Crystal structure of the interface formed by
thermo-sonic bonding and its effect

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ABSTRACT

Thin film sensors that can directly measure the pressure and temperature of sliding surfaces [1]-[4] are wired using ultrasonic bonding to extract signals. This bonding is conducted by aluminum wire vibrated using ultrasonic sound while imparting load. The oxide film at the interface is destroyed, and crystal grains are then brought together to interatomic distance, resulting in bonding[5]. However, the sensor film itself is also destroyed during bonding for some thin film sensor types. We employed transmission electron microscopy (TEM) observations and energy dispersive X-ray spectrometry (EDS) to discover that weak bonding where aluminum oxide film exists is possible, and this result is reported together with characteristic aluminum structures at the surface.

KEY WORDS

Ultrasonic bonding, Wire bonding, Plastic deformation, Cavity, Aluminum oxide film, TEM, EDS

INTRODUCTION

In-situ measurements are effective to analyze and understand behavior of sliding parts in general. We conducted many such measurements using thin film sensors.

More accurate analysis became possible by providing input data that describe the actual machine more accurately for computer aided engineering (CAE) analysis [6]. Simulations that reflect the actual machine more precisely were made possible by using thin film sensors, resulting in improved correlation to the actual machine [7], and thin film sensors made it possible to calculate oil film thickness on the sliding surface during operation [8].

These sensors are installed on or close to the sliding surface, thus electric signals from the sensor leads must be sent to, for example, an analog-to-digital converter or an amplifier. We used an ultrasonic bonding machine to bond lead wires to the sensor.

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Figure 1 show how lead wires to an amplifier are bonded to thin film sensor leads on a sliding surface. The photos show a thin film pressure sensor attached to the power transmission surface of an automotive continuously variable transmission (CVT). Photo (a) shows the bonding (thin line) that connects thick lead wires to leads of the thin film sensor, while photo (b) shows the configuration of the sensor; protective coating is not applied to expose the sensor.
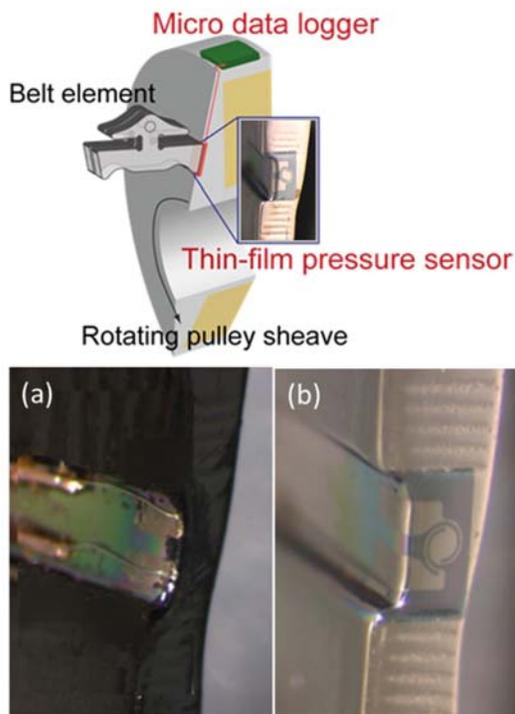

Figure 1. Lead wires bonded to a thin film sensor attached to a sliding surface.

The center circle of the photo (b) detects pressure, and the sensor lead extends to the left.

Various materials were used as the sensor film depending on the purpose. However, some were difficult to pressure-bond, such as chromel and alumel, which are used in thermocouples. The sensor film was easily destroyed by pressure bonding, thus many trial and error regarding bonding conditions were carried out.

Therefore, we observed in detail the metal structure at the surface and the interface just under the surface using transmission electron microscopy (TEM) to uncover the bonding mechanism and allow more precise connection of lead wires to a thin film sensor

EXPERIMENTAL METHODS

To connect lead wires to a sensor, a manual ultrasonic wire bonder (Model 7476D, West Bond) was used to pressure-bond aluminum thin wire to thin-film thermocouples (chromel / alumel).

Figure 2. Manual wire bonder.

