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Feeding of Submillimeter Microparts Along an Asymmetric Fabricated Surface by Double-Pulsed Femtosecond Laser Process

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Abstract: We previously showed that microparts can be fed along a saw-toothed surface using simple planar symmetric vibrations. Microparts move forward because they adhere to the saw-toothed surface asymmetrically. We used saw-toothed silicon wafers fabricated by a dicing saw applying bevel type blades. We then studied the movement of 2012-type capacitors (size:$\mathbf{2.0 \times 1.2 \times 0.6\ mm}$, weight:$\mathbf{7.5\ mg}$) and 0603-type capacitors (size:$\mathbf{0.6 \times 0.3 \times 0.3\ mm}$, weight:$\mathbf{0.3\ mg}$). In this study, we assessed the movement of smaller 0402-type capacitors (size:$\mathbf{0.4 \times 0.2 \times 0.2\ mm}$, weight:$\mathbf{0.1\ mg}$). A femtosecond laser process was used to fabricate an asymmetric surface. The characteristics evaluated were the differences in profiles of both inclined surfaces, the effect of adhesion decrease, and the friction angle of the 0402-type capacitors in both directions. Using the results of feeding experiments of these capacitors, we assessed the relationship between driving frequency and feeding velocity.

Keywords: asymmetric surface, microparts, unidirectional feeding, femtosecond laser process

1. INTRODUCTION

Devices to feed microparts, such as ceramic chip capacitors and resistors, have become more common, due to their use in sorting mass produced microparts. We have previously shown that a saw-toothed surface with simple planar and symmetric vibrations can be used to feed microparts (**Fig. ??**) [**?**]. Because of the difference in the area of surface contact of a micropart with the sloping side of a tooth and with the other side, microparts adhere more strongly in one direction than in the other. This results in the microparts moving in one direction, since adhesion is caused by electrostatic, van deer Waal's, and intermolecular forces, surface tension, humidity, and inertia, all of which influence the motion of the microparts [**?**]. Previously, we performed feeding experiments with **2012**-type (size:$2.0 \times 1.2 \times 0.6\,\mathrm{mm}$, weight:$7.5\,\mathrm{mg}$) and **0603**-type (size:$0.6 \times 0.3 \times 0.3\mathrm{mm}$, weight:$0.3\mathrm{mg}$) capacitors using saw-toothed surfaces with micro-fabricated silicon wafers. The dicing saw, high prescision cutting and grinding tool, was applied to process the surfaces by bevel type diamond blades according to each surface profile.

In the present study, we investigated the effect of an asymmetric micro-fabricated surfaces by a femtosecond laser processing tool on the feeding of smaller **0402**-type capacitors (size:$0.4 \times 0.2 \times 0.2\mathrm{mm}$, weight:$0.1\mathrm{mm}$). The double-pulsed femtosecond laser irradiation technique was used to create asymmetry of the micro-fabricated surface. Following inspection of the micro-fabricated surface by the atomic force microscope (**AFM**) system, we designed a three dimentional (**3D**) model of the micro-fabricated surface, and assessed the asymmetry by processing profile models derived from the **3D** model. We also evaluated the tribological characteristics of the micro-fabricated surface relative to environmental parameters, especially ambient humidity. The angle of friction of the **0402**-type capacitors were examined in both directions under different humidity, as well as the effect of adhesion decrease of the micro-fabricated surface compared with a no-fabricated surface. Finally, we performed feeding experiments of **0402**-type capacitors by the micro-fabricated surface. We then showed the relationship between feeding velocity and vibration frequency, as well as the effect of feeding velocity on feeding stability.

2. RELATED WORKS

The most popular partsfeeders are vibratory bowl-types [**?**], which use revolving vibrators to move parts along a helical track on the edge of a bowl. Linear feeders as well as an inclined mechanism and oblique vibrations for unidirectional feeding [**?**], have also been developed. In all of these systems, the aspect ratio of the horizontal/vertical vibrations must be adjusted to prevent parts from jumping. In our system, however, this adjustment is not necessary because only horizontal vibration is used.

A parts feeding method that employs non-sinusoidal vibrations [**?**], [**?**] has been developed. The part moves

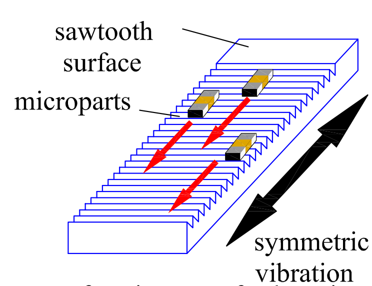

Fig. 1 Diagram of a microparts feeder using a saw-tooth surface with simple planar and symmetric vibration

to its target position and orientation or is tracked during its trajectory by using the difference between the static and sliding frictional forces. Our system realizes unidirectional feeding by symmetric vibration of a saw-tooth surface, which yields different contact forces in the positive and negative directions.

