Reliability Assessment of Flip-chip Assembly of Al Bumps

Hidekazu TANISAWA[*1,2], Kohei HIYAMA[*1,3], Takeshi ANZAI[*1,4], Hiroki TAKAHASHI[*1,5], Yoshinori MURAKAMI[*1,6], Shinji SATO[*1,2], Kinuyo WATANABE [*1], Fumiki KATO[*1,7], Hiroshi SATO[*1,7]
[*1]FUPET, [*2]Sanken Electric Co., Ltd., [*3]TOSHIBA CORPORATION, [*4]Calsonic Kansei Corporation, [*5]FUJI ELECTRIC CO., LTD., [*6]NISSAN MOTOR CO.,LTD., [*7]National Institute of Advanced Industrial Science and Technology
Address
Tsukuba Central 2, 1-1-1, Umezono, Tsukuba, Ibaraki 305-8568 Japan
Phone/Fax: +81- (0) 29-861-5698
Email: h-tanisawa@fupet.or.jp

Abstract

This paper reports on a flip-chip bonding technology using an aluminum bump at high temperatures, such as for SiC semiconductors. In recent years, double-sided mounting structures have been proposed for the purposes of miniaturization and low inductance. The surface mounting method requires durability to withstand high temperatures. We propose a new technique for the flip-chip bonding of an Al bump made from bonding wire. The recrystallization temperature of aluminum is under 250 °C. As a result, there is an expectation of mitigating mechanical stress between the chip and bonded substrate. A high-temperature exposure test at 250 °C for 3000 hours and a thermal-cycle test between -40 and 250 °C for 3000 cycles have been executed. Results indicate that shear strength of the Al bump meets the requirements set forth in the IEC60749-19 guideline until 2000 cycles at room temperature.

Key words

Al wire, Bump, Flip-chip, SiC, recrystallization

I. 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 released 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, 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 at which Si power semiconductors cannot operate. By utilizing this feature, as shown in Reference [1] , when an inverters is constructed upon setting the junction temperature to 200 °C or more, the junction temperature difference from the ambient temperature occurs, 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 capacity, and accordingly, the system can be downsized.

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

We propose bonding of an Al bump as a method for bonding a surface of a semiconductor chip for double-sided mounting. In this proposal, 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 of the bump formation process and the flip-chip process. This paper advances our previous reliability test [3] publication and we obtained bonding reliability test results after 3000 cycles of an air layer thermal cycle test at -40 to 250 °C including exposure to 250 °C for 3000 hours.

II. Experiment method

A. Sample structure and preparing method

The Al wire used for forming bumps in this experiment had a diameter of 200 μm and its recrystallization temperature was 250 °C or less. As chips, a 4mm-square Si dummy chip was used for the shear strength test, and a SiC-SBD was used for the electrical test. The substrate to which a chip with bumps was flip-chip bonded had a substrate portion made of Si3N4 ceramics and a copper wiring board with Au and Ni plating on the substrate portion. Details of the components are shown in Table 1. 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 a sample for shear strength measurement in the image of Fig. 1(a). In the case of the sample for electrical characteristics measurement, 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. 1(a) 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. 1(d) was 78 μm on average in the sample for strength measurement. Hereinafter, the direction of the bump in the vertical direction of Fig. 1(a) is referred to as a long-side direction, and the direction in the horizontal direction is referred to as a short-side direction.

B. Reliability test method

The conducted reliability test includes a high-temperature exposure test and a thermal cycle test. The samples subjected to the above-described 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.

As a high-temperature exposure test, the samples were held at 250 °C in the atmosphere. As a thermal cycle test, one cycle was set to 30 minutes in which the samples were held at 250 °C for 18 minutes and -40 °C for 12 minutes.

Table 1 Components

	Maker	Specifications
Al Wire	Tanaka Kikinzoku Handbai K.K.	TANW φ 200 um
Ceramics	Hitachi Metals, Ltd.	Base material: Si3N4 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)

C. Shear strength measuring method

As a bonding strength test, a shear test was applied from the short-side direction so that the chip conformed to IEC 60749-19. The standard IEC includes a shear strength standard, and is 6.1 MPa in the case of our samples. In this paper, this value is set as a reliability threshold. The reason why this value is used is that although the standard IEC is a standard of the shear strength of a die attach material for chip bonding, the object with which the method we developed this time is compared is a die attach material as shown in Reference [2] and there is no general standard of flip-chip bonding using bumps.

