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Reliability Assessment of Flip-Chip Assembly of Al Bumps

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Abstract —**This article reports on a flip-chip bonding technology using an Al bump at high temperatures, such as for SiC semiconductors. In recent years, double-sided mounting structures have been proposed for purposes of miniaturization and low inductance. The surface-mounting method requires durability against high temperatures. We propose a new technique for the flip-chip bonding of an Al bump made from bonding wire. The recrystallization temperature of Al is under 250°C. As a result, there is an expectation of mitigating mechanical stress between the chip and the bonded substrate. We conducted a high-temperature aging test at 250°C for 3,000 h and a thermal shock test between −40°C and 250°C for 3,000 cycles. Results indicate that the shear strength of the Al bump meets the requirements specified in the IEC60749-19 guideline up to 2,000 cycles at room temperature.**

Keywords —**Al wire, bump, flip-chip, SiC, recrystallization**

Introduction

In recent years, against the backdrop of global warming and the rise in oil prices, energy awareness has also increased. In line with this, various companies have developed energy-saving products, such as air conditioners, with inverters. Up until now, Si power semiconductors have been used for the main circuits of these inverters for driving motors; however, for realizing lower loss, the application of SiC power semiconductors has been considered.

SiC power semiconductors can operate with a low loss at a temperature of 150°C or more, where Si power semiconductors cannot operate. By utilizing this feature, as shown in [1], when an inverter is constructed upon setting the junction temperature to 200°C or more, a temperature difference develops between the junction and ambient, and efficient radiation is obtained, so that the cooling system that occupies a large volume in the inverter can be downsized. Further, SiC power semiconductors are capable of operating at high frequencies at which Si power semiconductors cannot operate, so that a filter capacitor necessary for an inverter becomes low in capacitance, and accordingly, the system can be downsized.

However, to utilize the advantages described above, low-inductance mounting compatible with high temperature is necessary to reduce ringing and switching surges. In [2], double-sided mounting is considered. However, the mounting method described in that study uses expensive Au for chip bonding, and this poses a problem in mass production.

We propose bonding an Al bump as a method for bonding the surface of a semiconductor chip for double-sided mounting. In this study, by using general equipment, bumps are prepared, and flip-chip bonding is performed by using ultrasonic bonding. With this method, dry processes at room temperatures can be realized in both the bump formation process and the flip-chip process. This article advances our previous reliability test [3], and we obtained bonding reliability test results after 3,000 cycles of thermal shock test in air from −40 to 250°C, and thermal aging at 250°C for 3,000 h.

Experiment Methods

A. Sample Structure and Preparation Method

The Al wire used for forming bumps in this experiment had a diameter of 200 μm. According to Tanisawa et al.[4], the material bonded by ultrasonic bonding was confirmed to be recrystallized at 250°C for 30 min. For the chips, a 4 × 4-mm^2 Si dummy chip was used for the shear strength test, and a SiC-Schottky barrier diode (SBD) (back-scattered electron) was used for the electrical test. The substrate to which a chip with bumps was flip-chip bonded was a Si_3N_4 ceramic with an Au- and Ni-plated copper wiring board. Details of the components are shown in Table I. Fig. 1 shows photographs after bump formation and after flip-chip bonding. Target positions on the chip at which the bumps were to be formed were 300 μm along the horizontal axis and 510 μm inward along the vertical axis from the edges of the sample used for shear strength measurement (Fig. 1a). For the sample used for electrical characteristic measurements, target positions were 600 μm along the horizontal axis and 771 μm inward along the vertical axis from the edges of the sample. During flip-chip bonding, the ultrasonic wave application direction was oscillated in the bump long-side direction in Fig. 1a unless otherwise stated. The bumps were formed so that the orientations of all four bumps were the same. The clearance between the substrate and the chip after flip-chip bonding shown in Fig. 1d was 78 μm on average in the sample for strength measurement. Hereinafter, the vertical direction of Fig. 1a is referred to as the long-side