Although distributed manipulation systems, using micro-sized air nozzles [**?**], ciliary systems [**?**], and vector fields [**?**], have been evaluated, the dynamics of microparts have not, including the effects of adhesion forces on the motion of the microparts.

The objective of our research was to examine the dynamics of microparts tens or hundreds of micrometer in size. We found that the motion of these parts depends on both inertial and adhesion force.

3. ANALYSIS OF THE MICRO-FABRICATED SURFACE

The feeder surfaces consist of a shim tape, a stainless material $0.5\mathrm{mm}$ in thickness, $10\mathrm{mm}$ in width, and $33\mathrm{mm}$ in length. To process a feeder surface with an asymmetrical profile, we used the double-pulsed femtosecond laser beam irradiation technique. In this technique, a single axis femtosecond laser beam is divided into two by a splitter. One side of the beam has an angle of 20° and a delay of 50 ps. Transpiration of the surface of the material starts 50 ps after irradiation by the first beam. By irradiating with the second beam at the same time, transpiration recoil forces shift in the direction of the incidence angle of the second beam, thus generating an asymmetric surface. **Fig. ??** shows a microphotograph of the micro-fabricated surface using the **AFM** system. There were many periodic convexities on the surface of the material. Analysis of the microphotograph yielded the obtained surface profiles as shown in **Fig. ??**. The period of the feeder surface was about $0.92\ \mu\mathrm{m}$ and the groove depth as $0.17\ \mu\mathrm{m}$. The roughness at the top of these convexities was about $0.025\ \mu\mathrm{m}$. We examined the asymmetricity of the feeder surface by evaluating inclinations of both side of each convexity. **Fig. ??** shows the profiles of some of these convexities. As shown in **Fig. ??**, each convexity could be approximated by the polynomial:

$$y(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0, \qquad (1)$$

where x and y indicate the position and height in **Fig. ??**, respectively.

To examine the asymmetry of these convexities, we calculated the inclinations of these approximation functions by solving their differential. Each approximation function was transformed to be the maximum value at the position $x = 0\ \mu\mathrm{m}$. **Fig. ??** shows the inclinations around the maximum points of these approximation functions. The averaged inclination was $y' = 0.43$ at the position $x = -0.25\ \mu\mathrm{m}$, while it was $y' = -2$ at the position $x = 0.25\ \mu\mathrm{m}$, indicating that the inclination of the convexity was greater on the right side than the left. That is, the micro-fabricated surface had asymmetry that differed by 32% between the two sides of the convexity.

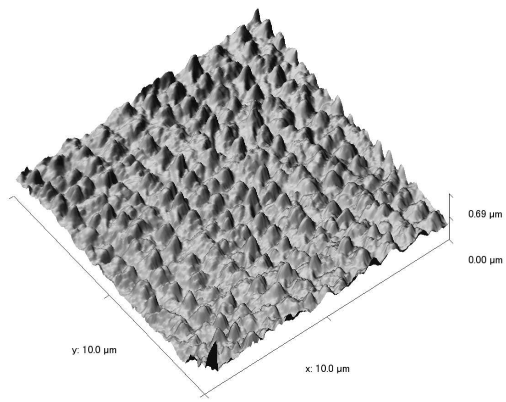

Fig. 2 Micro-fabricated surface profile, as shown by the atomic force microscope (**AFM**)

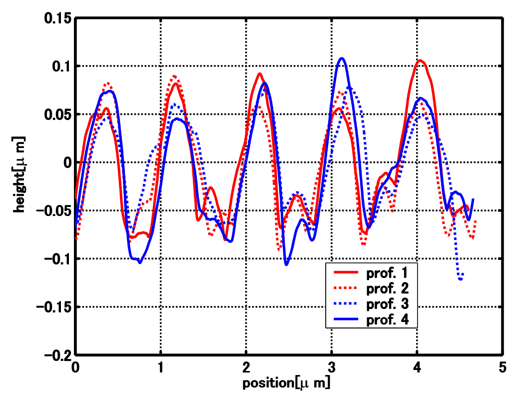

Fig. 3 Periodicity of the micro-fabricated surfaces

4. ANGLE OF FRICTION OF 0402-TYPE CAPACITOR

To evaluate directionality, experiments were performed three times using 35 capacitors in the positive and negative directions. For comparison, similar experiments were performed using a non-fabricated surface with only one direction because this surface has no directionality. We put capacitors on these surfaces, which were inclined until these capacitors fell. We then measured the angle of incline at which each capacitor started to fall. Some capacitors, however, remained even when the angle of incline exceeded 90°.

