Manipulation and welding of metal spheres above 10 µm using needle-like probe

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Abstract

A needle-like probe is the simplest tool to manipulate fine spheres. It catches fine spheres by adhesion forces without any holding device. Metallic spheres of 10–100 µm are difficult to manipulate with the needle-like probe, because the gravity rivals the adhesion forces in the dynamics of the spheres. Large and heavy spheres arranged on a substrate are easily disturbed because of the same reason. Here, a manipulator equipped with a direct power source, which applies voltage to the probe, is fabricated. Large and heavy spheres are adhered by the controllable electrostatic force. Besides the manipulation, the apparatus is designed to weld the spheres by using the probe as electrode for spot/arc welding. Experiments on the manipulation showed that the probe caught gold spheres of 40–80 µm by applying 20–50 V and released by putting them down after cutting the power off. Following to manipulation, welding experiments were carried out at various conditions. Two power sources, a high-voltage and low-current power source and a low-voltage and high-current power source, and two welding methods, arc welding and spot welding, are examined. The experiments showed that the gold spheres of 40–80 µm can be welded by the spot welding using the high-voltage and low-current power source, of which maximum power rating is 10 kV × 1 mA. The probe is kept to touch the sphere and 4 kV or more is applied. Electric sparks are generated at the interface of the probe and the substrate, and the sphere is welded to the substrate. In both the manipulation and welding, the contact pressure must be very low. A tower of gold spheres is fabricated as an example of three-dimensional microstructures composed of fine spheres.

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1. Introduction

Assembly of fine spheres is one of the built-up processes to obtain microstructures. Self-assembly [1] is efficient and attracts many researchers. Manipulation, which assembles one-by-one, is not efficient but it has an advantage, in comparison with the self-assembly, that each different sphere is placed at a precise point under the complete control of operator.

Various tools are investigated for the manipulation of fine spheres. The needle-like probes [2,3] are the simplest tool. Without any holding devices, the probe handles spheres using adhesion forces. Manipulation by the probe is, therefore, limited to fine spheres, of which dynamics are dominated by the adhesion forces [4].

Large and heavy spheres such as metal spheres above 10 µm are difficult to handle with the probe and are manipulated by other tools such as microgrippers/chopsticks [5–7], suction tubes [8], etc.

Assembled spheres are easily disturbed, if they are dominated by the gravitational force. Fixation by adhesives [9], soldering [10], and coating [11] are reported. Manipulation and fixation must be conducted at the same place for efficient and accurate assembly. It is, however, impossible for any combination of the above methods.

We, therefore, developed an apparatus, which has an ability of manipulation and fixation for metal spheres above 10 µm. Our idea is to enhance the adhesion force by applying voltage to the needle-like probe and to weld the metal spheres using the probe as an electrode of arc welding and/or spot welding. In this paper, details of the apparatus and the experiments to verify our idea are described.
2. Forces exerted on spheres during manipulation

When a sphere is picked up by a needle-like probe, the force to the probe is changed as shown in Fig. 1. The operation is divided into following four stages. The probe is moved downward till it touches the sphere (stage I), the probe pushes the sphere at a low contact pressure (stage II), and the probe is pulled up. The force monotonously increases till the sphere is off the substrate (stage III). The force suddenly decreases to $F_g$, the weight of the sphere, and become constant (stage IV).

The maximum force, $F_{\text{max}}$, is larger than the weight of the sphere, $F_g$. The difference is adhesion forces between the sphere and the substrate, $F_{\text{s-s}}$. Main source of the adhesion forces is van der Waals force, electrostatic force, and liquid bridge force [12]. Adhesion forces are exerted also between the probe and the sphere, which are expressed by $F_{\text{p-s}}$. The value of $F_{\text{p-s}}$ should be larger than $F_{\text{max}}$ for catch by the probe:

$$F_{\text{max}} = F_g + F_{\text{s-s}} < F_{\text{p-s}}$$  \hspace{1cm} (1)

The value of $F_g$ is, in general, negligible to the adhesion forces for fine particles smaller than $10 \mu m$. Adhesion forces of $F_{\text{s-s}}$ and $F_{\text{p-s}}$ are determined by the materials and shape of the probe, the sphere and the substrate to some extent. Release is possible by maneuvering the probe [13], even if $F_{\text{p-s}}$ is larger than the sum of $F_g$ and $F_{\text{s-s}}$.

