Numerical analysis of interfacial deformation and temperature rise during ultrasonic Al ribbon bonding

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Abstract. The plastic deformation, thermal behaviour and interfacial state during ultrasonic bonding of Al ribbon with substrate were analyzed based on numerical simulations. The numerical simulations were carried out by finite difference and element methods. The change of bond interface temperature with the bonding time $t$ was simulated. It is suggested that the interfacial frictional behaviour between ribbon and substrate does not only affect the temperature rising behaviour but also the stress situation and plastic deformation behaviour, i.e., the ribbon deformation and the frictional slip behaviours influence each other. It is also found that partial constraint (frictional slip) at the bond-interface increases interfacial shear stress drastically and controls the frictional heat input and temperature rise of the Al ribbon.

1. Introduction
In 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 controlling [1, 2]. These are very important for green innovations in the field of car electronic technologies, and wind and solar power controlling. The ultrasonic Al ribbon bonding is affected by temperature rise of the bond area and ribbon deformation [2]. The temperature rise is related to frictional slip behavior at the bond-interface. There have been few numerical studies of Al ribbon bonding, although there exist a few studies of experimental investigation. Basic knowledge on the bonding mechanism is essential for further development of ultrasonic bonding. However, it is difficult to analyze the mechanism experimentally due to the fine-scale phenomenon and short-time process of the bonding. Even now, the phenomenon occurring at the interface is not perfectly simulated, although many numerical studies of wire bonding have been reported [3-8]. In the present study, the effect of ultrasonic vibration on plastic deformation and temperature rise is, therefore, simulated in order to understand the bond interfacial state and the softening effect induced by the ultrasonic vibration.

2. Numerical modelling and simulation procedure
Figure 1 illustrates the ultrasonic ribbon bonding. Al ribbon is used in the power electronics packaging. Ultrasonic vibration is applied in the longitudinal direction of Al ribbon as illustrated in Figure 1. The area enclosed by dotted lines was considered in the present study, i.e., a two-dimensional model was adopted [2, 3]. The heat flow and deformation in the $z$ direction were ignored because the length of
Substrate in the $z$ direction is much greater than the thickness of substrate. It was assumed that the bottom of the substrate was kept at 300 K (in contact with a large heat sink) [2]. The top of the bonding tool was also kept at 300 K. The bonding tool was made of tungsten carbide (WC). It was assumed that the heat was not conducted to the ambient air. A silica plate was adopted as a substrate because Al ribbon could be connected to silica easily under the constant applied pressure together with ultrasonic vibration, i.e., the ultrasonic vibration (vibration behavior of bonding tool) for silica was more stable during bonding than that of Si-chip. Also, the thermal conductivity of silica is much lower than that of Si-chip. The temperature rising process of Al ribbon adhered to silica can, therefore, be simulated more clearly. The material constants of thermal behavior are listed in Table 1.

Figure 2 shows the mesh pattern of the two-dimensional model. The mesh division is enough to solve the visco-plastic deformation of Al ribbon, because the eight-node isoparametric elements were adopted [3]. The time increment had to be less than $\Delta t = 1 \times 10^{-10}$ s for calculating heat conduction if the mesh division was finer than that of Figure 2 [2]. The mesh pattern in Figure 2 is adequate for simulating interfacial deformation and heat conduction. It is assumed that the bonding tool and silica substrate are rigid bodies but the heat conduction occurs through them. Al thin electric pad on the

