Numerical analysis of deformation and thermal behavior during ultrasonic Al ribbon bonding†

SUZUKI Shinji *, OYAMA Yusuke *, MAEDA Masakatsu **, and TAKAHASHI Yasuo **

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1. Introduction

In the recent years, thick Al ribbon bonding has been applied to the packaging of power devices such as IGBT (Insulated Gate Bipolar Transistor) modules to secure high power density and to improve power control. These are very important for green innovations.

Al thick wire bonding is used in the power electronics packaging. The wire bonding process has been studied experimentally [1, 2, 3] and numerically [4, 5]. These studies are useful to understand the wire bonding mechanism, wire deformation and interfacial behavior during bonding. The Al ribbon bonding is affected by temperature rise of the bond-area and ribbon deformation. The temperature rise is related with frictional slip behavior at the bond-interface. In the present study, a simple numerical model of the ultrasonic Al ribbon bonding is proposed. The heat conduction between the Al ribbon and tool (substrate) is modeled to visualize the temperature change and distribution. The plastic deformation behavior affected by the friction slip is numerically examined. The calculated results are verified, based on the experimental results.

2. Numerical modeling and simulation procedure

Figure 1 shows the mesh pattern of the bonding tool, Al ribbon, Al electric pad, and Si chip (or SiO_2 substrate). The bonding tool is made of WC. The model is two dimensional and the heat flow in the z direction (perpendicular to the space) is ignored because the length of substrate in the z direction is 10 times greater than the thickness of the substrate (2.4 mm) and the bottom of the substrate is assumed to be cooled at 300K (in contact with a large heat sink). Two boundary conditions were given to the top of the bonding tool; 1) at 300K and 2) $J = 0$ in the y direction, where J is the heat flux. The heat conduction behavior was calculated by using a finite differential method, based on the control volume method. The heat generation at the bond-interface is produced by the friction slip at the bonding interface. The heat generation is affected by ultrasonic power input. For example, if the heat input of 4 W is given to the elements in the vicinity of the bond-interface and the bonding area is 1mm x 100μm, then the heat input per unit volume and unit time is calculated to be $4.0x10^{-9}Jm^{-3}s^{-1}$. The heat was supplied only to the elements in contact with the bond-interface in proportion to the volume of each element.

Calculation of plastic deformation of Al ribbon was carried out by using a finite element method[5]. The strain-rate-depending large plastic deformation was taken into account. The tool and the substrate were assumed to be rigid bodies. We assumed that the interface between tool and ribbon was fixed but the interface between ribbon and substrate was able to slip. The material constants of heat conduction and plastic deformation were given from literatures[5, 6].

3. Experimental procedure

The ribbon bonding tests are carried out under the condition of ultrasonic power 1~4 W, bonding force 1~5.0N and frequency 60kHz. The Al ribbon of 1mm wide and Si chip (or SiO_2 substrate) were used. The bonding time (duration of ultrasonic vibration input) was 100 ~ 400ms.

4. Results and discussion

Figure 2 shows the calculated results of heat conduction (change of temperature T with time t at positions A ~ G along y axis of Fig. 1. The bottom of chip and the top of tool are assumed to be cooled at 300K, i.e., $T_s = T_t = 300K$, where T_s is the temperature of imaginary elements (meshes) under the bottom of chip and T_t is the temperature of imaginary elements on the top of tool. The heat input rate into the bond-interface is constant during bonding. As can be seen in Fig.1, temperature continously increases at time $t > 0$ (after ultrasonic power is inputted) and decreases after $t > 100s$ (ultrasonic power is turned off). The temperature curves for the positions A~F are convex up during bonding but that of position G changes from concave to convex. This is due to thermal flow in the x direction. It is suggested that Al ribbon heats up to 393K.

Figure 3 shows the temperature distribution map when the substrate is silica and $T_s = T_t = 300K$ without heat resistance of the interfaces. The Al ribbon is heated up uniformly as shown in **Fig. 4**. Because thermal

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* Graduate student, Osaka University, Suita, Japan.
** Center for Advanced Science and Innovation (CASI), Osaka University, Suita, Japan.

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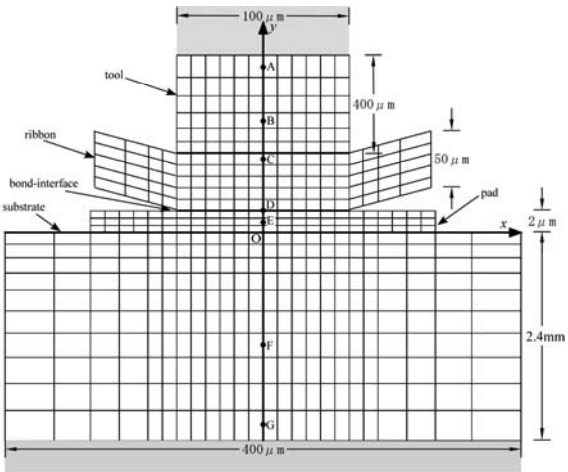

Fig. 1 Schematic illustration (Mesh pattern of cross section) of bonding tool, Al ribbon, Al pad, and substrate (Si chip or silica).

