Self-alignment of microparts using liquid surface tension—behavior of micropart and alignment characteristics

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Abstract

The purpose of this research is to establish a self-alignment technique for microparts assembly using liquid surface tension. The factors that influence alignment performance are examined and ways of performance improvement are discussed experimentally and theoretically. First, the relationship between the alignment accuracy and the behavior of the micropart and the water droplet is examined in the alignments with six different water droplet volumes. The experimental results show that the volume influences the alignment accuracy and the behavior. Next, the relationship between restoring force induced theoretically and the experimental alignment accuracy is discussed. Then, the effect of pattern change of the boundary between different wettability areas on the alignment accuracy is examined experimentally. In the experiments, the micropart with the hexagonal boundary pattern demonstrates smaller alignment error than those with the square, triangular, cross and star patterns.

Keywords: Self-alignment, Microparts, Assembly, Alignment, Liquid surface tension, Water, Alignment accuracy, Restoring force

1. Introduction

Microsystems have become an important research field and systems composed of microparts of which materials and shapes differ have been investigated. In order to realize such systems as industrial products, an assembly technique of the microparts is necessary with alignment being a very important task in the assembly. For microparts alignment, self-alignment methods have been studied. Methods that utilize attractive forces such as surface tension of liquid [1–3] and of molten solder [4], magnetic force [5] and electrostatic force [6], do not require servomechanisms such as micro-manipulators which have complex structures and sizes that are much larger than the assembled microparts. Therefore, using the self-alignment methods, the assembly equipment for microsystems is expected to become simpler and smaller.

The purpose of this research is to establish a self-alignment technique for microparts assembly using liquid surface tension. The methods using liquid surface tension have the following advantages: no heating is required when the surface tension of molten solder is used; freedom from magnetic noise; and no electrostatic damage to the parts. To this end, the self-alignment method using a liquid droplet and microparts with two different characteristic areas on the surface, has been studied [1].

In this study, the factors that influence the alignment performance are examined and ways of alignment performance improvement are discussed experimentally and theoretically. First, the alignments with six different water droplet volumes are made and the factors that lower alignment accuracy are examined by observing the micropart and the droplet behavior, and the alignment accuracy in the experiments. Next, the relationship between the restoring force induced theoretically and the experimental alignment accuracy is discussed. Then, the effect of the boundary pattern change between different wettability areas on the accuracy is examined experimentally and a suitable pattern is discussed.

2. Self-alignment method using liquid surface tension

Fig. 1 shows the principle of the self-alignment method using liquid surface tension. The surface of each micropart used in the method is divided into two areas, namely, high and low wettability areas. In the figure, the pattern of the high
wettability area in micropart 1 is similar to that in micropart 2. Using these microparts, the self-alignment is carried out as follows.

1. A droplet of liquid is put on the high wettability area of micropart 1.
2. Micropart 2 is put on top of micropart 1 so that the droplet comes in contact with the high wettability areas of the two microparts.
3. Micropart 2 is moved by the liquid surface tension so that the high wettability area pattern of micropart 1 overlaps with that of micropart 2 and the alignment is accomplished.

The alignment is carried out in air and evaluated. In this case, the micropart motion is susceptible to friction between the microparts. However, the alignment in air has the following advantages: freedom from liquid flow in the alignment and relatively easy elimination of the liquid, especially water, in comparison with methods on/in the liquid (for example, see [2,3]).

3. Behavior of micropart and liquid in the alignment and alignment accuracy

In this section, first, the alignment experiments with six different water droplet volumes are conducted and their alignment accuracies are measured. Next, on the basis of the measured alignment accuracy and the observed results, the factors that affect the accuracy are discussed.

3.1. Experimental equipment and microparts

Fig. 2 illustrates the experimental setup for observing the micropart and the liquid behavior and examining alignment accuracy. The position and the inclination angle of the microparts are measured by using an image acquisition and processing system with a CCD camera connected to a microscope. The system is adjusted so that the distance between the pixels corresponds to approximately 3.6 μm; thus, the measuring resolution of the position is higher than 3.6 μm. That of the inclination angle is set at higher than or equal to 1°. The position and the inclination angle of the microparts can be adjusted by using fine stages.