### Table 1. Thermal conductivity and specific heat of Al, SiO$_2$ and WC.

| Name                  | Symbol | Al       | SiO$_2$  | WC       | Unit          |
|-----------------------|--------|----------|----------|----------|---------------|
| Thermal conductivity  | $h$    | $2.37 \times 10^3$ | 1.38     | $8.00 \times 10^1$ | W m$^{-1}$K$^{-1}$ |
| Density               | $\rho$ | $2.70 \times 10^3$ | $2.19 \times 10^3$ | $2.70 \times 10^3$ | kg m$^{-3}$ |
| Absolute temperature  | $T$    |          |          |          | K             |
| Specific heat         | $C_p = a_1 + a_2 T + a_3 T^2 + a_4 T^3$ | | | | J kg$^{-1}$K$^{-1}$ |
| where                 | $a_1$  | 31.38    | 43.93    | 43.39    |               |
|                       | $a_2$  | -1.64$\times 10^3$ | 3.88$\times 10^3$ | 8.62$\times 10^3$ |               |
|                       | $a_3$  | -3.60$\times 10^3$ | -9.69$\times 10^3$ | -9.33$\times 10^3$ |               |
|                       | $a_4$  | 2.08$\times 10^6$ | -1.03$\times 10^6$ |            |               |
substrate is ignored so that the slipping mode can be simplified. Only the Al ribbon can be deformed during the bonding period when ultrasonic vibration is applied under the constant bonding pressure $P_B (= F/S)$, where $F$ is the bonding load and $S$ is the head area of the bonding tool. The bonding tool is too hard to deform plastically although it can vibrate. The ultrasonic vibration is parallel to the $x$ direction. It is assumed that the interface (tool-interface) between tool and ribbon is always fixed, because of simplification, i.e., the heat input is not produced at the tool interface. The amplitude $A_o$ changes with time $t$, as solid adhesion occurs at the bond-interface between ribbon and substrate along the $x$-axis. The average amplitude $A_o$ of Al ribbon vibration at the bond-interface differs from $A_o$ as the adhesion occurs at the bond-interface. This is due to the frictional slip. The top amplitude $A_o$ and the vibration ratio $R_d = A_o/A_s$ decrease step by step if the adhesion occurs gradually. In other words, if the adhesion progress is not steady, then $A_o$ and $R_d$ fluctuate. The change in $A_o$ and $R_d$ should be related to the frictional slip phenomena at the bond-interface, but it is very difficult to explain the relationship between the frictional slip and the solid adhesion quantitatively. Therefore, in the present study, the change of $A_o$ and $R_d$ with time $t$ was given as a boundary condition but the friction coefficient $\mu$ was not given for the bond-interface because the relation between adhesion and friction coefficient was unknown.

Figure 3 shows the three conditions (a), (b) and (c) for change of $A_o$ (red color) and $R_d$ (blue color). The dotted lines just suggest the actual changes in $A_o$ and $R_d$. The values shown by solid lines were given to $A_o$ and $R_d$ in calculation. The steady state adhesion progress is supposed in the present study. The ultrasonic vibration amplitude does not change up and down. The steady state (stable) bonding process is often observed under proper bonding conditions unless the ramp force is given and the gross slip motion can be produced even under the constant load [9, 10]. The ratio $R_d$ was decreased linearly from 1.000 to 0.999 in the first stage. For example, the first stage is $t = 0 - 40$ ms for Figure 3 (a).
Figure 3. Change in vibration amplitude $A_o$ and ratio $R_d$ as a boundary condition.

Figure 4. Schematic illustration of ultrasonic vibration wave pattern (displacement rate at the interface between tool and ribbon).
If the displacement (ultrasonic vibration) \( u \) is given by

\[
    u = A_o \sin \omega t,
\]

where \( \omega \) is the circular frequency \((= 2\pi f_v)\), the ultrasonic power \( P_w(t) \) is given by

\[
    P_w(t) = F_x(t) A_o \omega \cos \omega t,
\]

where \( F_x \) is the force in the \( x \) direction. The average \( P_w \) is obtained by \( 4F_x A_o f_v \) [11]. The displacement rate at the interface between tool and ribbon can be given by

\[
    (du/dt)_{\text{at tool}} = A_o \omega \cos \omega t.
\]

Therefore, the change in the displacement rate at the tool interface is given by Figure 4. The time increment \( \Delta t \) for calculating Al ribbon deformation was set by \( T_v/8 \) \((= 2.08 \times 10^{-6} \text{ s})\), where \( T_v \) is the period of ultrasonic vibration and \( f_v \) is the frequency \((= 60 \text{ kHz})\). Al ribbon deformation in unit cycle was calculated in 8 steps, as shown in Figure 4. It is necessary to solve \( F_x \) at finite elements of the bond-interface for obtaining the real power (heat) input to the bond-interface. The shear stress at the bond-interface can be obtained by calculating the deformation of Al ribbon. In the present study, it was assumed that the heat input was obtained by the frictional slip at the bond-interface. When the plastic deformation of Al ribbon was calculated, it was assumed that the temperature \( T \) (of each element) was kept constant in the period \( T_v \) unit cycle of ultrasonic vibration. This assumption makes it easy to give the heat inputs to the elements mated at the bond-interface. The shear stress \( \tau_{xy} \) at the bond-interface was solved for each finite element in each step \( \Delta t \). The heat input \( Q_m \) to each finite element at the bond-interface was given by

\[
    Q_m = \tau_{xy} S_b (du/dt)_{|\text{at bond-interface}},
\]

