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## Evaluation of contact welding and strengthening of joints by non-contact discharge

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#### Abstract

Our probe manipulation apparatus has the ability to weld using a tungsten needle-like probe as an electrode, assisting with ease of manipulation of fine metal particles. Gold particles  $60-80 \,\mu\text{m}$  in diameter were welded to a gold substrate using the apparatus. Contact welding is carried out by applying high voltages of 4 kV or more to the probe which is in contact with the particle at a very low contact pressure. In this paper, estimation of the welding strength is done and the joint is strengthened by arcing. After welding, the joint was fractured by tensile loading, and the fractured surface was observed by SEM. The area of the joint is within a circle of 5  $\mu$ m in diameter regardless of welding time of 0.5–10 s. The fracture load is estimated to be about  $2.6 \times 10^{-3}$  N. This value is 50,000 times greater than the weight of an 80- $\mu$ m gold particle, but is only 0.26 gf. Arcing by the apparatus, which we term 'non-contact discharge', appears to strengthen the joint. The probe is positioned above the welded particle and 2 kV is applied to the probe. The particle is taken off after the non-contact discharge, and the surface is observed to be fractured. Non-contact discharge was conducted in air and in N<sub>2</sub> gas flow. Only non-contact discharge in N<sub>2</sub> gas flow is effective for strengthening the joint. The top of the particle is sputtered by the discharge streamers. The sputtered droplets are scattered around the particle during non-contact discharge in the air but pile up near the root of the particle with N<sub>2</sub> gas flow. The droplets form an annular ridge to which the particle becomes attached. The welding strength is, therefore, increased by non-contact discharge in N<sub>2</sub> gas flow.

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## 1. Introduction

Particle assemblage is a microstructure fabrication technique that has the potential to supersede lithographic methods. The handling methods of fine particles can be classified into two types. In one, multiple particles are arranged in one step, such as by self-assembly [1,2]. In the other, fine particles are handled individually, such as by manipulation using a probe [3,4], laser [5] or microgripper [6].

The former type of method features high productivity, and has attracted considerable research interest. Photonic crystals and biosensors are fabricated this way [7,8]. The latter types of methods are being investigated mainly in relation to robotics [3] and MEMS [9,10]. Individual

particles can be arranged with a high degree of freedom and with high reliability. For example, a photonic crystal with a special crystal structure is fabricated in this way [11].

We have been investigating probe manipulation and have fabricated a probe manipulator for particle assemblage. The adhesion force of the manipulator is enhanced by applying a voltage to a tungsten needle-like probe. Relatively heavy metal particles greater than  $10 \,\mu\text{m}$  in diameter can, therefore, be caught one by one using the tungsten needle-like probe [12].

It has been shown that fine metal particles can be welded to a metal substrate by applying a high voltage to the probe [12,13], a process termed contact welding. In our previous paper, we have described only the contact welding procedure. In this paper, the welding strength is estimated from the fractured surface and the joint is strengthened using the same apparatus.

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## 2. Experiments

## 2.1. Apparatus

A worktable is a metal substrate placed on a motor stage system. A tungsten needle-like probe (hereinafter referred to as a probe) is positioned vertically above the worktable. Two microscopes focus on the tip of the probe and the surrounding area from different directions on the horizontal plane. The probe and the microscopes are fixed and the worktable is moved using the stage system. In this paper, however, we describe the process as if the probe moves. Pictures of the microscopes are displayed on a monitor and recorded on a video player through CCD cameras attached to the microscopes.

A DC power supply (Max-Electronics, RHV) is used to apply voltage between the probe and the substrate. The maximum output voltage is 10 kV and the maximum output current is limited by a resistance to 1 mA. A stainless steel tube with an internal diameter of 8 mm is arranged concentrically around the probe and an inert gas is passed down through the tube.

The apparatus is placed in a room where the humidity and temperature are kept at 5-15% and 18-20 °C, respectively. Details of the apparatus are described in a previous paper [12] except for the inert gas flow mechanism. The apparatus was used for the experiments in this study.