Fig. 3 demonstrates the experimental microparts used in this section. The microparts are fabricated through the process of Fig. 4. They have high wettability areas made of glass, and low wettability ones on which water repellent (Shin-Etsu Chemical Co., KP801M) is coated. The water repellent is
transparent like the glass. The Cr layer is made under the water repellent so that the high wettability area is distinguishable from the low wettability one and so that the position and inclination angle of microparts can be measured by the image processing system of Fig. 2. The sum of thicknesses of the water repellent and the Cr layer on the microparts is about 50 nm. The left side of the figure shows micropart 1 and the right side, micropart 2. The size of micropart 2 is 1 mm × 1 mm. The size of the high wettability area of the two microparts is 0.8 mm × 0.8 mm. The fabrication process used in this research can make profile error of the high wettability area <5 μm.

Fig. 5 shows the side views of the water droplets on the two wettability areas. Fig. 5(a) is the droplet on the high wettability area, and Fig. 5(b), that on the low one. The water droplets were observed after ultrasonic cleaning of the areas with acetone and pure water. The figure shows that the contact angle between the water and the glass is 45° and that between the water and the water repellent is 110°. White rings on the water droplet in Fig. 5 are reflected images of the microscope ring illuminator, but not voids.

3.2. Effect of water volume change on alignment accuracy

In [1], it is demonstrated that the alignment accuracy depends on the liquid volume. However, the reason is not shown. Therefore, by using six different water volumes between 12 and 92 nl, alignment experiments were conducted to clarify the reason. Fig. 6 illustrates the alignment errors in the x, y and θ directions. Using each water volume, 10 similar alignments were made. In the experiments, micropart 2 was released from a height of 500 μm from micropart 1 after its initial errors were set at 100 μm in the x direction, 0 μm in the y direction and 0° in the θ direction. The relationship between water volume and alignment error in the x, y and θ directions is shown in Fig. 7.

In case of water volume greater than or equal to 23 nl, the average and the standard deviation of the alignment errors in the x direction become large as the volume increases. However, the average and the standard deviation of the alignment errors for the 12 nl water volume are larger than those for the 46 nl one. The relationship between alignment error and water volume in the y direction is almost the same as that in the x one although the initial error in the y direction is set at zero. The alignment error in the θ direction is also minimized by the 23 nl water volume.

Fig. 8 shows photographs of the states of micropart 2 and the water droplet after the alignment. Top photographs of Fig. 8 are the side views of the states and bottom ones are the top views. The top photographs show that finally, micropart 2 is not parallel to micropart 1 and touches micropart 1. Therefore, the alignment accuracy is considered to be influenced by friction force. The bottom photograph of Fig. 8(a) shows the states of micropart 2 and the water droplet after the alignment.
Fig. 7. Relationship between droplet volume and alignment error in the x, y and θ directions.

that the water does not cover the entire high wettability area of micropart 1, and the wet area supporting micropart 2 in Fig. 8(a) is smaller than those in Fig. 8(b) and (c).

In Fig. 8(b), water is retained only in the high wettability area of micropart 1; however, this is not so in Fig. 8(c). In the case of Fig. 8(c), the surface tension force does not work in order to eliminate alignment errors completely. Fig. 9 shows the frequency in which water overflows to the low wettability area. Ten similar experiments for each water droplet volume were conducted. When the volume is >35 nl, the alignment error increases as the frequency increases. This indicates that the overflow deteriorates the alignment accuracy.

The alignment error for 23 nl volume is better than that for 35 nl volume although the water covers the high wettability area and does not overflow to the low one in both cases of 23 and 35 nl volumes. This is due to the influence of friction force and the difference of the restoring force, as described in the next section.

4. Theoretical analysis

From Section 3.2, liquid overflow and friction force between the microparts are considered to be the major factors deteriorating the alignment accuracy. Therefore, the liquid volume that does not cause any overflow, and a large restoring force between microparts for inhibiting the effect of the friction force, are required for realizing high alignment accuracy. In this section, first, a simple static model is shown so that the expression relating liquid volume and overflow is deduced. Then, the calculation procedure of the restoring force applied to the microparts in the three directions on basis of the theoretical static liquid surface tension, is introduced. The theoretical restoring force is used to examine the effect
of the boundary pattern between the different wettability areas in the next section, but not to determine the exact value of the force.

Fig. 10 illustrates the static model of the alignment elements in the translational direction when the boundary patterns between the different wettability areas are squares. The model of the liquid droplet is simplified based on the following assumptions: (1) the radius of curvature of the liquid is uniform, (2) the thickness of the liquid is uniform, (3) four angles of tension from straight lines $ab$ or $cd$ are equal to each other (see Fig. 10), (4) the angle $\gamma$ changes or the liquid overflows only so that the wetting angle $\gamma$ is kept in the range from 0° to the contact angle on the high wettability area (see Fig. 10(b) and (c)).