D. Electrical characteristics measuring method

A sample that had bumps formed on SiC-SBD and was 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 measurement was performed by dropping the needles of one side to the chip back-side electrode and the needles of the other side to the substrate portion to which the chip was flip-chip bonded. In this measuring method, the resistance of the Al bump and the conductive resistance of SBD are measured. As measurement results, resistance changes caused by high-temperature exposure and thermal cycle tests were noted upon defining the electrical resistivity after flip-chip bonding as 100 %.

III. Results and discussions

E. High-temperature exposure test

The sample was exposed to 250 °C for 3000 hours, and

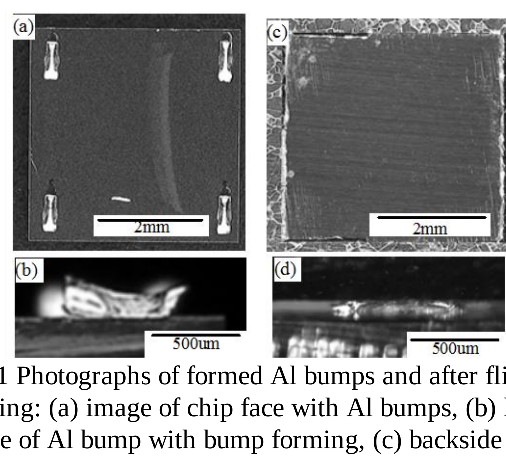

Fig. 1 Photographs of formed Al bumps and after flip-chip bonding: (a) image of chip face with Al bumps, (b) lateral image of Al bump with bump forming, (c) backside image of chip after flip-chip bonding and (d) lateral image of the bump after flip-chip bonding.

results of measurements of the shear strength and electrical resistance change at each time are shown in Fig. 2. A sharp rise in shear strength was observed after 20 hours of the high-temperature exposure. Thereafter, high strength was maintained, and had a margin of 6.5 times the standard IEC after 3000 hours. The electrical resistance did not change even by 5 % even after 3000 hours, so the high-temperature exposure test determined that reliability was not a problem.

Next, a shear test was conducted by using samples in the initial state and after being exposed to 250 °C for 20 hours, and bump angles left on the substrate looking upward from the substrate and cross-sectional images of the bumps are shown in Fig. 3.

Concerning the direction of the shear test, the chip was pushed from the right to the left with respect to the photographs of Fig. 3(a) and Fig. 3(c). The results of observation of the cross-sections of the bumps along the white lines shown in Fig. 3(a) and Fig. 3(c) are shown in Fig. 3(b) and Fig. 3(d). When the sample in the initial state was subjected to the shear test, bump deformation was hardly observed and most of the ruptures occurred at the chip bonding interface as shown in Fig. 3(a) and Fig. 3(b). On the other hand, observing the sample after being exposed to 250 °C for 20 hours, as shown in Fig. 3(c) and Fig. 3(d), the bumps were deformed by being pulled by the chip bonding portion, and most of the ruptures were not occurring at the chip bonding interface, but were inside bulk breakages that caused Al bump pieces to remain on both of the chip side and the substrate side. The four bumps were deformed in the same manner, so that it is judged that all four bumps had been bonded. This rupture tendency was also observed in the sample exposed to 250 °C for 3000 hours.

Fig. 4 shows bump cross-sectional SEM images in the initial state and after exposure to 250 °C for 20 hours before a shear test. 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 bonding center 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 Fig. 4(a) and Fig. 4(b), however, after exposure to 250 °C for 20 hours, the grain size increased to approximately 38 micrometers on average. Generally, as the relationship between the crystal grain size and the yield stress, the smaller the grain size, the higher the yield stress as shown in the Hall-Petch relationship [4]. In the experiment [5] of the Al wire using a wire made of the same material as that of the bumps, a tendency for the rupture strength to lower as the grain size increased was observed. However, the results of this experiment were contradictory in which the sample exposed to 250 °C and increased in grain size had higher shear strength. Reference [6] shows that the ductibility is lower in the work-hardened state than in the recrystallized state. In these experimental samples, ultrasonic bonding was applied twice to the Al bump at the times of bump formation and flip-chip bonding, and it is considered that the samples are in the state where the bumps are entirely work-hardened and low in ductibility. Therefore, it is considered that the yield stress in the initial state was increased to be higher than that after exposure to a

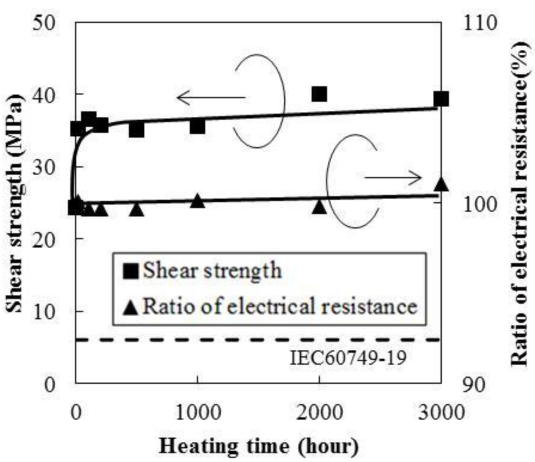

Fig. 2 Shifts of shear strength and relative electrical resistance on heat treatment.