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Table I
Components

	Maker	Specifications
Al wire	Tanaka Kikinzoku Handbai K.K.	TANW φ 200 um
Ceramics	Hitachi Metals, Ltd.	Base material: Si_3N_4 ceramics (0.3 mm) Substrate wiring: oxygen-free copper foil plated with electroless nickel phosphorus (5 μm) and Au (0.5 μm)
Dummy chip	Shiima Electronics Inc.	Si wafer, chip size: 4.0×4.0 mm^2 Thickness: 365 μm Chip face metallization: Al-Cu0.5 (1 μm)
Chip	Semisouth Laboratories, Inc.	SiC-SBD, chip size: 3.8×3.8 mm^2 Thickness: 368 μm, anode metallization: Al (3 μm) Cathode metallization: Ni/Ag (1.1 μm)

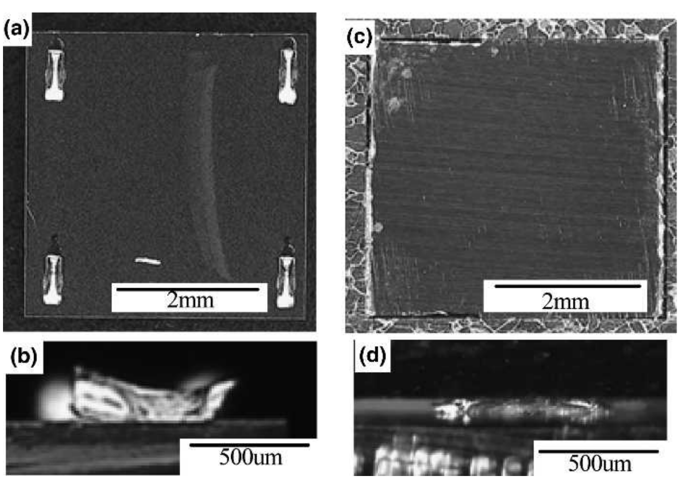

Fig. 1. Photographs of the formed Al bumps and after flip-chip bonding: (a) image of the chip face with Al bumps, (b) lateral image of the Al bump with bump forming, (c) back-side image of the chip after flip-chip bonding, and (d) lateral image of the bump after flip-chip bonding.

direction, and the horizontal direction is referred to as the short-side direction.

B. Reliability Test Method

The conducted reliability test includes a high-temperature aging test and a thermal shock test. The samples used in the experiment were subjected to a shear test and an electrical resistance measurement. In these tests, the number of samples used was four unless otherwise stated, and average values are shown as results.

For the high-temperature aging test, the samples were held at 250°C in the atmosphere. For the thermal shock test, each cycle was set to 30 min in which the samples were held at 250°C for 18 min and −40°C for 12 min, as shown in Fig. 2.

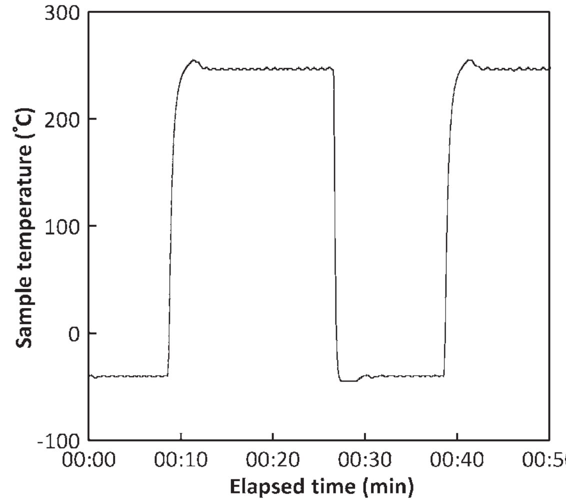

Fig. 2. Sample temperature recorded during one cycle of a thermal shock test from −40°C to 250°C.

C. Shear Strength Measuring Method

For the bonding strength test, a shear test was applied from the short-side direction so that the chip conformed to IEC 60749-19. After flip-chip bonding, the projected area of the four Al bumps on the substrate was 0.94 mm^2. The IEC shear strength standard is 6.1 MPa in the case of our samples. In this study, this value is set as a reliability threshold. This value is used because although the IEC shear strength standard is for a die attach material for chip bonding, the object that we compared our method with is a die attach material as described in [2], and there is no general standard for flip-chip bonding using bumps. The result of the shear test is the average shear strength of the four samples. Except for the results at the high-temperature state described in section High-temperature shear test, the shear tests were conducted at room temperature.