In this case, the wetting angle $\gamma_i$ in the ideal and stable states (see Fig. 10(a)) is expressed by the model parameters in Table 1, on basis of the surface tension characteristics [7], as follows:

$$
\gamma_i = \cos^{-1}\left( -2\pi A^2TV - \frac{4L^2A^2TV^2 - \pi^2L^2A^2TV^2}{4L^2A^2TV^2} \right).
$$

Eq. (1) shows that the wetting angle $\gamma_i$ depends on the volume of the droplet. The maximum value of $\gamma_i$ is equal to that of the contact angle between water and the water repellent, 110°. Using $\gamma_i = 110°$, the values of the parameters in Table 2 and $V \approx Ah$, the volume is determined to be 91 nl. Volumes greater than 91 nl lead to overflow theoretically. The experimental result in Fig. 9 also shows that 92 nl water volume always leads to overflow. In case of 46 and 69 nl volumes, overflow is often observed. The reason is considered to be that the motion energy of micropart 2 works so that the liquid overflows.

The restoring force caused by the surface tension on the boundary between the high and low wettability areas, is calculated by using the direction of the surface tension vector with respect to the micropart. In the model of Fig. 10, the direction of the surface tension vector is determined from that of line $ab$ in case the micropart with a square high wettability area is used and its alignment error is observed only in the $x$ or $y$ direction. To determine the direction of the surface tension vector without these conditions, virtual surfaces $abcd$, $d'c'd'$, $d'd$, and $a'b'ab$ shown in Fig. 11 are used. In Fig. 11, the square $add'$ is the high wettability area of micropart 2, and

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**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tr>
<td>$T$</td>
<td>Surface tension of liquid $7.28 \times 10^{-5}$ N/mm [7]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Wetting angle</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass of micropart 2 $3.9 \times 10^{-4}$ kg</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>$p_l$</td>
<td>Pressure of liquid</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of liquid</td>
</tr>
<tr>
<td>$A$</td>
<td>Area of high wettability surface</td>
</tr>
<tr>
<td>$L$</td>
<td>Distance around high wettability area</td>
</tr>
<tr>
<td>$h$</td>
<td>Thickness of liquid</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration</td>
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</table>

**Table 2**

<table>
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<tbody>
<tr>
<td>$T$</td>
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</tr>
<tr>
<td>$m$</td>
<td>$3.9 \times 10^{-4}$ kg</td>
</tr>
<tr>
<td>$h$</td>
<td>$36 \mu m$</td>
</tr>
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</table>

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Fig. 10. Static model of the self-alignment element with error in the translational direction.

Fig. 11. Virtual surface when there is 100 $\mu m$ alignment error in the $x$ direction.
Fig. 12. Direction of surface tension $T$ when there is 100 $\mu$m alignment error in the $x$ direction.

Fig. 13. Calculated restoring force in the linear direction using the micropart with the square boundary pattern ($0.8 \times 0.8$ mm).

Fig. 14. Experimental microparts ($L = 2.4$ mm).

Fig. 15. Calculated restoring forces in the $x$ direction using the micropart with convex boundary patterns ($0^\circ$ error in the $\theta$ direction).

5. Effect of boundary pattern change between different wettability areas on alignment performance

In the alignment, the restoring force is generated on the boundary between the high and low wettability areas. Theoretically, its magnitude in each direction depends on not only the total length of the line but also the boundary pattern. In this section, using five kinds of microparts with different boundary patterns, three convex and two concave ones, the effect of the boundary pattern change on alignment performance is discussed experimentally and theoretically.

Fig. 14 illustrates three kinds of microparts with different convex boundary patterns (square, triangular, and hexagonal patterns). The theoretical restoring forces for these microparts in the $x$ direction are shown in Fig. 15. In this figure, two restoring forces of hexagonal boundary
Fig. 16. Experimental alignment error in the linear direction using the micropart with convex boundary pattern (0° error in the θ direction).

Fig. 17. State of the water droplet and the micropart after the alignment (triangular pattern).

Fig. 18. Calculated restoring forces in the x direction using the micropart with convex boundary patterns (15° error in the θ direction).