Ultrasonic bonding vibrated the sensor surface and lead wires with ultrasonic sound. The oxide film and contaminants on the sliding surface were instantaneously removed, and pressure bonding at temperatures about 1/3 of the melting point was possible because crystal grains approached each other until they reached interatomic distance [9]-[10]. Bonding conditions were examined in the relation of the magnitude of the power. Whether bonding happened or not was visually inspected. Table 1 shows the bonding conditions..

Table 1. Bonding conditions.

Output Condition	Power [mW]	Time [msec]	Load [gf]
Normal	300	100	30
Weak	150	100	30

The aluminum thin wire used in bonding was a standard product by SPM with diameter 25 μm (Al 99% and Si 1 %). The thin film sensor was alumel or chromel, and AlN insulating film was deposited between SCM420 substrate and the sensor film. The film deposition was conducted by radio frequency (RF) sputtering under the conditions in Table 2.

Table 2. Sputtering conditions

Type of thin film	Power [W]	Thickness [μm]	Source gas
Alumel film	800	0.29	Ar
Chromel film	800	0.24	Ar
Insulation film: AlN	800	2.0	Ar 90 %, N2 10 %

EXPERIMENTAL RESULTS

Figure 3 shows a scanning electron microscopy (SEM) images of aluminum thin wire bonded on alumel and chromel thin films.
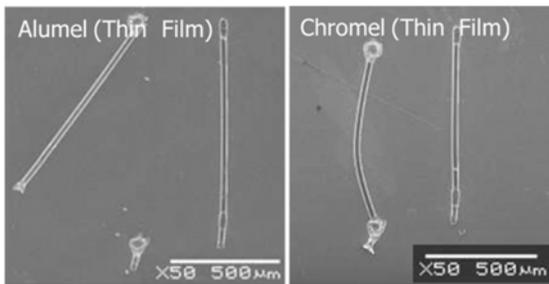

Figure 3. SEM images of bonding on alumel or chromel under normal conditions.

The aluminum thin wire was pressure-bonded on a smooth sensor film at the top of the image. The other end was drawn toward the bottom of the image and then pressure-bonded. Observation by SEM and transmission electron microscopy (TEM) was conducted on the bonding surface.

EXPERIMENTAL RESULTS (Normal Condition)

Figure 4 shows SEM images of the bonding on the surfaces of alumel and chromel thin film sensors.
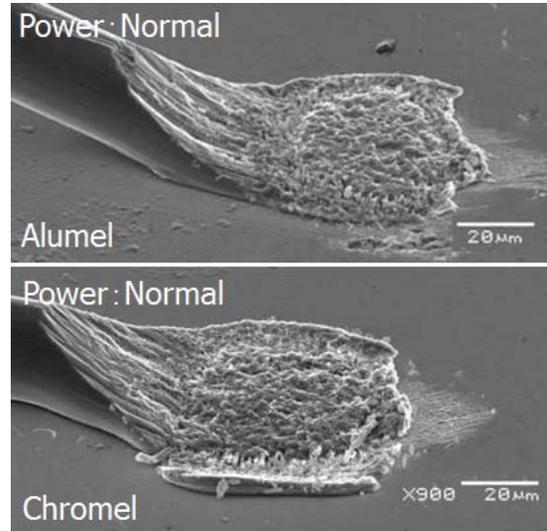

Figure 4. SEM images of bonding part on alumel or chromel.

The bonded part deformed significantly, and the tip was torn off. Moreover, rubbing marks were found on the sensor surface. The deformation of the alumel and chromel surfaces showed almost no difference.

TEM specimens were cut out using a focused ion beam (FIB) from the center of the pressure-bonded area that underwent significant deformation. Figure 5 shows SEM images of a specimen machined using an FIB.
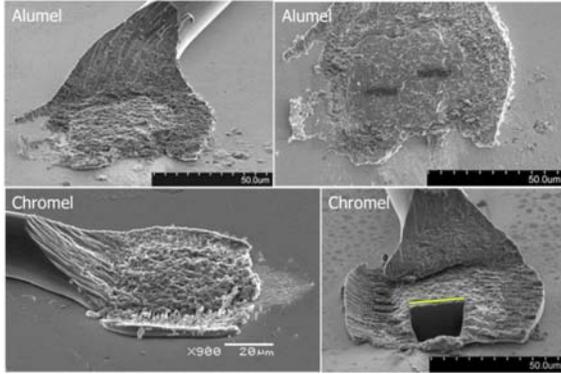
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Figure 5. FIB machined parts that were cut out (SEM image).