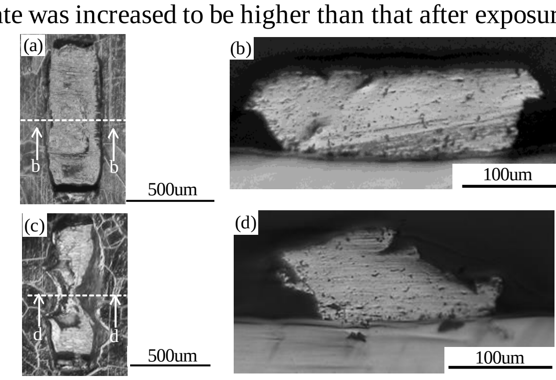

Fig. 3 Photographs of the left bump after the shear test: (a), (b) the sample when the heat treatment was not applied; and (c), (d) the sample after the heat treatment was applied at 250 °C for 20 hours. (a), (c) are top views and (b), (d) are cross sectional views of the bump.

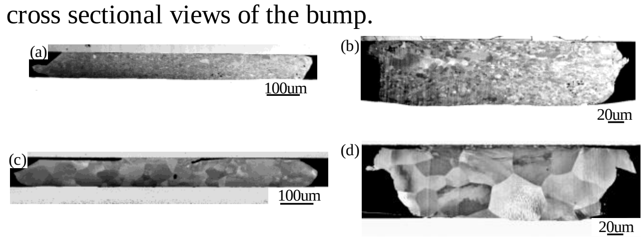

Fig. 4 Cross-sectional SEM images of the Al bumps: (a), (b) the sample when the heat treatment was not applied; and (c), (d) the sample after the heat treatment was applied at 250 °C for 20 hours. (a), (c) are of the longer sides and (b), (d) are of the shorter sides of the bump.

high temperature due to the fine grain size and work hardening, however, the stress of the shear test is not uniformly applied to the four bumps, and stress concentration partially occurs and breakage occurs from there, so that it is presumed that the peak strength in the shear test was detected to be low. In order to support this reasoning, the following experiment was conducted. A shear test was conducted in such a manner that samples in the initial state and after being exposed to 250 °C for 100 hours were prepared, and a shim tape was inserted into the clearance between the substrate and the chip and one of the bumps was eliminated by cutting so as not to affect other bumps. The results of comparison between the strength in this case and the strength in the case where the bump was not eliminated are shown in Fig. 5. The strength of the sample in the initial state was lowered by only 9.8 % even by reducing one bump. On the other hand, the strength of the sample after being exposed to 250 °C for 100 hours was lowered by 20.9 % when one bump was eliminated. 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 lowers by approximately 25 %, however, lowering in strength of the sample in the initial state significantly deviated from this, and the sample after being exposed to 250 °C for 100 hours lowered in strength to the same level as the estimated value. Therefore, in the initial state, ductibility lowered due to work hardening, so that the stress was not uniformly applied to the four bumps, and the shear strength lowered.

F. Thermal cycle test

Fig. 6 shows changes in shear strength and electrical resistance in each cycle obtained through a thermal cycle test conducted 3000 times. As 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

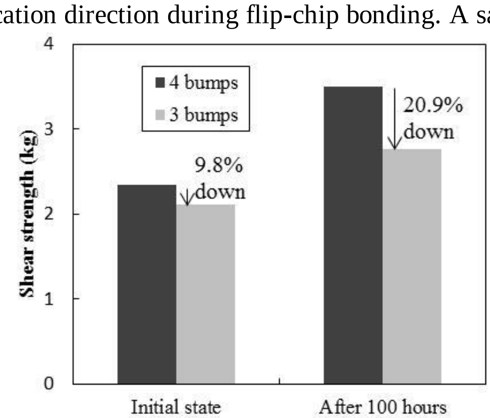

Fig. 5 Difference in shear strength caused by the number of bumps in the sample and by the heat treatment.

which ultrasonic waves oscillated in the long-side direction were applied is referred to as type A, and a sample to which ultrasonic waves oscillated in the short-side direction were applied is referred to as type B. Test results of the type B were obtained only in the initial state and after 500 cycles because of the sample.