D. Electrical Characteristics Measuring Method

A sample that had bumps formed on SiC-SBD and subjected to flip-chip bonding was used for a forward-direction resistance measurement. The four-terminal method was used as the measuring method, and the measurements were performed by connecting the needles of one side to the electrode on the backside of the chip; the needles of the other side were connected to the substrate portion to which the chip was flip-chip bonded. In this measurement method, the resistance of the Al bump and the conductive resistance of SBD are measured. In the measurement results, resistance changes caused by the high-temperature aging and thermal shock tests were noted on defining the electrical resistivity after flip-chip bonding as 100%.

Results and Discussion

A. High-Temperature Exposure Test

The sample was aged at 250°C for 3,000 h, and the measurement results of the shear strength and electrical resistance change at each time are shown in Fig. 3. A sharp rise in shear strength was observed after 20 h of the high-temperature aging. Thereafter, high strength was maintained, and had a margin of

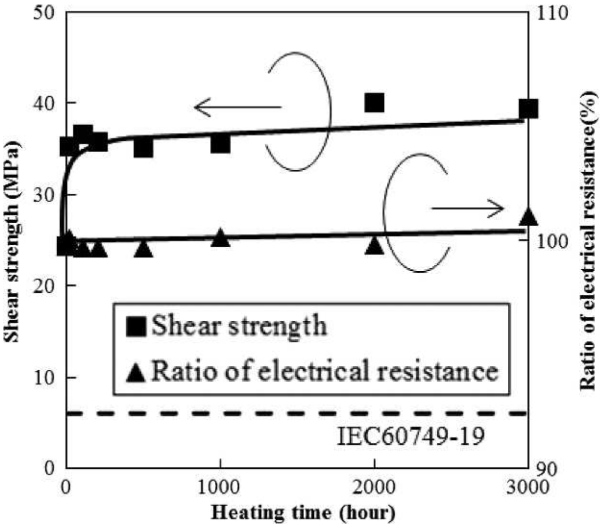

Fig. 3. Shifts of shear strength and relative electrical resistance by heat treatment.

6.5 times the IEC standard after 3,000 h. The electrical resistance did not change more than 5% even after 3,000 h, so the high-temperature aging test was not a problem for reliability.

Next, a shear test was conducted using samples in the initial state and after being exposed to 250°C for 20 h. Bump angles left on the substrate looking upward from the substrate and cross-sectional images of the bumps are shown in Fig. 4.

Concerning the direction of the shear test, the chip was pushed from right to left with respect to the photographs in Figs. 4a and 4c. The results of the bump cross sections along the white lines shown in Figs. 4a and 4c are shown in Figs. 4b and 4d. When the sample in the initial state was subjected to the shear test, little bump deformation was observed and most of the ruptures occurred at the chip bonding interface as shown in Figs. 4a and 4b. On the other hand, after the sample was exposed to 250°C for 20 h, as shown in Figs. 4c and 4d, the bumps were deformed by being pulled by the chip bonding portion, and most of the ruptures did not occur at the chip bonding interface, but were inside bulk breakages that caused

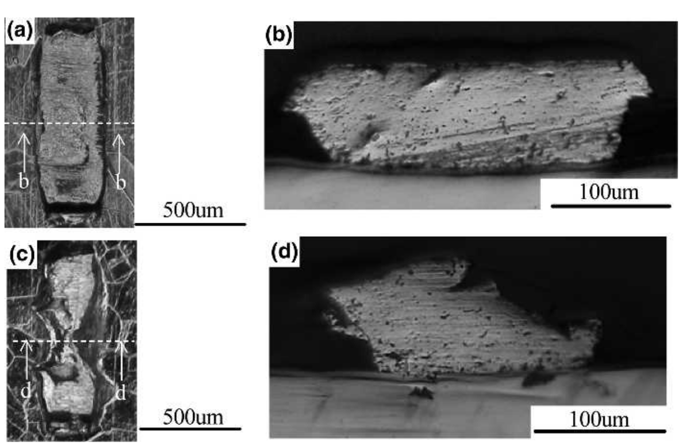

Fig. 4. Photographs of the left bump after the shear test: (a) and (b) the sample when the heat treatment was not applied; and (c) and (d) the sample after the heat treatment was applied at 250°C for 20 h. (a) and (c) are top views and (b) and (d) are cross-sectional views of the bump.

