Study of Simulation of Micro-Cutting Process of Alternatively-Arranged Resin and Metal

Ryuji IWASHITA1, Hiroyuki SASAHARA1
1Graduate School of Bio-applications and Systems Engineering, Tokyo University of Agriculture and Technology, Japan, 50007401201@st.tuat.ac.jp

Abstract: For the planarization process of LSI wafers, metal bumps covered with polymer glue are machined with a diamond tool. In this study, the deformation process and temperature field in this process are analytically simulated with FEM. In order to analyze the cutting process for resin which has a viscosity, the cutting simulator first has to treat the visco-elastic-plastic material property. Secondly, to analyze the cutting at the micro-meter level depth of cut, the analysis model was scaled down. Finally, to simulate the cutting process of a LSI wafer, PVC and 70% Cu-30% Zn brass were assigned a resin and a metal part, respectively.

Keywords: FEM, simulation, Micro cutting, machining, resin

1. Introduction

Recently, high performance, downsizing and energy saving have been demanded for electronic devices. In order to achieve these, “3-D stack integration” has been proposed through which some layers of functional chips are stacked and bonded, hence allowing a very short wiring length and a high density packaging of LSI to be realized. In order to connect LSI chip layers with each other face-to-face mechanically and electrically, high accuracy planarization technologies, which can make a flat surface on a metal bump and a certain kind of insulating polymer, have been used. It is difficult, however, for conventional planarization technologies such as CMP or precision grinding to achieve the flatness required for the next-generation LSI. Alternatively, precision diamond cutting on a chip surface after making a circuit on a wafer has been proposed. As shown in Figure 1, this technology enables the creation of a planar surface on the bumps, wirings, and insulating adhesive resin on a wafer with high accuracy, but the rather rapid wear rate of the tool and its chipping have become problems. It is difficult to observe the actual cutting process in-situ because the depth of cut in this diamond cutting is of a micro- or sub-micrometer order. Therefore, in this study, the deformation process and temperature field of this cutting process were analytically studied and the process made visible by using a developed simulation system for the micro-cutting process for alternatively-arranged resin and metal with a finite element method.

2. Outline of simulation

In this study, a simulation system has been developed based on a system which can simulate a metal-cutting process developed by one of the authors. It is composed of three modules: a tool modeling module, a cutting simulation module with FEM and a GUI module to set the cutting conditions and run the simulation. All of these can be operated on a windows-based PC.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Cutting planarization process of LSI}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Visco-elastic-plastic model}
\end{figure}

\begin{align*}
\dot{\varepsilon}^e & : \text{Velocity of strain on elastic element} \\
\dot{\varepsilon}^v & : \text{Velocity of strain on voigt element} \\
\dot{\varepsilon}^p & : \text{Velocity of strain on plastic element} \\
\dot{\varepsilon} & : \text{Velocity of strain on all element}
\end{align*}
The system can simulate a chip-forming process, a temperature field coupled with a deformation analysis and a thermal analysis that considers a change of material property as dependent on the temperature, strain and strain rate.

In order to analyze the cutting process with resin which has a large viscosity, a cutting simulator has been modified to be a visco-elastic-plastic model\(^3\), as shown in Figure 2. The Voigt model, which can treat the behavior of the viscosity, was added to the elastic-plastic model. Additional formulations of viscosity are shown as follows. First, the stress acting on a dashpot part of the Voigt model \(\{\varepsilon_i\}\) (1/s) is given as

\[
\{\varepsilon_i\} = \gamma \{\dot{\varepsilon}_i\} \{\varepsilon_i\}
\]

where \(\gamma\), \(\dot{\varepsilon}_i\), \(\varepsilon_i\) and \(\varepsilon_i\) respectively, are the viscosity coefficient (GPa·s), the stress of the elastic-plastic deformation, the elastic modulus matrix and the strain on the Voigt model.

Then, the nodal force rate \(\{\dot{F}_i\}\) , a reactive force rate due to the viscosity, is derived by the strain rate \(\{\dot{\varepsilon}_i\}\) of the voigt model described as

\[
\{\dot{F}_i\} = \int \varepsilon_i \{\dot{\varepsilon}_i\} dv
\]

where \(\varepsilon_i\) and \(\dot{\varepsilon}_i\) are the interpolation function matrix and the plastic coefficient matrix, respectively.