Figure 6 shows the TEM image of the aluminum side of pressure bonding on the alumel surface.
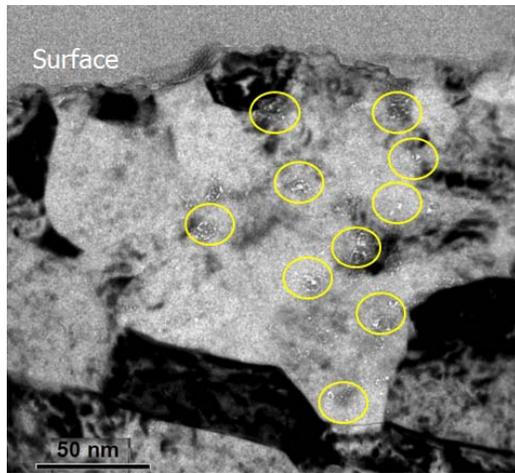

Figure 6. Aluminum side TEM image of the pressure-bonded part on an alumel surface.

Many white minute aluminum oxides were found in crystal grains of aluminum thin wire. Voids were also found, though these were too small to identify, not only at the surface but also inside grains. The might be have formed from sudden plastic deformation [11].
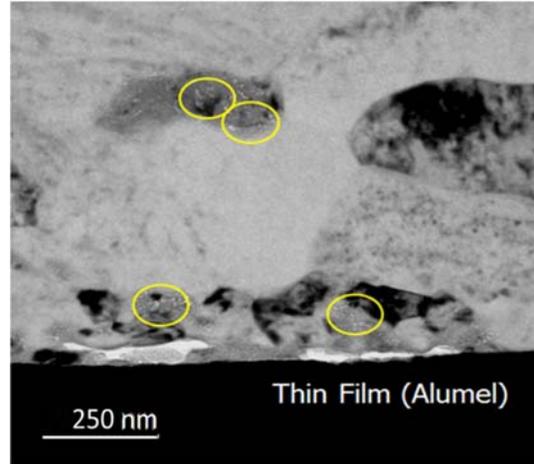

Figure 7. Alumel side TEM image of the pressure-bonded part on an alumel surface.

Figure 7 shows the TEM image of the alumel side of pressure bonding on the alumel surface.

Cavities (white color) with width less than 100 nm were found at the interface with thin film alumel, but close bonding between aluminum thin wire and alumel without any inclusions was confirmed in many interfaces.

Figure 8(A) is a TEM image of unused aluminum thin wire. There are no cavities or gaps at the interface as in Fig. 6. Moreover, the oxide film forms a layer at the surface. This means that ultrasonic bonding formed the cavities and gaps. Figure 8(B) is a TEM image of unused thin film alumel. An oxide film was observed, albeit thinner than that in Fig. 8(A).
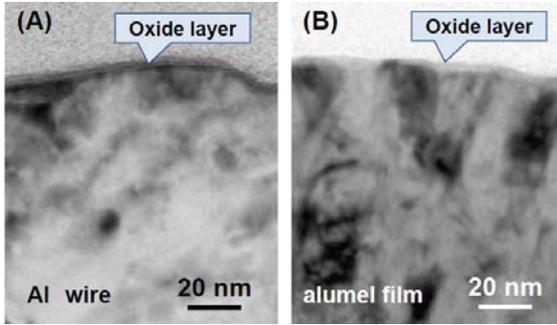
Figure 8. Cross-sectional TEM images of Al wire (A) and Alumel film (B). In each case, the surface is covered by oxide layer of about 5nm thick.

TEM observations were conducted similarly for bonded regions on a chromel surface. A metal structure similar to Figs. 6 and 7 was found for both aluminum and thin film chromel sides. Figure 9 shows the chromel side TEM image of the pressure-bonded part on a chromel surface.