where \( S_b \) is the area of the finite element at the bond-interface and \( (du/dt)_{|\text{at bond-interface}} \) is the displacement rate of the nodal point of the Al ribbon side at the bond-interface. This corresponds to the local frictional slip rate and it can change along the position \( x \) due to the plastic deformation of Al ribbon but it was constant for each step \( \Delta t \) \((= T_v/8)\). It was assumed that the average of \( (du/dt)_{|\text{at bond-interface}} \) at time \( t \) was equal to \( A_o \omega R_d \) at time \( t \). The heat input \( Q_m \) was assigned only to the elements (Al and silica) mated at the bond-interface in proportional to the volume of each element. Al ribbon was assumed to be a rate-sensitive material with material constants listed in Table 2 for the low temperature region of Al. The equivalent strain rate \( \dot{\varepsilon} \) is given by

\[
    \dot{\varepsilon} = A_o \left[ 1 + B \exp(-C\varepsilon) \right] \left( \frac{D_b G}{kT} \right) \left( \frac{\bar{\sigma}}{G} \right)^n \exp \left( -\frac{Q_a}{RT} \right),
\]

where \( A_o, B \) and \( C \) are a non-dimensional constant, \( \bar{\varepsilon} \) the equivalent strain, \( D_b \) a frequency factor, \( b \) the Burgers vector, \( G \) the shear modulus, \( k \) the Bolzmann’s constant, \( T \) the absolute temperature of the specimen, \( \bar{\sigma} \) the equivalent stress, \( n \) the stress exponent, \( Q \) the activation energy for the visco-plastic flow, and \( R \) the gas constant [3, 6]. The finite element method (eight-node isoparametric elements) was used [3]. As the equivalent stress increases, \( n \) can be high enough to prevent stress enhancement but it is assumed in the present study that \( n \) is constant.

On the other hand, the heat conduction was simulated by the time step \( \Delta t = 1 \times 10^{-10} \text{ s} \), assuming the heat input was constant for a few cycles \((mT_v)\), where \( m \) is an integer). The cycle number \( m \) was increased as the bonding progressed from early stage to latter stage, because the task would be very hard if a unit cycle was adopted for solving ribbon-deformation, i.e., the distribution of temperature \( T \) (the heat flow) was solved under the assumption that the heat input due to frictional slip was constant for several cycles. The heat flow was calculated by a finite difference method [2]. The assumption on heat input can reduce the hard task (numerous simulations) of the heat flow phenomenon by the ultrasonic vibration power.
3. Results and discussion

Figure 5 shows the temperature change at the center of the bond-interface. Strictly speaking, it is the temperature of two elements of ribbon-side closed to the origin O (x, y) = (0, 0). Figure 5 (a), (b) and (c) are the calculated results for the boundary conditions of Figure 3 (a), (b) and (c), respectively. Because the amplitude \( A_0 \) and the vibration ratio \( R_d \) are given in stairs-like patterns as shown in Figure 3, the temperature changes discontinuously. The conditions (a) and (c) correspond to the case when the partial adhesion occurs suddenly at \( t = 40 \) ms. On the other hand, the condition (b) is for the case when the adhesion more gradually occurs. The temperature rising of Figure 5 (a) or (c) is very different from that of Figure 5 (b). This suggests that if the adhesion is gradually produced, then the temperature rise can be facilitated. The temperature at \( t \approx 50 \) ms of Figure 5 (a) is larger than that of Figure 5 (c). The vibration ratio of condition (c) is less than that of (a) at \( t = 40 - 50 \) ms. The slight difference in \( R_d \) can also control the temperature rising, resulting in the difference of temperature rising between (a) and (c) at \( t = 40 - 60 \) ms. Figures 5 (a) and (b) imply that if the frictional slip continues by the latter stage of bonding, then temperature cannot fall easily. Figure 5 (c) suggests that the further adhesion occurrence at the latter stage of bonding reduces temperature rising of the specimen, i.e., the specimen is cooled down rapidly if the interface is fixed without friction. The early sudden sticking at the bond-interface reduces the temperature rising and makes the bonding process unstable. As seen in Figure 5, the temperature is roughly kept constant after \( t = 110 \) ms because the frictional slip is assumed to be produced after full adhesion. In rotational frictional pressure welding [12], the specimen can keep rotating at high bonding temperature after full adhesion is produced, till the specimen is cooled down to the room temperature. The adhered (bonded) interface is not necessarily fixed at high temperatures, i.e., the frictional slip occurs even after bonding so that temperature rise can occur.