## 2.2. Welding method

Contact welding is analogous to spot welding. A particle adhered at the tip of the probe is placed on a metal substrate and high voltages of 4 kV or more are applied to the probe which is held at a very low contact pressure with the particle. The particle is thus welded to the substrate.

The current is far lower and voltage is far higher than in spot welding. The contact pressure must be very low to maintain the resistance between the probe and the substrate at above  $100 \text{ k}\Omega$ . Again, in contrast to spot welding, the work pieces are pressed by the electrode and the pressure must be maintained during heating. Our method is, therefore, called contact welding.

#### 2.3. Evaluation of welding

Evaluation of the welding strength is difficult, because the particle is very small. Indirect estimation from fractured area is carried out. The tip of the probe is adhered to the top of the particle, which is welded to the substrate, using a small amount of cyanoacrylate glue (Toagosei Co., Ltd., GL-10). The welded joint is fractured by pulling up the probe, and the fractured surface is observed using an SEM.

#### 2.4. Specimen

The probe is a tungsten needle (NPS Inc., W26-05-01 × 1-1/2), as used for probe cards. The diameter and the point radius of the probe are 660 and 2  $\mu$ m, respectively. The particle is a gold sphere 60–80  $\mu$ m in diameter. The substrate is a gold thin plate 300  $\mu$ m in thickness, bonded with an adhesive agent to a 1.5 mm-thick copper plate. The resistance between the copper plate and the gold plate is less than 1  $\Omega$ /cm<sup>2</sup>, since high pressure is applied during adhering.

## 3. Results and discussion

#### 3.1. Contact welding

A gold particle is welded to the substrate by contact welding. The probe is placed above the particle and is moved downward till it touches the particle. The power supply, set to 10 kV, is turned on and then turned off after a prescribed time.

A flash of bright white light is seen immediately after the switch on, but nothing further is seen during the process. Video evidence demonstrates that the flash is generated at the contact point between the particle and the probe. Fig. 1 shows a frame of the video.

The flash is due to spark discharge caused by breakdown of the thin oxide film on the probe. No flash is observed at the contact area between the particle and the substrate. The particle is, however, welded to the substrate. Blue light is seen around the probe in Fig. 1. It is due to reflection of ordinary illumination, because it is observed before switch-on.

Fig. 2 shows a top view of a particle welded by the contact welding. The welding time was 2 s. The irregular mark near the center of the particle is a trace of local fusion caused by the spark discharge. Except for this trace, no other change caused by contact welding is observed on the particle or the substrate.

## 3.2. Evaluation of contact welding

Contact welding was conducted at various welding times ranging from 0.5 to 10 s, after which the particles were detached using the method described in Section 2.3. Fig. 3 shows SEM photographs of the substrates after they had been removed. The white irregular marks are the fractured surface. When the welding time is 0.5 s, the white mark is mostly within a 5- $\mu$ m circle. The area does not extend even if the welding time is prolonged to 10 s. Any difference in shape is thus likely to be due to irregularities in particles and the substrate. The numerous cracks seen in the substrate are generated when the gold plate is pressed onto the copper plate during the adhering process.

It may be concluded that the joint strength is not affected by the welding time. The tensile strength of gold is



Fig. 1. Bright light generated during contact welding.



Fig. 2. Top view of gold particle welded to gold substrate by contact welding.

about 108 MPa [14]. Assuming that the contact area is a circle of  $5 \,\mu\text{m}$  in diameter, the fracture load on the welded part is estimated to be about  $2.6 \times 10^{-3} \,\text{N}$ . This value is 50,000 times greater than the weight of the 80- $\mu$ m gold particle.

## 3.3. Mechanism of contact welding

Contact pressure is reported to be an important factor in contact welding. The resistance between the probe and the

substrate is, therefore, greater than  $100 \,\mathrm{k}\Omega$  as described above. In this study, the welding area is shown to be almost constant, regardless of welding time. These results indicated that the gold particle is welded to the gold substrate by contact welding in the following manner.