The above indicates that aluminum and chromel directly bond at many locations as the number of voids decrease, though porous aluminum oxide film still exists at the bonding interface.
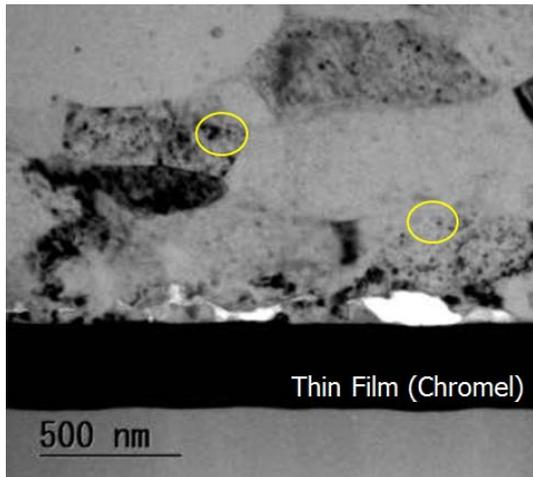

Figure 9. TEM image of a pressure-bonded chromel part. Yellow rings indicate cavities.

Therefore, bonded aluminum thin wire was forcibly peeled off to confirm whether bonding was sufficient.
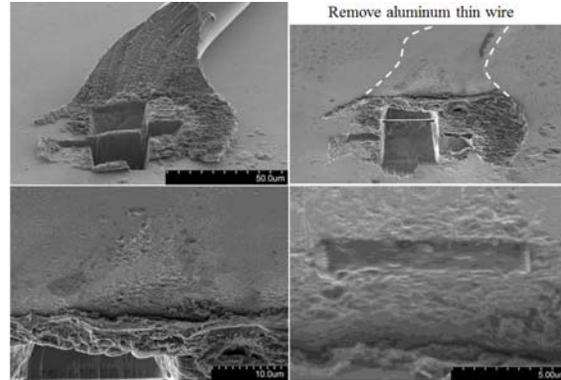

Figure 10. FIB machined specimen of region just below an alumel surface where pressure-bonded aluminum thin wire was removed.

Figure 10 is a TEM observation of just below an alumel surface where pressure-bonded aluminum thin wire was forcibly removed using tweezers. Figure 11 shows a cross-section of the structure near the surface where aluminum wire was forcibly removed.
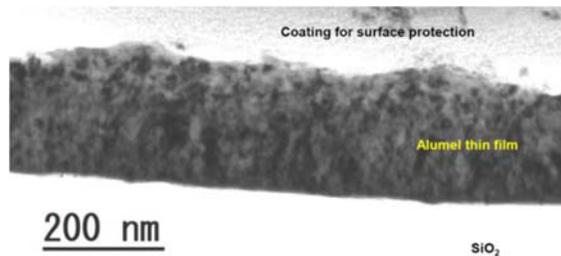

Figure 11. TEM image of region just below an alumel surface where bonded aluminum thin wire was removed.

Peeling occurs inside the alumel layer and not at the interface, which means that the bonding strength at the interface is very large. The ultrasonic power under normal conditions is higher, thus the alumel

film strength may be relatively weak. However, there was no significant change in the alumel thin film.

EXPERIMENTAL RESULTS (Weak Condition)

Figure 12 shows SEM images of the pressure-bonded region on an alumel thin film sensor.
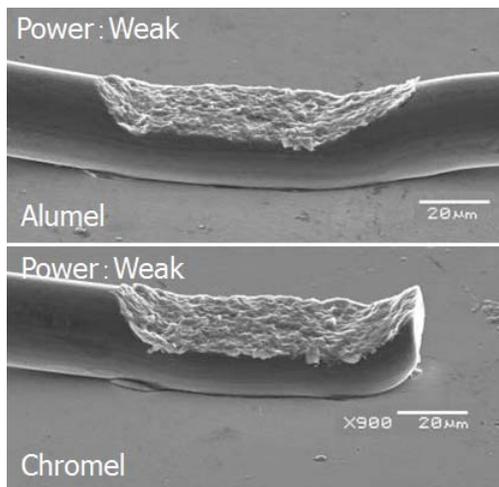

Figure 12. SEM image of bonded region on alumel and chromel.