Environmetal factors, including ambient humidity and temperature, as well as, van Der Waal's force and electrostatic forces, can effect adhesion, and also affect the movement of submillimeter-sized or smaller microparts. We therefore performed experiments at 50 %, 60 %, and 70 % ambient humidity and at a temperature of 24 ℃. All experimental equipments and capacitors were equilibrated for one day in a sealed room at the desired humidity.

The experimental results are shown in **Figs. ??** and **??**. To estimate the effect of fabrication on adhesion, we compared the number of capacitors thet fell. Despite the ambient humidity, this number was higher on micro-fabricated than on non-fabricated surface. For example, at 60% ambient humidity, 43 capactors fell from the non-

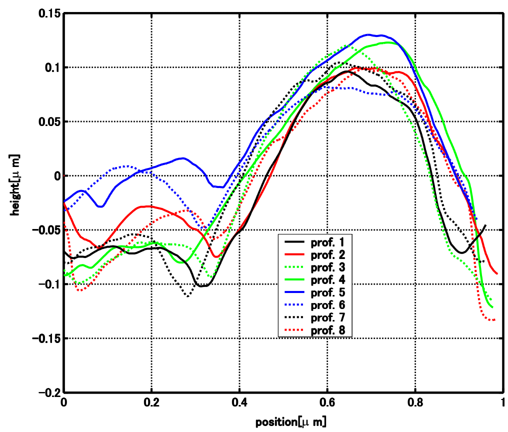

Fig. 4 Profiles of convexities on the micro-fabricated surface

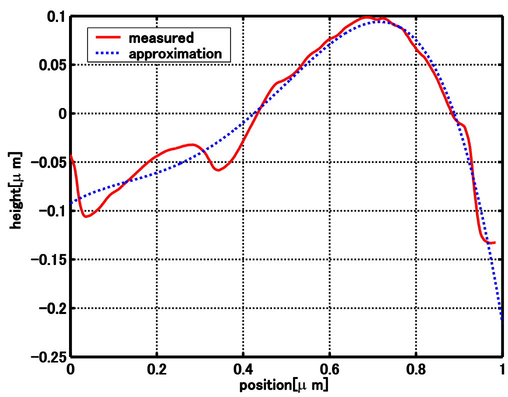

Fig. 5 Approximation function of a convexity

fabricated surface, whereas 65 and 61 capacitors fell from the micro-fabricated surface inclined in the positive and negative directions, respectively. These results indicate that micro-fabrication leads to decrease adhesion, due to the decrease in contact area between a feeder surface and micropart.

We next assessed the effect of ambient humidity on adhesion. The number of fallen capacitors at 50 %, 60 %, and 70 % ambient humidity was 41, 43, and 25, respectively. When we assessed the difference between non-fabricated and micro-fabricated surfaces at these, we found that the ratio at 50 %, 60 %, and 70 % ambient humidity was 193 %, 147 %, and 154 %, respectively. Therefore, both adhesion of the micro-fabricated surface and the decrease in adhesion caused by micro-fabrication was smallest at 60% ambient humidity.

When we evaluated the effect of ambient humidity on directionality of the angle of friction, we found that, at 50 %, 60 %, and 70 % humidity, the angle of friction in the positive direction was 1.6 %, 24%, and 14 % smaller, respectively, than the angle in the negative direction. Although there wes directionality regardless of humidity, little was observed at 50 % humidity, whereas it was maximum at 60 % humidity.

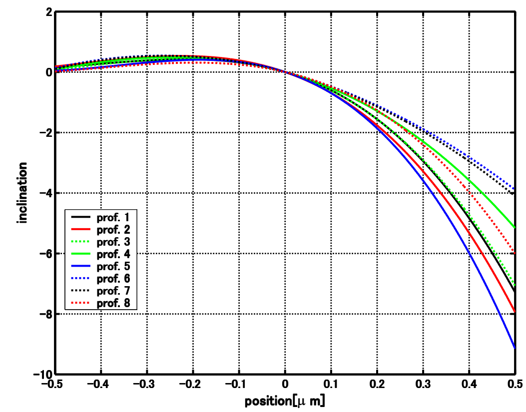

Fig. 6 Inclinations of the approximation functions around maximum values

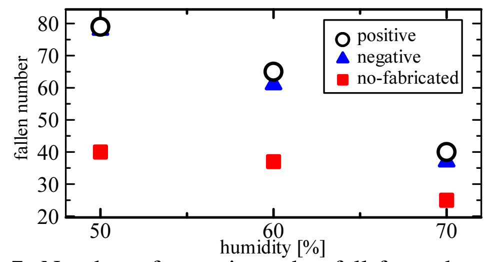

Fig. 7 Number of capacitors that fell from the micro-fabricated surface in 105 capacitors