Table 2. Material constants for aluminum deformation at low temperatures.

| Name                  | Symbol | Al  | Unit      |
|-----------------------|--------|-----|-----------|
| Equivalent strain rate| \( \dot{\varepsilon} \) |     | s\(^{-1}\) |
| Equivalent strain     | \( \varepsilon \) |     |           |
| Equivalent stress     | \( \sigma \) |     | Pa        |
| Absolute temperature  | \( T \) |     | K         |
| Boltzmann's constant  | \( k \) | 1.3806504 × 10\(^{-23}\) | J K\(^{-1}\) |
| Gas constant          | \( R \) | 8.314 | J mol\(^{-1}\)K\(^{-1}\) |
| Frequency factor      | \( D_o \) | 0.1 × 10\(^{-4}\) | m\(^2\)s\(^{-1}\) |
| Constant              | \( A_o \) | 2.14 × 10\(^{5}\) |           |
| Constant              | \( B \) | 5.60 × 10\(^{2}\) |           |
| Constant              | \( C \) | 1.00 × 10\(^{2}\) |           |
| Burgers vector        | \( b \) | 2.86 × 10\(^{-10}\) | m         |
| Stress exponent       | \( n \) | 6.4 |           |
| Activation energy     | \( Q \) | 75.4 | kJ mol\(^{-1}\) |
| Melting temperature   | \( T_m \) | 933 | K         |
| Shear modulus         | \( G(T) = a_G (T/T_m)^{\alpha} + b_G (T/T_m) + c_G \) | N m\(^{-2}\) |
|                       | where  |     |           |
|                       | \( a_G \) | -9.4 × 10\(^{8}\) |           |
|                       | \( b_G \) | -5.3 × 10\(^{9}\) |           |
|                       | \( c_G \) | 2.9 × 10\(^{10}\) |           |
Figure 6 shows the change in the temperature distribution with time under the condition of Figure 3 (a). Because the substrate is made of silica, the heat is not easily conducted to the bottom. Al ribbon is heated up dominantly and the temperature is roughly uniform. This makes it easy to analyze the deformation behavior of Al ribbon during bonding. The temperature rise of Al ribbon due to frictional slip is about 80 - 100 K. The bonding tool is also heated up, as seen in Figure 6 (b). After that, the temperature of Al ribbon and tool decreases and is nearly equal to that of substrate, as shown in Figure 6 (d), and the whole is cooled down.

The ratio $R_d$ is close to unity in the early stage of bonding and decreases with increasing $t$. This is an assumption in the present study but possible and right in general because the bonding (adhesion) is produced. If $R_d$ is perfectly equal to unity ($R_d = 1.00$), then the interface between Al ribbon and substrate can slide freely. Therefore, the deformation of Al ribbon for $R_d = 1.00$ is not facilitated by the ultrasonic vibration. In other words, it is just the deformation given by applying the bonding pressure $P_b$ without ultrasonic vibration ($A_o = 0.00 \, \mu m$). The maximum equivalent stress of Al ribbon does not increase, compared with the value of $P_b$. However, if $R_d$ decreases a little, the equivalent stress increases very much as an effect of the ultrasonic vibration [2].

**Figure 5.** Temperature change of Al ribbon (bottom side) with time. (a), (b) and (c) are the calculated results for conditions of Figure 3 (a), (b) and (c), respectively.
Figure 7 shows the calculated results of the equivalent stress distribution under the condition of Figure 3 (a) ($P_B = 28$ MPa). Even if $R_d = 0.9999$, the equivalent stress of Al ribbon goes up to 190 - 250 MPa (seven to ten times the $P_B$ value) immediately after ultrasonic vibration is turned on, as seen in Figure 7 (a) at $T = 300$ K, $t \approx 0$ ms. This is derived from the shear stress enhanced by the frictional slip. The value of the shear stress at the central area was obtained by $\tau_{xy} \approx 125$ MPa from the calculated results, being much greater than $\sigma_y \approx P_B$. If $R_d$ is constant, the stress decreases as shown in Figure 7 (b) at $t = 8$ ms. Al becomes soft and the shear stress decreases. The frictional work also decreases. As the deformation can be enhanced, the adhesion progresses. The deformation-restriction and hardening occurs and then the frictional work is again produced, resulting in temperature rise. If temperature increases further, Al ribbon becomes soft again and deforms to harden, repeatedly. The adhesion goes on further, and $R_d$ decreases and the interface constraint still increases. The equivalent stress increases even if temperature increases ($T \approx 360$ K) as seen in Figure 7(c) at $t \approx 40$ ms. The
shear stress decreases as temperature further increases and then the frictional work finally decreases, i.e., the heat input decreases. The specimen begins to be cooled down. To sum up, frictional slip, heating, softening and hardening are produced repeatedly by applying the ultrasonic vibration. The shear stress often fluctuates. Actually, the adhesion may be broken down discontinuously, if the shear stress increases very much. As reported elsewhere [13], if temperature rises to $T = 400$ K, then the equivalent stress goes down clearly.