Regarding the shear strength, the strength of the type A showed a tendency that the strength increased once to be higher than in the initial state, however, the strength lowered as the number of cycles increased, and lowered to almost the same value as the initial strength in the 500th cycle. Thereafter, as shown in the figure, the strength lowered almost linearly until the 1500th cycle. The margin in the 1500th cycle with respect to the standard IEC is 1.5 times. However, after that, the tendency of strength lowering changed to gradual strength lowering until the 3000th cycle. After 3000 cycles, the strength was found to fall below the standard IEC.

Although test results of the 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 the type B differed by 2.2 % in the initial state and differed by 9.7 % after 500 cycles from those of the type A, and these are considered to be substantially within the margin of error, and there were no differences depending on the ultrasonic wave application direction.

Most of ruptures of the type A occurring in the shear test were bulk breakages around the chip bonding portion until the 500th cycle as in Fig. 3(c) and Fig. 3(d), however, as the number of cycles increased, large deformation as shown in Fig. 3(c) 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 the type B, most

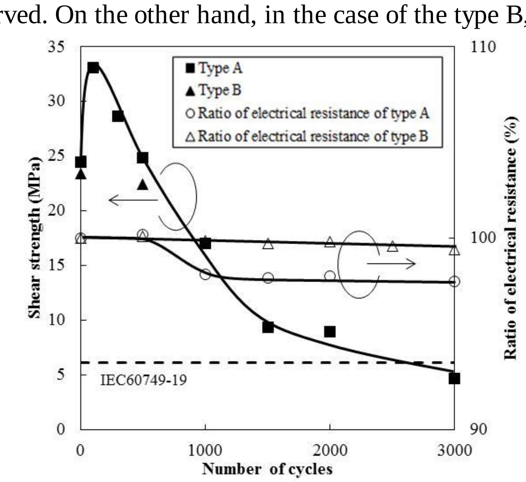

Fig. 6 Shifts of pull strength and relative electrical resistance on the number of thermal cycles.

of ruptures were also bulk breakages as shown in Fig. 3(c), 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 the type A and the type B were not more than 5 %, so we judge the changes do not pose a problem in reliability.

Fig. 7 show bump cross-sectional SEM images in the long-side direction and the short-side direction after 500 cycles, 1000 cycles, and 2000 cycles of the thermal cycle test of the 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 column of "Location of Al bump" on the left of the images correspond to the symbols of the bumps shown in Fig. 7(a), and the observation direction is a direction of viewing the bump from the outside of the chip.

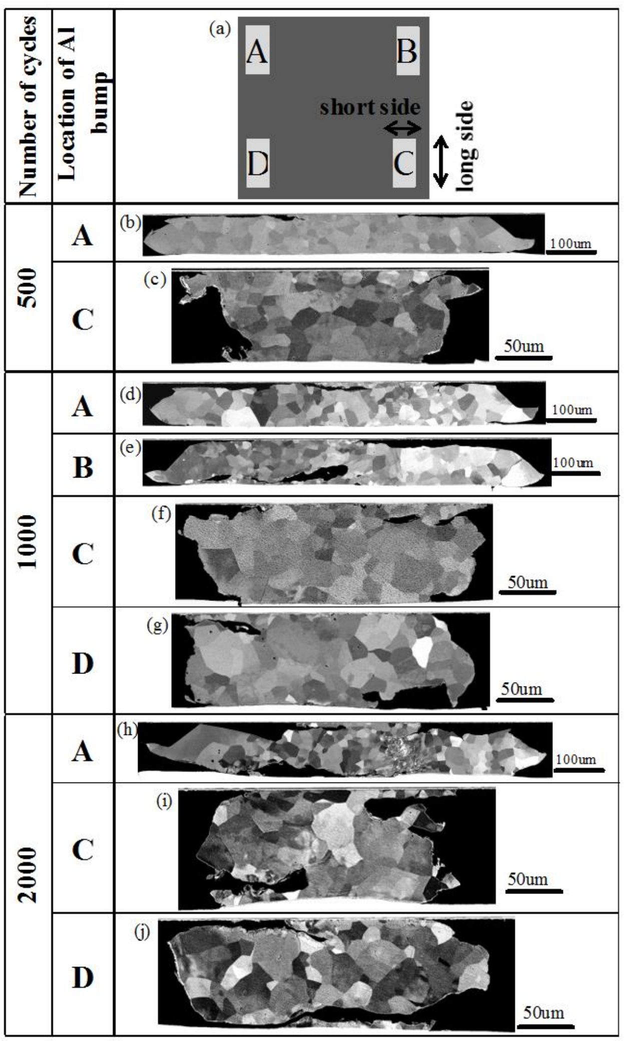

Fig. 7 Cross-sectional SEM images of the Al bump on the number of thermal cycles: (a) is image of Al bump location, (b), (d), (e), and (h) are of the long sides and (c), (f), (g), (i), and (j) are of the short sides of the bump.