Al bump pieces to remain on both the chip side and the substrate side. The four bumps were deformed in the same manner, so it is judged that all four bumps had been bonded. This rupture tendency was also observed in the sample aged at 250°C for 3,000 h.

Fig. 5 shows bump cross-sectional SEM (BSE [back-scattered electron]) images in the initial state and after aged at 250°C for 20 h. The upper side of the image shows the chip and the lower side shows the substrate. The position of the cross section was set to pass through the chip side of the bump. The crystal grain size of the bump is small as a whole and mainly several micrometers in the initial state as shown in Figs. 5a and 5b.

However, after aged at 250°C for 20 h, the grain size is increased to approximately 38 μm on average. Generally, in the relationship between the crystal grain size and yield stress, the smaller the grain size, the higher the yield stress as shown in the Hall-Petch relationship [5]. In the experiment [4] of the Al wire using a wire made of the same material as that of the bumps, a tendency was observed for the rupture strength to decrease as the grain size increased. However, the results of this experiment were contradictory; the sample that was aged at 250°C and exhibited increased grain size, had higher shear strength.

To clarify the phenomenon, the following experiment was conducted. The sample was prepared in the same way as in the other tests. First, samples in initial state and after being aged at 250°C for 100 h were prepared. Then, one of the four bumps was scraped off so as not to affect the other bumps, and a shear test was conducted. The shear strength was compared with the result of same heat treatment sample with four bumps, as shown in Fig. 6.

The shear strength of the sample in the initial state was reduced by 9.8% by reducing one bump. On the other hand, the shear strength of the sample after being aged at 250°C for 100 h was reduced by 20.9% by reducing one bump. It is considered that if the stress of the shear test is uniformly applied to the four bumps, in the case where one bump is eliminated, the strength would decrease by approximately 25%. However, the reduction in shear strength in the initial state differed from this estimate. On the other hand, the sample after being exposed to 250°C for 100 h decreased in strength to the same level as the estimated value. The study in [6] shows that the ductility is lower in the work-hardened state than in the recrystallized state. The study in [7] shows that the bonding process causes work-hardening in the material of the bump. Namely, the sample in the initial state is broken before the stress of the shear test is uniformly applied to the bumps, because in the initial state, the ductility is reduced by ultrasonic bonding at the time of bump formation and flip-chip bonding. Because of the recovery in ductility, the sample after heat treatment is broken after the stress of the shear test is uniformly applied to the bumps. Thus, when viewed as the shear strength of the chip, it appears that the strength of the sample is higher after heat treatment than in the initial state.

B. Thermal Shock Test

Fig. 7 shows changes in shear strength and electrical resistance in each cycle obtained through a thermal shock test for

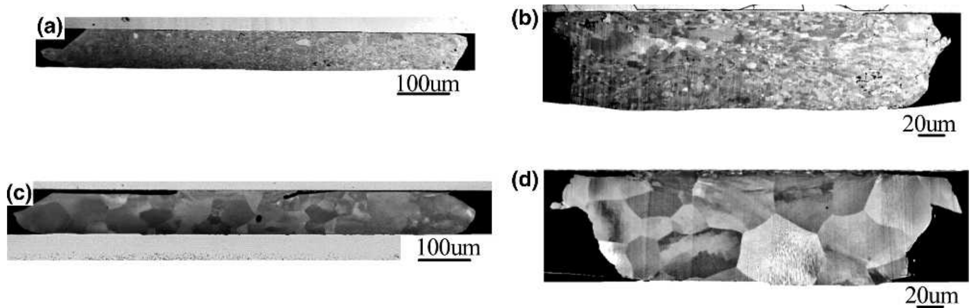

Fig. 5. Cross-sectional SEM (BSE) images of the Al bumps: (a) and (b) the sample when the heat treatment was not applied; and (c) and (d) the sample after the heat treatment was applied at 250°C for 20 h.