Contact welding uses the Joule heat, as does spot welding. The amount of generated Joule heat, Q, is given by the following equation:

$$Q = I^2 \times R,\tag{1}$$



Fig. 3. Traces of gold particles welded by contact welding. Gold particles are taken off after being joined by contact welding lasting (a) 0.5 s, (b) 1 s, (c) 2 s and (d) 10 s.

where I is current and R is contact resistance. Since the current is limited to 1 mA, Q is proportional to R.

The particle placed on the substrate touches the substrate over a very small area of asperity contact from the microscopic viewpoint. High temperatures are locally generated at the contact interface immediately after the current begins to flow, and the contact area fuses. Once the contact area has fused, no further heat is generated, since the resistance falls to near zero. The asperity contact area thus fuses and solidifies almost instantaneously. Contact welding is complete at the moment of the flash. This is the reason why the welding area does not increase with an increase in the welding time.

## 3.4. Strengthening by non-contact discharge

When a 60–80  $\mu$ m gold particle is welded onto the gold substrate by contact welding, the fracture load of the welded part is estimated to be about  $2.6 \times 10^{-3}$  N. This

value is sufficient to fix the particle, but the particle is disjoined only by a load of 0.26 g. The strengthening of the joint was, therefore, examined.

The manipulator is designed to examine two kinds of welding. One is contact welding, which corresponds to spot welding. The other corresponds to arc welding, i.e., high voltage is applied to the probe which is positioned above the particle. The latter welding method failed, since the particle was blown away by the arcing pressure.

We applied it to strengthening the joint by contact welding. Hereinafter, the method is referred to as 'non-contact discharge'. The probe is positioned  $20 \,\mu\text{m}$  above a gold particle welded by contact welding. Arcing occurred when  $2 \,\text{kV}$  or more was applied to the probe.

Non-contact discharge was carried out in air (without gas flow) and in  $N_2$  gas flow. The rate of  $N_2$  gas flow was 0.751/min. In both experiments, a bright white light was observed during the switch on period between the probe and the particle and between the particle

and the substrate. The particle was not dislodged by the arcing.

It is clear from the frame-by-frame playback of the recorded video that arcing occurred between the probe and the particle for non-contact discharge in the air, and the light seen between the particle and the substrate is only a reflection. In  $N_2$  gas flow, the discharge occurred between the probe and the substrate, with the discharge flow appearing to envelop the particle. One frame of the video taken during each experiment is shown in Figs. 4(a) and (b).

Figs. 5(a) and (b) are a top view of the particle after the non-contact discharge carried out for 2 s in the air and in  $N_2$  gas flow, respectively. Many small craters are observed on the upper surface of the particles in Fig. 5(a), while in Fig. 5(b), the craters are concentrated in a small circular area. The area where the craters are distributed in Fig. 5(b) is less than one fifth of that in Fig. 5(a). The small particle

at the side of the particle was attached there before the welding experiments.

The side view shows that the crater-distributed area for the particle carried out in air is greatly scooped. The discharge streamers cause the craters. The spot reached by each discharge streamer fuses and droplets are ejected. The bright contrast on the substrate is due to traces of collisions of these droplets. The traces of collisions are equally distributed around the particle in Fig. 5(a), while the traces in Fig. 5(b) are thinly distributed.

#### 3.5. Evaluation of non-contact discharge method

The particle undergoes non-contact discharge in the air and in  $N_2$  gas flow, and is fractured by the tensile loading as described above. Figs. 6(a) and (b) show the fractured surface on the substrates. The SEM photographs are taken by tilting the substrate more than  $60^{\circ}$ .



Fig. 4. Bright light generated during non-contact discharge. Non-contact discharge is carried out (a) in air and (b) in  $N_2$  gas flow following contact welding.



Fig. 5. Top view of gold particle after non-contact discharge. Non-contact discharge is carried out (a) in air and (b) in  $N_2$  gas flow following contact welding.



Fig. 6. Trace after removal of particles. The particles previously underwent non-contact discharge (a) in air and (b) in  $N_2$  gas flow following contact welding.