As the value of $F_g$ is relatively large for metal spheres larger than $10 \mu m$, catch by the probe is difficult. If voltage is applied to the probe, electrostatic force, $F_{\text{es}}$, will be added to $F_{\text{p-s}}$. Eq. (1) is replaced by Eq. (2):

$$F_{\text{max}} = F_g + F_{\text{s-s}} < F_{\text{p-s}} + F_{\text{es}}$$  \hspace{1cm} (2)

The electrostatic force caused by the contact potential difference cannot be controlled, while the value of $F_{\text{es}}$ can be controlled by the applying voltage.

3. Experiments

3.1. Apparatus

Fig. 2 shows the schematic illustration of the apparatus developed to verify our idea that metal spheres larger than $10 \mu m$ will be manipulated and welded by applying voltage to a needle-like probe.

A needle-like tungsten probe (diameter: $660 \mu m$, point radius: $2 \mu m$) is held vertically above a gold substrate ($10 mm \times 10 mm$) placed on a worktable. The probe and the substrate are insulated from the holding tool and the worktable, respectively. A direct power source is equipped to apply voltage between the probe and the substrate.

Two power sources are prepared. One is a high-voltage and low-current power source (Max-Electronics, R HV), whose maximum power rating is $10 \text{kV} \times 1 \text{mA}$. The output is adjustable from $0$ to $10 \text{kV}$ at a step of $10 \text{V}$.

The other is a condensing type low-voltage and high-current power source (Nippon Avionics, NRW-50). The latter is commonly used in the spot welding. Charges accumulated in a capacitor of $750 \text{mF}$ are released for a very short period of $1.6–4.8 \text{ms}$. The peak current is varied from $3700$ to $1800 \text{A}$ with the period of discharge. As the welding time is very short, this kind of power source is used for welding of small objects.

The tip of the probe and the around are monitored by stereomicroscopes from two horizontal directions. The operator manipulates and welds, watching pictures on a monitor through CCD cameras attached to the stereomicroscopes. The probe and the stereomicroscopes are fixed and the worktable is moved by a stage system. In this paper, however, we describe as if the probe had moved. For example, when the substrate moves downward, it is expressed as the probe moves upward. The minimum resolution of the $Z$-axis stage is $0.1 \mu m$ and that of the $X$-axis stage and $Y$-axis stage is $1 \mu m$. 

![Fig. 1. Schematic variation of force exerted on the probe during picking up a sphere.](image1)

![Fig. 2. Schematic illustration of apparatus for manipulation and welding for fine metal spheres.](image2)
3.2. Procedure

Experiments for the manipulation are conducted as follows. Gold spheres of 40–80 μm were sprinkled on the substrate. The probe was moved just above an objective sphere, and was lowered at each 0.1 μm, which is the minimum resolution of the Z-axis stage, till the tip touched the upper surface of the sphere. Voltages less than 100 V were applied and the probe was pulled up, and we judged whether the sphere was picked up or not by the pictures on a monitor.

For the welding, two welding methods are examined. One is conducted referring to the arc welding and the other referring to the spot welding. For the former experiments, the probe is moved where the tip is just 20 μm above a gold sphere of 40–80 μm. The voltage is applied to the probe to make arc. In the latter experiments, voltage is applied after the probe is lowered to touch the sphere. The current flows through the probe, the sphere, and substrate. After the experiments, the sphere is pushed by the probe to know whether the sphere is welded to the substrate.

Only the high-voltage and low-current power source is used for experiments of manipulation, and both the high-voltage and low-current power source and the low-voltage and high-current power source are used for welding experiments.

4. Results and discussion

4.1. Manipulation and additional electrostatic force

The probe caught the sphere without fail when 20–50 V were applied. Less than 10 V, spheres always remained on the substrate. Above 60 V, it succeeded in some cases, and sparks are observed in some cases.

Additional electrostatic force, \( F_{es} \), is considered to be Johnsen–Rahbeck’s force. Johnsen–Rahbeck’s adhesion force is caused by a large voltage drop between two contact substances [14].

The electric resistance between the probe and the substrate, \( R_t \), was measured to be an order of 100 kΩ when the tip of the lowering probe touched the sphere first. \( R_t \) is the sum of contact resistance between the probe and sphere, \( R_{p-s} \), and that between the sphere and substrate, \( R_{s-s} \), because of the negligible resistance of metal sphere and metal substrate. A very thin oxide film covers the probe, while no oxide film is on the gold sphere and on the gold substrate. The large part of high \( R_t \) will be, therefore, due to high \( R_{p-s} \).

As information on the actual contact area at a sub-microscopic scale is an important factor, theoretical analysis of Johnsen–Rahbeck’s force is difficult. We can say only about qualitative dependency that it increases with an increase in voltage drop, and that the voltage drop increases with an increase in applied voltage and contact resistance. The force was not large enough when applied voltage was less than 10 V.