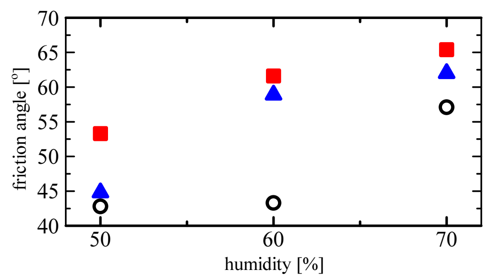

Fig. 8 Average friction angle of fallen capacitors: capacitors that adhered were not considered

5. FEEDING EXPERIMENTS OF 0402-TYPE CAPACITOR

Using a micro-fabricated shim tape, we performed feeding experiments of **0402**-type capacitors. **Fig. ??** shows the relationship between driving frequency and feeding velocity of capacitors at driving frequency $f = 120.5, 121.0, \cdots, 126.5$ Hz and a vibration amplitude $A = 0.5\,\mathrm{mm}$. Experiments at each frequency were performed four times using 10 capacitors under ambient humidity of 70 % and temperature of 25℃. The symbol ◯ represents each averaged velocity, and the symbol × represents measured velocity. We used a digital video camera at 30 fps to record the movement of the capacitor. Velocity was calculated by counting the number of frames it took for a micropart to move 33 mm along the micro-fabricated surface. In addition, the variance of velocity

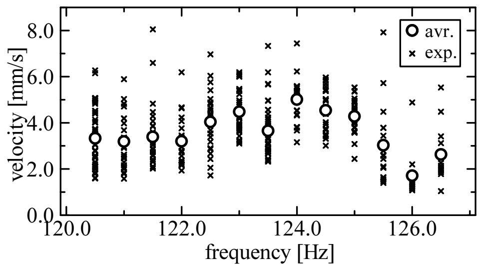

Fig. 9 Relationship between frequency and velocity

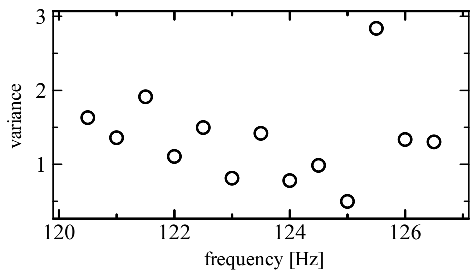

Fig. 10 Variance of experimental results

(**Fig. ??**) was calculated according to equation (**??**) as:

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(\bar{v} - v_i)^2, \tag{2}$$

where, n, $\bar{v}$, and v_i indicate the number of points, averaged velocity, and individual velocity, respectively. At the frequency $f \leq 122.0$ Hz, the average velocity was approximately 3.2 to $3.3\ \mathrm{mm/s}$. The variance, however, tended to grow in proportion to driving frequency. The maximum averaged velocity was $5.1\ \mathrm{mm/s}$ realized at a frequency of $f = 124.0$ Hz, which could provide 765 parts par minute. The minimum variance was $s^2 = 0.50$ at a frequency $f = 125$ Hz, and the second smallest variance was $s^2 = 0.78$ at $f = 124.0$ Hz, which achieved maximum averaged velocity. When the frequency was 123 Hz or less, variance became larger as the driving frequency decreased. This finding indicates that the driving forces of the capacitors transferred from the feeder surface were not sufficient to feed the capacitors steadily because the driving frequency decreases. In addition, the variance became largest at $f = 125.5$ Hz, and kept $s^2 \approx 1.4$ at $f = 126.0$ Hz or larger. Consequently, most stable feeding was realized at the frequency of 124.0 to 125.0 Hz.

6. CONCLUSION AND FUTURE WORK

We examined unidirectional feeding of the smaller **0402**-type capacitor. The femtosecond laser process, especially double-pulsed femtosecond laser irradiation technique, was used to micro-fabricate an asymmetric periodic profile surface on a stainless shim tape. In order to evaluate the asymmetry of the micro-fabricated surface, we derived the profile models based on measurements using the **AFM** system. We also evaluated the tribological characteristics by measuring friction angle of **0402**-type capacitors. We performed feeding experiments on **0402**-type capacitors using the micro-fabricated surface, and then verified the relationship between feeding velocity and driving frequency. We also verified the variance in measured velocities to determine steadiness of feeding.

Future studies will include:

- optimization of the processing parameters of the double-pulsed femtosecond laser irradiation technique to obtain more appropriate surface for feeding,
- derivation of dynamics including adhesion based on contact model estimated by measurements, and
- simulation of feeding of **0402**-type capacitors and comparison with the experimental results to evaluate the derived dynamics.

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