Fig. 19. Alignment results using microparts with the square, cross, and star boundary patterns.

patterns are illustrated. The hexagon-x pattern coincides with the hexagon-y one rotated by 90°. They are calculated on the condition that there is no alignment error in the y and θ directions. All the microparts have the same length of the boundary line. The water volume used for each micropart is determined so that each theoretical liquid thickness is equal to the others. The values of restoring forces acting on the four microparts are almost equal when an alignment error less than 20 μm is induced in only the x or y direction. Fig. 16 illustrates the experimental alignment errors in the linear direction when the initial error is 100 μm. The experimental average errors for the two hexagonal patterns and the square one are <5 μm. The average error for the triangular
pattern is 15.4 μm and three times larger than that for the others.

Fig. 17 shows the state of the water droplet and the microparts with the triangular pattern after the alignment. In the figure, an acute angle edge of the triangle in the oval is not covered with water and water overflows to the low wettability area. This phenomenon is observed only in the micropart with the triangular boundary pattern. This is considered to be the main reason for its large alignment error.

Fig. 18 shows the effect of the 15° alignment error in the θ direction on the restoring force in the x direction. The alignment error in the θ direction makes the restoring force of the micropart with the triangular boundary pattern lower than that with the other patterns in the x or y direction. While micropart 2 was being dropped on micropart 1, the rotational motion of micropart 2 was sometimes observed. Therefore, the low restoring force in the linear direction with the rotational error is also considered to be one of the reasons why the alignment error of the micropart with the triangular boundary pattern is larger than that of the microparts with the other patterns.

The existence of overflow to the low wettability area and no wet areas on the high wettability areas is also observed on microparts with concave boundary patterns. Fig. 19 illustrates the alignment results for the microparts with the square, cross, and star boundary patterns. The lengths of the boundary lines of all the microparts are equal (L = 3.2 mm). The photographs in this figure show the states of the microparts and water after the alignment. Only in the alignment for the cross and star boundary pattern microparts, water overflowed to the low wettability area and no wet areas were observed on the high wettability areas. The bottom part of the figure shows the alignment errors. The averages of the errors for these microparts are three times larger than that for the square boundary pattern micropart. The reason is considered to be that the difference of wettability between the high and low wettability areas is not large enough to retain water only in the acute high wettability area.

Fig. 20 shows the average and the standard deviation of the alignment error in case of the initial error in the x direction from 100 to 250 μm.

Fig. 21. Alignment result on the condition of 15° initial error in the θ direction.
The results show that the restoring force influences the alignment. In Fig. 15, the difference in restoring force between the hexagonal and the square boundary pattern microparts increases with the increase of the error when the error is greater than approximately 20 μm. When the initial error is 200 μm in the x direction, the average error in the x direction for the square boundary pattern microparts is 18.5 μm and the errors in the x direction are greater than 20 μm in three experiments. The results show that the restoring force influences the alignment error when water exists only on the high wettability area.

In the above discussion, the hexagonal boundary pattern micropart makes a smaller alignment error than the other microparts under the condition of the initial error in the x direction. The restoring force for the hexagonal boundary pattern micropart in the linear direction is less than that for the square one and less than 30°. These results show that the theoretical restoring force is a useful index for determining the suitable boundary pattern. Concave boundary patterns such as the cross and star ones, and convex boundary patterns of which internal angles are acute ones, such as the triangle, cause large alignment errors.

For the mass production of microsystems, the parallel alignment of many microparts by means of a simple system is important. Therefore, future work will focus on the realization of the parallel alignment of many microparts.

Fig. 22. Calculated restoring torque in the θ direction using microparts with the square and hexagonal boundary patterns.

6. Conclusions

In this study, the factors that influence alignment performance were examined and ways of alignment performance improvement were discussed experimentally and theoretically. First, the alignments with six water droplet volumes were made and the factors that lowered alignment accuracy were examined on basis of observations of the micropart and droplet behavior and the alignment accuracy in the experiments. Next, the model for calculating the restoring force theoretically was introduced and the relationship between the magnitude of the theoretical restoring force and the experimental accuracy was discussed.

The results show that the alignment accuracy is decreased by the friction force between the microparts, the existence of areas which are no wet on the high wettability area and the overflow to the low wettability area, and that the microparts with larger restoring force in the linear directions generally make a smaller alignment error. The effect of boundary pattern change between different wettability areas on the alignment accuracy was examined experimentally. The experimental results show that the hexagonal boundary pattern micropart has better performance than the other microparts. The hexagonal boundary pattern theoretically produces a larger restoring force than the other patterns in the linear direction. These results show that the theoretical restoring force is a useful index for determining the suitable boundary pattern. Concave boundary patterns such as the cross and star ones, and convex boundary patterns of which internal angles are acute ones, such as the triangle, cause large alignment errors.

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