Observation of sparks indicated that thin tungsten oxide film broke down at asperity microcontacts and large current flowed through the interface of probe and sphere by the local discharge. It lowered the contact resistance and Johnsen–Rahbeck’s force will be reduced not to satisfy Eq. (2). It will be the cause of the fails above 60 V. As the intensity of additional adhesion force, \( F_{es} \), depends on uncontrollable contact resistance, good reproducibility is not expected even if the same sphere is used. Thus, catch sometimes fails and sometimes succeeds above 60 V.

The contact resistance changed drastically by the contact pressure. After the probe touched the sphere first, it was further lowered up to 1 μm downward. \( R_t \) is reduced to less than 1 Ω. Johnsen–Rahbeck’s force will be, therefore, almost 0 when the voltage is applied. The probe, indeed, did not succeed in catch at any voltage as expected.

Once the sphere is picked up in the air, Johnsen–Rahbeck’s force disappears, because the potentials of the probe and the sphere become almost the same. The sphere, however, stayed at the tip of the probe. The sphere did not fall even if the applied voltage is cut off. It means that \( F_{p-s} \) is not so large as to pick up the sphere, but large enough to hold it. In this case, order of the magnitude of the forces is as follows:

\[
F_g < F_{p-s} < F_{max} = F_g + F_{s-s} < F_{p-s} + F_{es} \quad (3)
\]

Eq. (3) leads us to a simple release method. The direct power source is cut off, the probe is lowered till the sphere touches the substrate, and the probe is pulled up. Then the sphere remains on the substrate. Validity of the method was verified by experiments.

The value of \( F_g \) is estimated to be 0.1 nN for 10 μm gold sphere and 50 nN for 80 μm gold sphere. The former sphere is a critical size for the manipulation by the needle-like probe. It means that adhesions of 50 nN or more are generated by applying 20–50 V to the probe.

4.2. Spot welding using high-voltage and low-current power source

The spot welding is a coalescing process by the flow of electric current through the resistance of metals held together under pressure. Joule’s heat generates at the contact interface where the resistance is the highest in the current path. In many cases, metals are clamped by upper and lower rod-like electrodes. The probe corresponds to upper electrode and the substrate corresponds to both lower electrode and a workpiece.

The power source is the same with that used for manipulation. High voltages of 0–10 kV are generated by a two stage Cockcroft–Walton voltage doubler circuit with capacitors of 1000 pF connected in series. The feature is...
the quick recharge time. The output voltage returns to a setting value within 3 ms after discharge.

Our experiments showed that the important factor was the clamping force, i.e. the contact pressure. The probe must be in contact with the sphere at a degree in which \( R_{p-s} \) is an order of 100 k\( \Omega \). The moment 4 kV or more is applied, sparks were observed around the sphere and the sphere was welded at the substrate (see Fig. 5). The welding time was about 1 s. When the sphere was pressed by the probe so as to \( R_t \) was less than 1 \( \Omega \), sparks were not observed at any voltages, and the sphere did not weld. The probe position of the welding is the same with that of the last step of the release. The welding can be, therefore, carried out immediately after the sphere is placed.

When the clamping force is low, the sphere is in contact with the probe and the substrate through the asperity microcontacts. Current must flow narrow paths. Current density at the asperity microcontacts is high so that the sparks are observed. They are, therefore, locally heated, at least, to the melting point of gold by Joule’s heat, even if the current is only 1 mA.

Interface between the probe and the sphere, and that between the sphere and the substrate are in the same situation. As \( R_{p-s} \) is greater than \( R_{s-s} \), much more heat is generated at the former interface. The sphere is, however, welded to substrate and is not welded to the probe. The probe is made of tungsten and its melting point is about 2000 \( ^\circ \)C higher than that of gold. Molten gold at the contact points exerts surface tension force on the interfaces. The sphere will be attracted to substrate rather than to probe, because tungsten is one of the hard-to-bond materials. These are the reasons that the sphere does not weld to the probe.

The value of \( R_t \) under high clamping forces is about 10,000 times smaller than that under low clamping forces. As the current is limited to 1 mA, almost the same current flows from the probe during the welding experiments, regardless of the clamping forces. If so, Joule’s heat generated under high clamping forces is about one-10,000th of that generated under low clamping forces. On the other hand, the contact area to be heated is increased with an increase in the clamping force. This is a reason to fail to weld at high clamping forces.