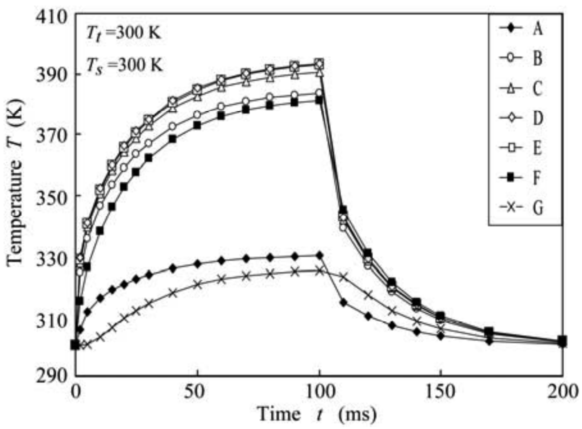

Fig. 2 Temperature change of representative positions A~G which are denoted in Fig. 1.

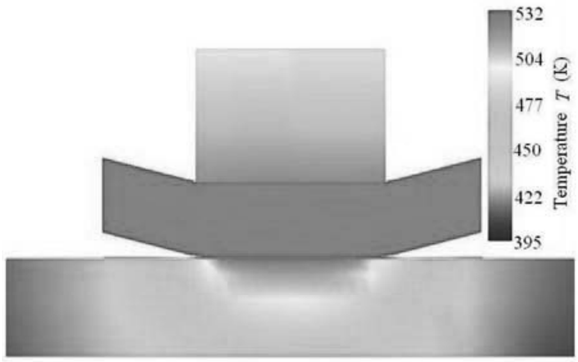

Fig. 3 Temperature distribution for silica substrate, T_t = T_s = 300K. The temperature of Al ribbon is about 530 K because of small thermal conductivity of silica.

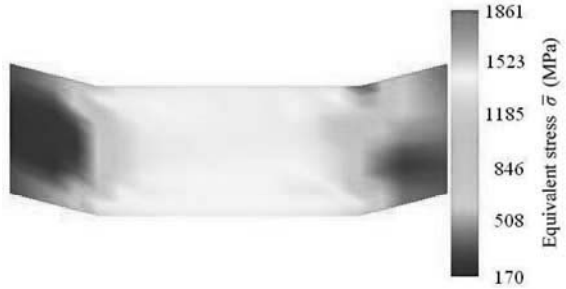

Fig. 4 Equivalent stress distribution of Al ribbon when the displacement rate of 1.88x10^{-2} m/s is applied to right hand direction of the top of ribbon. The bonding pressure P = 15MPa, the ultrasonic vibration amplitude is 50nm at the top side of Al ribbon. Bond-interface can frictionally slide ($\dot{u}_x \approx$1.76x10^{-2}m/s at the bond-interface).

conductivity of silica is smaller (1/10^2), than that of silicon, Al ribbon heats up to 532K. The temperature at the bonding interface was measured experimentally. It was about 365~370K during bonding. Actual temperature rise is about 100K at the highest.

Al ribbon is deformed as the temperature rises. The plastic deformation with strain rate dependence was simulated by the assuming that the Al ribbon is kept at T = 373K, where T is average temperature of the ribbon. Figure 4 shows the equivalent stress distribution in the Al ribbon. Fig. 4 is for the frictional slip condition.

As can be seen in Fig. 4, the equivalent stress strikingly increases up to be 10 times greater than the bonding pressure. This is an ultrasonic vibration effect. As a result, a large plastic strain rate is produced by ultrasonic vibration. After the bond- interface is fixed, a revolving moment is produced. The very high shear stress greater than 1700 MPa causes the increase of the equivalent stress.

5. Conclusions

The ultrasonic bonding of Al ribbon is necessary for power electronics packaging technologies. The temperature rise and plastic deformation during the ultrasonic bonding were simulated. The temperature distribution and stress distribution were visualized. The main results are as follows;

(1) Al ribbon heats up to about 373 K, if the ultrasonic power is less than 4W.
(2) Insulating or heating of the bonding tool is effective for heating Al ribbon.
(3) Large stress is not obtained under the free slip condition, i.e., the large compression of Al ribbon cannot be produced.
(4) Large stress is produced under the frictional slip or fixed conditions and Al ribbon largely deforms. This is a softening effect of ultrasonic vibration.
(5) Revolving moment is produced after Al ribbon adheres to Al Pad.

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