrooves. The width of a microgroove was 10 μm and the depth was 27 μm.

IV. CONCLUSION

This paper describes the fabrication of the laser microgrooves on a curved surface using the measurement of the curved surface with a confocal system. Both continuous laser and pulse laser were used to measure the curved surface using the confocal system. The measurement results were compared. Using the measured curved surface data microlaser fabrication was performed. Using the microgrooves on a curved surface that was fabricated as part of this study, the micropatterned plastic surface can be manufactured at a low cost. This plastic surface can be applied to a superhydrophobic surface, a self-cleaning surface or a biochip.

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