4.3. Spot welding using low-voltage and high-current power source

Under a low clamping force similar to the experiments using the high-voltage and low-current power source, current did not flow. When the probe pushed down so as to stick in the sphere, sparks generated at the tip of the probe and the sphere was welded to the substrate. It is, however, concluded from the SEM observation of the probe that spot welding using high-current and low-voltage power source is not practical, because of the severe damage to the probe.

Fig. 3 shows the SEM photograph of the probe as received and those after the welding experiments. Tip of the probe is lost for 50–60 \( \mu \)m and rounded after one time welding using the low-voltage and high-current power source, as shown in Fig. 3(b). The probe must be exchanged for every few welding operations or it fails in welding. The spheres were blown off at the welding if the probe with rounded tip was used.

When the high-voltage and low-current power source is used, the tip of the probe is lost about 10 \( \mu \)m at the first time.

Fig. 3. Tip of the probe before and after the welding experiments: (a) as received, (b) after one time welding using the low-voltage and high-current power source, (c) after one time welding using the high-voltage and low-current power source, and (d) after 10 times welding using the high-voltage and low-current power source.
welding as shown in Fig. 3(c). Fig. 3(d) shows the tip after 10 times welding using the same power source. From Fig. 3(c) and (d), loss of the tip on and after two time welding is estimated to be about 10 μm, only 1 μm at each welding operation. Substance adhered to the tip shown in Fig. 3(b)–(d) was sputtered gold.

The high-voltage and low-current power source is, therefore, better than the low-voltage and high-current power source. Though proper heat must be given only to contact area for welding of fine objects, it is not so easy for the latter type of power source. Welding time of a few milliseconds is too long to prevent heat diffusion, and current above 1800 A is so large that the probe becomes white-hot.

4.4. Arc welding

The experiments did not succeed for both high-voltage and low-current power source and low-voltage and high-current power source. Voltages were applied to the probe, positioned 20 μm above the sphere using each power source.

In the case of the former power source, discharge occurred at above 1 kV or more. The sphere was, however, blown off by the arcing pressure. In the case of the latter one, discharge did not occur.

4.5. Example of microstructure

Fig. 4 shows the process to assemble fine particles by the apparatus. The tip of the needle-like probe is made to touch the objective sphere on the worktable (a). The sphere is picked up by the probe by applying 20–50 V (b). The sphere is carried to a predetermined point after turning the voltage off (c). Fig. 4(c) is end of the manipulation process and the start of welding process. High voltage of 4 kV or more is applied in the situation of Fig. 4(c). Sparks are generated around the contact points of the sphere (d) and it is welded to the substrate. The probe is pulled up to manipulate other spheres. The operator maneuvers the probe by watching the pictures of the CCD cameras attached to the microscopes.

Three-dimensional microstructure will be constructed by repeating the process. Fig. 5 is an example of such the microstructures. Three gold spheres of 40–60 μm are heaped up on the gold substrate. As shown in this picture, the sphere can weld not only to the substrate but also to other metal sphere. Top of the sphere is welded at the edge of the second sphere to show that the sphere does not fall.

The welding method is applicable to other metal spheres. Various kinds of metal spheres can be manipulated and welded by the same manner with that for gold spheres [15]. Inert gas must be flowed down from the chuck of the probe during the welding to prevent the oxidation.

We can demonstrate that metal spheres are manipulated and welded using the same probe. The contact pressure or the contact resistance is a key of the process. However, they were not measured while the tower of gold spheres in Fig. 4 is fabricated. Next step of our work is to equip the apparatus for measurement of the contact pressure or the contact resistance. It will be necessary for further understanding of the process and for improvement of the process.

5. Conclusion

An apparatus having an ability of manipulation and welding is developed. A high-voltage and low-current direct power source is equipped to the apparatus to apply voltage between a needle-like probe and a metal substrate. Large and heavy metal spheres of 40–80 μm, which are difficult to manipulate with the needle-like probe, can be picked up by the apparatus when 20–50 V is applied. Experiments showed that the probe should touch the sphere at very low contact pressure.

Once the sphere is picked up, it does not fall even if the applied voltage is cut off. The probe can be released by
lowering the probe till the sphere touches the substrate and pulling up the probe. For welding of the sphere, voltage of 4 kV or more must be applied to the probe. Sparks are generated around the contact points of the sphere and the sphere is welded to the substrate. Tower of three gold spheres is fabricated as an example of a microstructure using the apparatus.

We have added the manipulation and welding of relatively large metal spheres to the repertoire of manipulator using needle-like probe. In the probe manipulation method, each sphere is arranged one-by-one. Thus, specific one sphere can be added to microstructures of spheres by the probe. This feature and the welding ability will shine by combining with other fabrication methods such as self-assembly, lithography, colloidal method, etc.

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