3,000 cycles. For the test samples used in this test, two kinds of samples were prepared to confirm whether the reliability differed depending on the ultrasonic wave application direction during flip-chip bonding. A sample to which ultrasonic waves oscillating in the long-side direction were applied is referred to as type A, and a sample to which ultrasonic waves oscillating in the short-side direction were applied is referred to as type B. Test results of type B were obtained only in the initial state and after 500 cycles.

Regarding the shear strength, the strength of type A showed a tendency to increase once to be higher than in the initial state; however, the strength decreased as the number of cycles increased, and fell to almost the same value as the initial strength in the 500th cycle. Thereafter, as shown in Fig. 7, the strength decreased almost linearly until the 1,500th cycle. The margin in the 1,500th cycle with respect to the standard IEC is 1.5 times. However, after that, the tendency of strength reduction changed to a gradual decline until the 3,000th cycle. After 3,000 cycles, the strength was found to fall below the IEC standard.

Although test results of type B were obtained only in the initial state and after 500 cycles, after 500 cycles, the strength also reached almost the same value as the initial strength, and the strength of type B differed by 2.2% in the initial state and differed by 9.7% after 500 cycles from those of type A, and these are considered to be substantially within the margin of error; thus, there were no differences depending on the ultrasonic wave application direction.

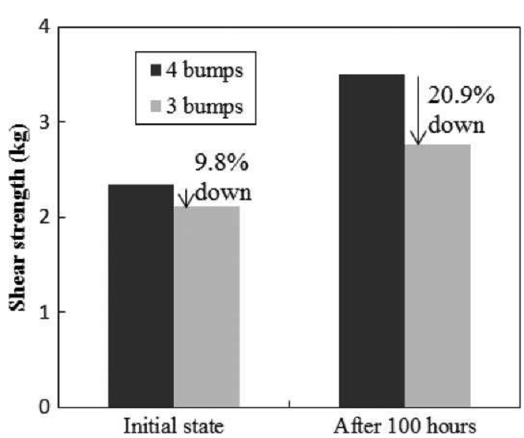

Fig. 6. Difference in shear strength caused by the number of bumps in the sample and by the heat treatment.

Most of the ruptures of type A occurring in the shear test were bulk breakages around the chip bonding portion until the 500th cycle as in Figs. 4c and 4d; however, as the number of cycles increased, large deformation as shown in Fig. 4c was not observed although the positions of the ruptures did not change. In addition, a rupture that caused the bump to halve in the long-side direction and remain on the chip side and the substrate side was also occasionally observed. On the other hand, in the case of type B, most of the ruptures were also bulk breakages as shown in Fig. 4c; however, a tendency that the rupture reached the substrate-side bonding portion was occasionally observed although these are the results until the 500th cycle. The changes in electrical resistance of type A and type B were not more than 5%, so we judge that the changes do not pose a problem in reliability.

Fig. 8 shows bump cross-sectional SEM (BSE) images in the long-side direction and the short-side direction after 500 cycles, 1,000 cycles, and 2,000 cycles of the thermal shock test of type A. In the images, the layout is set so that the chip is on the upper side and the substrate is on the lower side. The symbols in the "Location of Al bump" column to the left of the images correspond to the symbols of the bumps shown in Fig. 8a, and the observation direction is that of viewing the bump from the