Figure 7 shows the stress distributions along the bond-interface (Al ribbon side) at $t = 40$ ms of Figure 7 (c). The displacement rate due to ultrasonic vibration is applied to the right-hand side (step 1 in Figure 4). The abscissa is the number of nodal point along the bond-interface as shown in Figure 2. No. 13 corresponds to the origin O, and No. 1 and 25 are the edge points of the bond-interface. The shear stress $\tau_{xy}$ is roughly constant and about 500 MPa, which is close to the equivalent stress as shown in Figure 7 (c). The shear deformation is dominant. The stress $\sigma_y$ in the y direction is compressive in the right-hand edge of the bond-interface and tensile in the left-hand edge. The equivalent stress becomes larger in both edges. Because the friction is assumed to be gross slip, the friction coefficient is not constant at the position x, and the friction coefficient in the central area (No. 5 to No. 21 of nodal points) is greater than ten. The adhesion must already be produced but the frictional slip continues after adhesion. If this is not so, the temperature does not rise after $t > 40$ ms. Because the temperature rises even after $t > 40$ ms as seen in Figure 5, it is suggested that adhesion and frictional slip occur simultaneously.
Figure 9 shows an experimental result of temperature change of bonding interface with bonding time. The temperature was measured by a micro thermo-couple embedded in the bonding interface. The experimental condition was $F = 7.0$ N, $P_w = 3.8$ W, $f_v = 60$ kHz. The width of Al ribbon was 1.0 mm. The tool width was 0.25 mm (2.5 times the calculating condition, 0.1 mm, because it was difficult to embed the micro thermo-couple). As the bonding area was about $0.25 \text{mm}^2$, $P_b \approx 28$ MPa. As can be seen in Figure 9, temperature keeps rising until $t = 80$ ms, fluctuates and then decreases for $t > 100$ ms. The maximum temperature is about $T \approx 370$ K at $t = 70 - 90$ ms. The maximum temperature is nearly equal to that of Figure 5 (a) or (c). In calculating, the bonding area was assumed to be $0.1 \times \ldots$
10^6 m^2 (100 µm x 1 mm). The average shear stress at the bond-interface is 500 MPa from Figure 8. The displacement rate due to frictional slip is \( (du/dt) = A_o\omega R_d \approx 6.8 \times 10^{-2} \text{ m/s} \). The heat input is, therefore, about 3.4 W as obtained by Eq. (4). This is nearly equal to that of the experimental condition. There is no difference between calculated and experimental results with respect to ultrasonic power input and applied force.

On the other hand, the temperature decreases more slowly than that of the calculated results in Figure 5. The heat input from the top of the Al ribbon must occur at the latter stage of bonding due to the frictional slip at the tool interface. The heat input at the tool interface was neglected in calculated results, although the frictional slip at the bond-interface is taken into account \( (R_d > 0.2) \). It is suggested that it is necessary to take into consideration the frictional slip at the tool interface in the latter stage of bonding. It is found from calculated and experimental results that the ribbon temperature rises rapidly due to the frictional slip in the early stage of bonding, i.e., the temperature goes up to 360 - 400 K in 50 ms. The frictional work decreases after the ribbon temperature increases. The three slip conditions are roughly classified into 1) free slip, 2) frictional slip and 3) fixed bond-interface. It is, however, suggested that the bond-interface is not fixed perfectly in the period when the ultrasonic vibration is inputted under high temperature conditions.

4. Conclusions
It is very important to understand the thick Al ribbon bonding applied to power electronics packaging. The deformation and thermal phenomena of Al ribbon due to ultrasonic vibration were simulated. The main results are shown as follows.

1) The equivalent stress of Al ribbon is strikingly enhanced by the ultrasonic vibration. This is due to the frictional slip at the bond-interface. If the amplitude is kept constant, as the frictional constraint increases, the stress becomes higher.

2) If the frictional condition is the same, as temperature increases, the equivalent stress decreases. However, if the frictional constraint increases due to the partial adhesion, the stress increases and deformation is facilitated. The deformation of aluminum with softening and hardening is repeated by the ultrasonic vibration and temperature increases. This is related to the adhesion phenomena.

3) The ribbon temperature is heated up to about 360 - 400 K rapidly in 40 - 50 ms when frictional heat due to the ultrasonic power is generated at the bond-interface.

4) The frictional slip can occur even after adhesion at high temperatures. Adhesion and frictional slip occur simultaneously.

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