Next, this force is substituted into the force term of the stiffness equation. Finally, the stiffness equation can be formulated by an updated Lagrangian form\(^6\) that considers the large deformation in the chip-forming process and the viscosity of the material:

\[
\{\dot{F}_i\} \{\varepsilon_i\} = \{\varepsilon_i\} - (\varepsilon_i) \{\dot{\varepsilon}_i\} \{\varepsilon_i\}
\]

where \(\{\varepsilon_i\}\) and \(\{\dot{\varepsilon}_i\}\) are the nodal force rate vector and nodal velocity vector, respectively. \(\varepsilon_i\) is the modified stiffness matrix, in which the incompressibility is relaxed using the Nagtegaal-Rice functional\(^5\), \(\varepsilon_i\) is the geometrical stiffness matrix, and \(\varepsilon_i\) is the load correction matrix.

The tool-chip contact surface was treated as a non-linear frictional boundary\(^8\) described as

\[
\frac{\sigma_i}{\tau_c} = 1 - \exp\left(-\frac{\sigma_i}{\tau_c}\right)
\]

where \(\sigma_i\) and \(\tau_c\) are the normal and frictional stresses on the tool-chip contact surface, respectively, and \(\tau_c\) is the yield shear stress of the chip at the point considered. \(\lambda\) is the frictional characteristic constant.

A geometrical criterion is used to judge the contact between the tool and the chip. When the distance between the chip surface node and the rake face becomes smaller than the settled value, the chip node is judged to contact the rake face, and the boundary condition is changed. The separation of the tool and the chip is determined by using the nodal force, which is derived from the stress field in the elements. When the vertical component of the nodal force on the chip surface contacting the tool reaches a negative value, the node gets off the rake face and becomes a free boundary node.

As shown in Figure 3, as the finished surface is generated by separating of material in front of the cutting edge as the tool progress, the node which comes up to tool tip must be separated to two nodes on the chip and the machined surface. The node is separated when the following geometrical conditions are satisfied:

1. The node to be separated comes to within fiftieth cutting depth of the cutting edge;
2. The chip surface node generated at the last separation is on the tool rake face.

3. Simulation results

3.1 Analysis of resin

It is very time consuming process to obtain the stress-strain relationship and viscosity property of the adhesive resin used for stacking of LSI layers. As a first step, a elastic-perfectly plastic model with considering the viscosity was employed as a material property of the adhesive resin. Material property concerning the viscosity which was studied by Obikawa et. al. was used.

Material properties of workpiece and tool are listed in Table 1 and 2.

In this study, since the actual material properties of
the adhesive resin were unknown, the influence of the viscosity coefficients has been researched. Figure 4 shows the simulated results. Figure 4(a) shows the case of the elastic-plastic model which has no viscosity element. Figure 4(b) shows the case of using a visco-elastic-plastic model where the viscosity coefficient is 1.1 (GPa·s), which is the value of PVC. Comparing (a) and (b), the influence of viscosity is seen to be rather small. On the other hand, as the viscosity coefficient becomes small (one-tenth that of PVC), the deformation of the Voigt element becomes large, and then the chip deformation also becomes significantly large, as shown in Figure 4(c). If the viscosity coefficient becomes small, it will change the deformation process significantly, and it is considered that it makes the adhesive resin flowing.

Secondly, the influence of the thermal characteristic was researched assuming two kinds of tool materials: carbide and diamond. When the diamond tool is used, it can be seen that heat is diffused through the diamond tool, as shown in Fig. 5(a). On the other hand, heat is not diffused through the carbide tool and is built up locally around the rake face. The temperature differences affect the chip deformation process, and the shear angle of (b) becomes larger than that of (a).

In this way, a small thermal difference has an influence on the chip shape. Therefore, to improve the prediction accuracy, the stress-strain relationship and other material properties need to be measured accurately.

### Table 1: Work material properties

<table>
<thead>
<tr>
<th>Work piece</th>
<th>PVC</th>
<th>70%Cu-30%Zn brass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress</td>
<td>MPa</td>
<td>150.6</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>1.325</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.333</td>
<td>0.37</td>
</tr>
<tr>
<td>Consistency</td>
<td>kg/m³</td>
<td>1.39</td>
</tr>
<tr>
<td>Specific heat</td>
<td>J/(kg·K)</td>
<td>837.21</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/(m·K)</td>
<td>0.17</td>
</tr>
<tr>
<td>Coefficient of linear expansion</td>
<td>K⁻¹</td>
<td>50×10⁻⁶</td>
</tr>
<tr>
<td>Coefficient of viscosity</td>
<td>GPa·s</td>
<td>1.100</td>
</tr>
</tbody>
</table>

### Table 2: Tool material properties

<table>
<thead>
<tr>
<th>thermal conductivity</th>
<th>density</th>
<th>specific heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>W·m⁻¹·K⁻¹</td>
<td>kg·m⁻³</td>
<td>J·kg⁻¹·K⁻¹</td>
</tr>
<tr>
<td>Carbide tool</td>
<td>37+0.059×T</td>
<td>1100</td>
</tr>
<tr>
<td>Diamond tool</td>
<td>500</td>
<td>3520</td>
</tr>
</tbody>
</table>
3.2 Influence of the scale of the cutting depth on the cutting temperature field

In this section, the influence of the depth of the cut was studied, comparing cases of the depth of cut of 0.25mm and 0.002mm where the material to be cut was adhesive resin and assuming 70% Cu-30% Zn brass as the metal bump. The model size of the finite elements of the tool and work varied according to the depth of cut. Cutting conditions for the simulation are listed in Table 3. It should be noted that not only the depth of cut, but also the cutting length and time varied for each model.