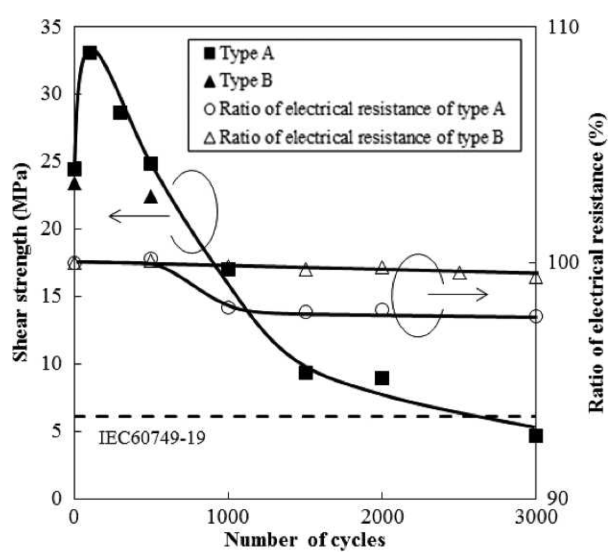

Fig. 7. Shifts of pull strength and relative electrical resistance on the number of thermal cycles.

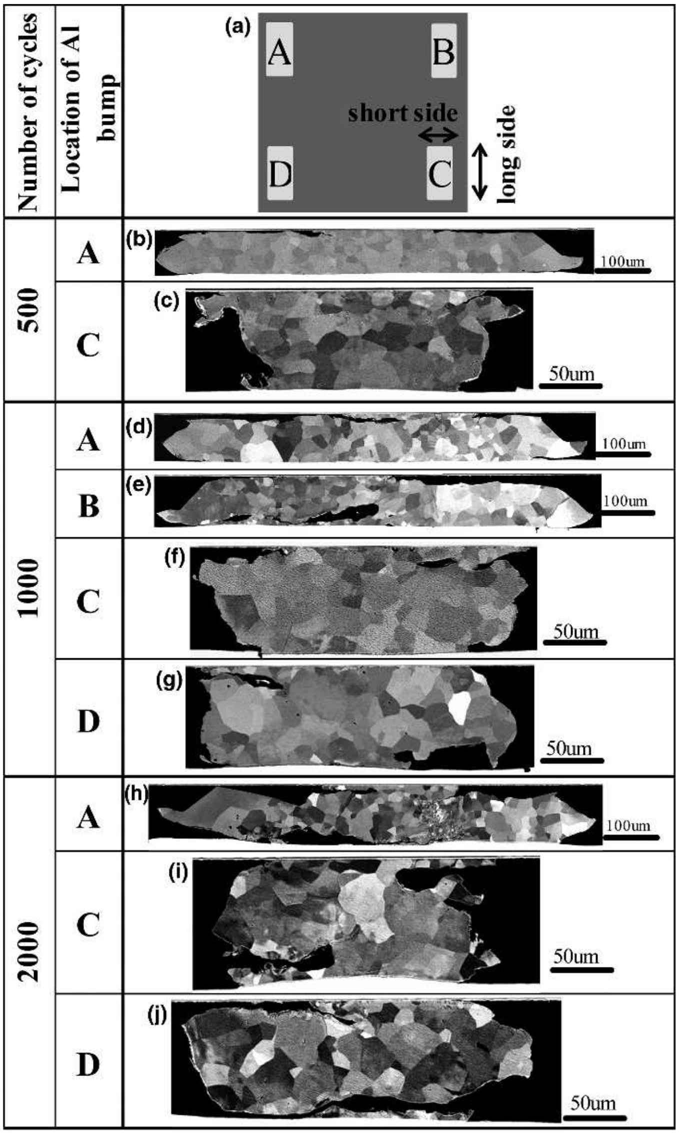

Fig. 8. Cross-sectional SEM (BSE) images of the Al bump vs. the number of thermal cycles: (a) shows the Al bump location, (b), (d), (e), and (h) are the long sides of the bump, and (c), (f), (g), (i), and (j) are the short sides.

outside of the chip. The cross section position was set so as to pass through the center of the chip bonding portion.

After 500 cycles, the grain size is larger than in the initial state shown in Figs. 5a and 5b. In both Figs. 8b and 8c, cracking occurs at a position outside the chip on the chip bonding surface side.

On observing the bumps after 1,000 cycles, grown cracks were found; besides this, large deformation from the original shape is observed in Figs. 8e and 8g. Characteristically, the bump shown in Fig. 8g is deformed so as to collapse inside the chip. However, the findings show that all four bumps are bonded.