Only half of aluminum wire deformed at the bonding region, which is different from the normal conditions in Fig. 4. No rubbing marks on the sensor surface were found unlike under the normal conditions. Under weak conditions, as was also the case under normal conditions, there was no change in surface deformation between alumel and chromel surfaces.

A TEM specimen was cut out from the half-deformed center of the pressure-bonded part using a FIB.
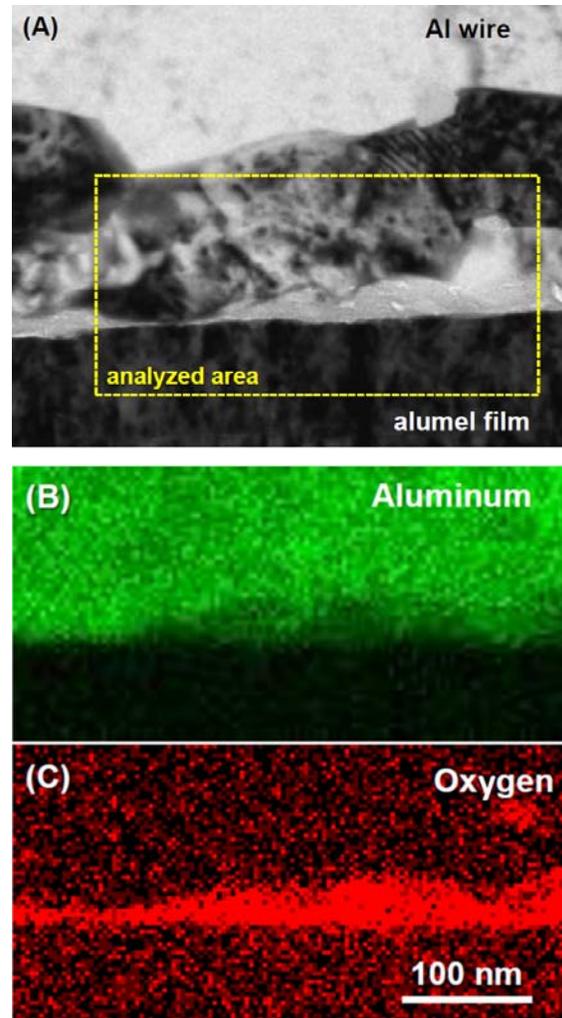

Figure 13. Alumel side TEM image of the pressure-bonded part on an alumel surface and EDS analysis results.

Fig. 13 shows a TEM image of the alumel side of a pressure-bonded part on an alumel surface as well as energy dispersive X-ray spectrometry analysis results. An oxide film with thickness 1~100 nm formed over the entire interface with alumel on the thin film. Moreover, numerous minutes objects, which could be oxides containing void, were found nearby Al crystals.

The weak conditions had only half of the power of the normal conditions, but the aluminum thin wire appeared to be pressure-bonded. However, the cross-section structure image from TEM shows that the

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interface consisted of many voids and aluminum oxide layers, and there were very few locations where alumel of the thin film and aluminum came into direct contact.

Very interestingly, the aluminum oxide layer was much thicker than the intrinsic oxide film of the aluminum wire and had a porous structure that contained a lot of nanosize cavities. This indicates that oxygen in air reacts with aluminum under ultrasound processing to form aluminum oxide and that atom vacancies, which are generated by vibration from ultrasound, come together to form cavities.
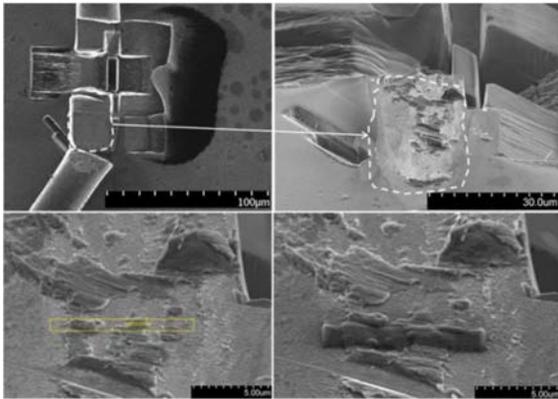

Figure 14. FIB machined specimen of region just below a chromel surface where pressure-bonded aluminum thin wire was removed.