The white marks in the center of the photographs are the same as those observed in Fig. 3, and are the traces of the joint made by contact welding. Annular bare substrate is distributed around the trace, and a surface with numerous dimples is observed on the outside of the bare substrate.

Collisions of sputtered gold cause these dimples. Discharge between the lower surface of the particle and the substrate may cause them, but this was not observed in the recorded pictures. The outer diameter of the bare substrate is about  $15 \,\mu$ m, which is smaller than the particle's diameter which is greater than  $60 \,\mu$ m. This suggests that the sputtered gold droplets collide with the substrate behind the particle.

The chief difference between Figs. 6(a) and (b) is the outside border of the circular bare substrate. It is elevated about  $1-2 \,\mu\text{m}$  in Fig. 6(b), whereas no ridge is observed in Fig. 6(a).

The joint caused by contact welding is not strengthened by non-contact discharge in the air, but is strengthened by the non-contact discharge in  $N_2$  gas flow.

To remove the particle, the probe adhered to the particle is pulled up by the motorized stage. The movement of the stage, i.e., the movement of the probe, is displayed by a digital panel meter on the stage controller. After noncontact discharge in the air, the particle was detached without any resistance immediately after turning the stage on.

On the other hand, a particle which has undergone noncontact discharge in N<sub>2</sub> gas flow is removed only after the digital panel meter indicates  $1-2\,\mu m$ . The probe cannot move till the particle is taken off, so the reading of  $1-2\,\mu m$ is due to lost motion of the stage and/or strain on the apparatus. In any case, it shows that the joint is qualitatively strengthened by non-contact discharge in N<sub>2</sub> gas flow.

## 3.6. Mechanism of strengthening by non-contact discharge

The strengthening is attributed to the circular ridge on the bare substrate. The particle will also stick to the inside slope of this ridge. Assuming an annular joint area that is  $1 \mu m$  wide and  $25 \mu m$  in diameter, the joint area is calculated to increase by a factor of about 9 due to noncontact welding in N<sub>2</sub> gas flow.

When non-contact discharge is conducted under the  $N_2$  gas flow, the discharge flows around the particle. As described above, the dimples on the substrate are the traces of collisions of sputtered gold droplets. From these observations, the following mechanism is proposed on the formation of the ridge: the sputtered gold droplets are entrained with the discharge flow, and most of them collide near the root of the particle, piling up to form the ridge.

## 4. Conclusion

The probe manipulator that we fabricated for the manipulation of fine metal particles is designed to weld fine metal particles using a tungsten needle-like probe as an electrode. We have previously reported that gold particles can be welded to a gold substrate by applying high voltages to the needle-like probe which is in contact with the particle (contact welding), but have not reported on the welding strength.

The strength of the joint was evaluated. A gold particle  $60-80\,\mu\text{m}$  in diameter, welded to the gold substrate, was detached by tensile loading using the needle-like probe, and the fractured surface was observed by SEM. The following conclusions were obtained.

- (1) The welding begins and ends at the moment of the discharge.
- (2) The welding area is within a 5-μm circle regardless of whether the welding time is 0.5 or 10 s.

(3) The fracture load of the welded part is estimated to be about  $2.6 \times 10^{-3}$  N, which is 50,000 times greater than the weight of the 80 µm gold particle.

To strengthen the joint by contact welding, high voltages were applied to the needle-like probe positioned  $20 \,\mu m$ above the welded particle (non-contact discharge). After the non-contact discharge, the particle was detached in the same manner, and the fractured surface was observed by SEM. The following conclusions on the non-contact discharge were obtained:

- Non-contact discharge in N<sub>2</sub> gas flow strengthens the joint.
- (2) The top of the particle is sputtered by the discharge streamers. The sputtered gold droplets pile up near the base of the particle and form an annular ridge. The particle fuses to the inner slope of this ridge, increasing the welding strength.
- (3) Non-contact discharge in the air does not strengthen the joint, since the sputtered droplets are dispersed around the particle and do not form a ridge.

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