After 2,000 cycles, deformation of the short side of the bump further increased, and in Figs. 8i and 8j, the bumps have shapes collapsing inside the chip. In addition, in Fig. 8j, the bump ruptures. In Fig. 8h, the bonding portion on the substrate side peels halfway, and a partial crack growth and a dappled pattern are observed because of the fine grain size and dislocation near the tip end of the grown crack.

The results of this observation show that, as shown in Figs. 8g, 8i, and 8j, the short side of the bump is deformed so as to collapse inside the chip, and this becomes pronounced as the number of cycle increases. It is considered that the recrystallization temperature of the Al bump material is not more than 250°C and the strength decreases as temperature increases [4], so that the material itself is very soft at a temperature around 250°C, and the stress is used to deform the entire bump, and stress concentration at one point like cracking is suppressed. Enomoto and Sato[8] explain that if the elongation of the bump material is small, peeling is observed in an early cycle of the thermal shock test, and when a material with good elongation is used, life in the thermal shock extends, and the deformation is similar to the bump deformation in the short-side direction, as seen from the results of the experiment described above. Therefore, softness of the Al bump material makes it harder for the bumps to rupture, so it can be said that the results of the experiment are satisfactory.

Results in Fig. 7 can be explained that the reason the shear strength increased at the beginning is because the recovery of ductility caused by recrystallization and crack growth. The reason for strength reduction after that is because the stress generated by the thermal shock changed as evidenced some bumps being ruptured were observed in the 2,000th cycle.

C. High-Temperature Shear Test

Fig. 9 shows the measurement results of the shear strengths in high temperature up to 250°C for samples extracted in the initial state, 1,000th cycle, and 2,000th cycle of the thermal shock test. The findings show that the shear strength decreases as the temperature rises. This trend is also observed with the Al wire using the same material as described in [4], so that this is regarded as a general tendency of this material. The sample in the initial state has a margin of 2.4 times IEC 60749-19 at 250°C. The shear strength tested at 250°C of the sample extracted in the 1,000th cycle is the same as specified in the standard IEC. In the case of the samples in the 2,000th cycle,

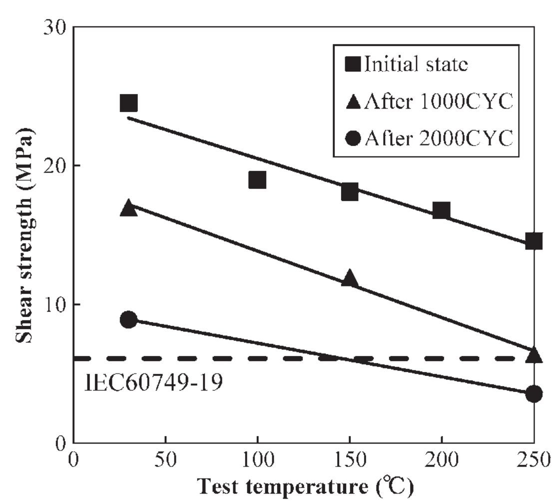

Fig. 9. Dependence of the shear strength of a sample without heat treatment on high temperature.

the strength satisfied the standard IEC at room temperature, but was below the standard IEC at 250°C.

Conclusions

The results of this experiment show that flip-chip bonding of Al bumps using Al wire satisfied the IEC 60749-19 guidelines up to 2000 cycles of the thermal shock test at temperatures of −40°C to 250°C, including exposure to 250°C for 3,000 h. Even when the high-temperature shear strength at 250°C is taken into consideration, flip-chip bonding satisfies the IEC standard up to 1,000 cycles. There was no difference in strength depending on the ultrasonic wave application direction during flip-chip bonding until the 500th cycle. In the initial state, work-hardening was strongly applied, so that at the time of shear test the concentration of the stress occurred and the shear strength became low; however, the findings show that the shear strength could be improved by annealing. The findings also show that because of the softness of the Al bump material, little stress concentration occurred in the short-side direction, and deformation of the entire bump made it harder for the bump to rupture. The electrical resistance change was within 5%, and this is considered a level that poses no problem in use. Therefore, the Al bump is a technique capable of securing constant reliability in the temperature range from −40°C to 250°C.

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