Therefore, aluminum thin wire that was bonded was forcibly peeled off to confirm whether bonding was sufficient. Fig. 14 is a TEM observation of the chromel side where pressure-bonded aluminum thin wire was forcibly removed using tweezers.

Figure 15 is a TEM observation of just below the chromel surface where the aluminum thin wire was forcibly removed.
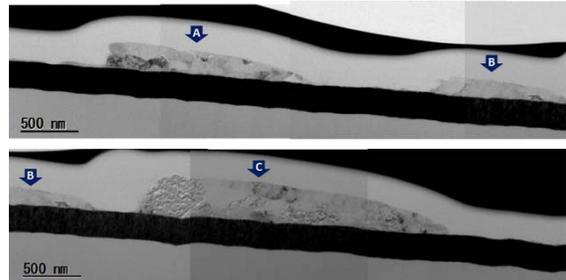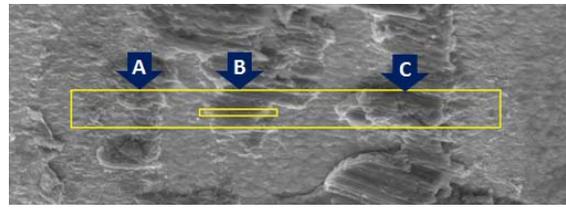

Figure 15. TEM image of region just below a chromel surface where bonded aluminum thin wire was removed.

Delamination cracks propagate mainly through the porous oxide layer or the aluminum wire, thus the aluminum wire/ aluminum oxide layer and alumel film/ aluminum oxide layers are not fragile at all. The strength of porous oxide film is thought to determine the bonding strength.

Figure 16 shows a TEM image of region C. The effect of ultrasonic processing is not limited to the interface but can be also found on the inside far from the interface.

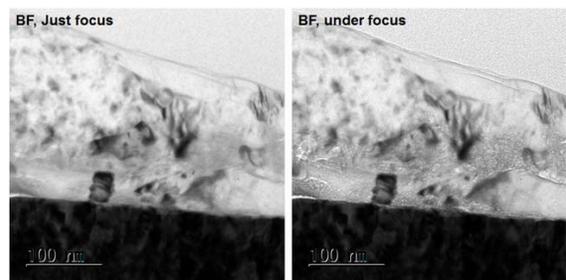Minute cavities and slightly large aluminum oxide particles are newly generated.

Figure 16. TEM image of region C.

These findings suggest that penetration and diffusion of oxygen is active and atomic voids generate in aluminum crystals under ultrasound load.

SUMMARY

The following changes in structure and morphology happen in aluminum wire after ultrasonic bonding.

① The oxide film at the surface and interface thickens and the internal structure becomes porous.

② Nanosize cavities and aluminum oxide particles form inside aluminum wire under normal conditions.

CONCLUSIONS

At the bonding interface under normal conditions, the oxide film between aluminum thin wire and alumel or chromel thin film disappeared and the points of direct contact increased, suggesting that high bonding strength was maintained. Indeed, cracks that formed after forcibly removing aluminum wire only propagated in the alumel or chromel thin film, and the interface did not separate.

The bonding interface under weak conditions contained a porous aluminum oxide film that grew much thicker compared to the intrinsic oxide film, and there were many cavities that did not contribute to the bonding. The delamination at the interface mostly propagated through the aluminum oxide layer, and it is thought that the mechanical strength of this layer determined the bonding strength.

The above indicates that, even under conditions where the oxide film is not removed, pressure-bonding can be performed by carefully utilizing minute unevenness of surface roughness to grow the aluminum oxide layer and increase bonding strength.

We will investigate and uncover these mechanisms by, for example, looking into the possibility of atom vacancy formation through plastic deformation and very fast deformation.

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