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

Observing the state after 500 cycles, the findings show that the grain size is larger than in the initial state shown in Fig. 4(a) and Fig. 4(b). In both of Fig. 7(b) and Fig. 7(c), cracking occurs at a position outside the chip on the chip bonding surface side.

Observing the bumps after 1000 cycles, grown cracks are observed, and aside from this, large deformation from the original shape is observed in Fig. 7(e) and Fig. 7(g). Characteristically, the bump shown in Fig. 7(g) is deformed so as to collapse inside the chip. However, the findings show that all four bumps are bonded.

After 2000 cycles, deformation of the short side of the bump further increased, and in both of Fig. 7(i) and Fig. 7(j), the bumps have shapes collapsing inside the chip. In addition, in Fig. 7(j), the bump ruptures. In Fig. 7(h), the bonding portion on the substrate side peels halfway, and a partial crack growth and a dappled pattern due to the fine grain size and dislocation near the tip end of the grown crack are observed.

The results of this observation show that, as shown in Fig. 7(g), Fig. 7(i), and Fig. 7(j), the short side of the bump is deformed so as to collapse inside the chip, and this becomes pronounced as the number of cycles increases. It is considered that the recrystallization temperature of the Al bump material is not more than 250 °C and the strength lowers as the temperature becomes high [5], 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. Reference [7] describes that if the elongation of the bump material is small, peeling is observed in an early cycle of the thermal cycle test, and when a material with good elongation is used, life in the thermal cycles extends, and the deformation is similar to bump deformation in the short-side direction being 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.

It can be described that, from the results shown in Fig. 7, the reason why the shear strength increased once and reached the same strength as in the initial state in the 500th cycle in Fig. 6 is recovery of ductibility caused by recrystallization and crack growth. The reason why the tendency of strength lowering changed before and after the 1500th cycle is that, although all four bumps were bonded until the 1000th cycle, some bumps being ruptured were observed in the 2000th cycle, so that the stress generated by the thermal cycle changed.

G. High-temperature shear test

Fig. 8 shows the results of measurement of the shear strengths in high-temperature states up to 250 °C of samples extracted in the initial state, 1000th cycle and 2000th cycle of the thermal cycle test. The findings show that the shear strength lowers as the temperature rises. This tendency is also observed with the Al wire using the same material as described in Reference [5], 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 even at 250 °C. The shear strength of the sample extracted in the 1000th cycle reached a value 1.05 times the standard IEC at 250 °C. In the case of sample in the 2000th cycle, the strength satisfied the standard IEC at a room temperature, but was below the standard IEC at 250 °C.

IV. Conclusion

Through this experiment, the findings show that flip-chip bonding of Al bumps using Al wire satisfied the IEC 60749-19 until 2000 cycles of the thermal cycle test at temperatures of -40 to 250 °C including exposure to 250 °C for 3000 hours. Even when the high-temperature shear strength at 250 °C is taken into consideration, said flip-chip bonding satisfies the standard IEC until 1000 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 stress concentration of the stress from the outside 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 due to the softness of the Al bump material, stress concentration hardly occurred in the short-side direction, and deformation of the entire bump made it harder for the bump to rupture.

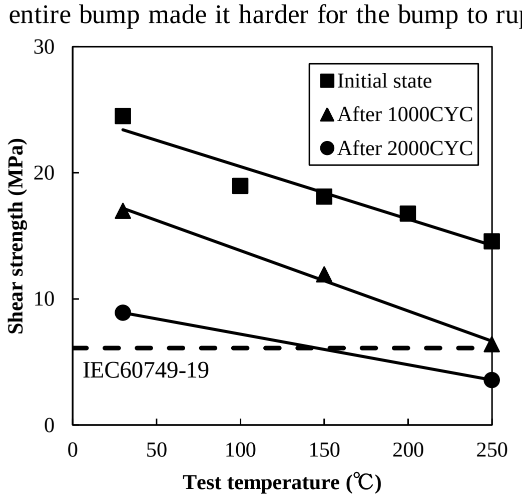

Fig. 8 Dependence of the shear strength of a sample without heat treatment on high temperature.

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 to 250 °C, and from now, we will consider measures for further improvement in reliability.

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