Figures 6(a) and (b) show the results of the analysis with a depth of cut of 0.002mm and 0.25mm. Comparing (a) and (b), the chip shape is similar, but the temperature distribution and the highest temperature value are different. In particular, in (a), the micro-cutting, the highest temperature can be seen around the shear plane, whereas in the normal-size cutting of (b), the highest temperature is seen on the tool rake face. In addition, in the case of (a), a considerable amount of heat was conducted under the machined surface. In the case of (b), the temperature rise was been seen mainly on the chip. There were large differences for the highest temperature, 99.3 °C and 659.3 °C, in the cases of (a) and (b), respectively. As mentioned above, a large difference appeared between the micro cutting and the conventional sub-millimeter-order cutting.

On the other hand, with the resin cutting, a small temperature difference in the tool can be seen, but little differences existed regarding the temperature of the chip and the inside of the workpiece, quite different from the case of the metal cutting.

One of the reasons for these results is believed to be the difference in thermal conductivity of the workpiece. Heat is conducted easily in the metal with its large thermal conductivity, but heat does not conduct easily in the resin because of its small thermal conductivity. Consequently, in the temperature distribution of (a) that results from the metal micro-cutting, the heat generated by deformation in the shear zone was diffused immediately. In the case of (b), most of the heat generated by the plastic deformation flows with the chip as advection, and the amount of heat transferred downward on the shear plane is low. On the other hand, in the PVC, with a small thermal conductivity, in the cases of both (c), the micro-cutting, and (d), the conventional scale cutting, the amount of the heat diffused under the machined surface is small. Therefore, the temperature distribution and highest temperature remained almost the same in both cases.

Table 3: Cutting condition for simulation

<table>
<thead>
<tr>
<th>Work material</th>
<th>70%Cu-30%Zn brass</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed</td>
<td>m/min</td>
<td>300</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>mm</td>
<td>0.25, 0.002</td>
</tr>
<tr>
<td>Tool material</td>
<td></td>
<td>Diamond</td>
</tr>
</tbody>
</table>

Figure 6: Comparison of temperature distributions
3.3 Analysis of the compound material of resin and metal

In this study, as shown in Figure 7, to simulate the cutting process of the LSI wafer in which the metal bump and the resin glue for stacking were alternatively arranged, a workpiece model composed of a resin and metal part was developed. PVC and 70% Cu-30% Zn brass were assigned as the resin and metal parts, respectively. In addition, it was assumed that the fracture or the exfoliation did not occur at the boundary between the metal bump and the resin. The frictional property on the node at the boundary between the tool and the chip was assumed such that the frictional characteristic constant was an average of both.

Results of analyses are showed in Figure 8. It was found that the resin part became largely deformed and that the shear angle was very low there. The deformation of the metal part was rather small and, it was sheared off at the cutting edge. In addition, as shown in Figure 9, it can be seen that the right side edge of the metal was uplifted in a left-upward direction so that the left side of metal bump was deformed in a leftward direction, thus the height of the finished surface becoming uneven. This situation is very similar to the formation of the exit burr which led to the exit failure of the cutting tool. At the end of the workpiece, the shear plane moved towards the end face, and then finally the shear direction turned downwards, where the clearance face of the tool was forced by the rotating chip and the so-called “foot.” This led to a chipping of the cutting edge. In consequence, for the compound material, it was considered that the resin is much softer than the metal, so that the left side of metal becomes a free face. A decreasing contact length with tool and work can cause a tool failure like the exit failure.
In addition, the cutting force on the metal part increased as much as that of the resin part. It is considered that the initiation of the failure contrasts with the exit failure.

4. Conclusions
In this study, the deformation process and temperature field in the micro-cutting process of alternatively-arranged resin and metal were analytically studied and the process made visible by use of a developed simulation system. Conclusions are offered below:

1. It is found that as the viscosity coefficient becomes small (one-tenth that of PVC), the chip deformation also becomes significantly large.
2. In the cutting of the resin, the temperature distribution and highest temperature remained almost the same if the depth of the cut went to a micro-meter scale. In the metal cutting, the chip shape was similar, but the temperature distribution and the highest temperature value was quite different because of heat transfer around the cutting point.
3. As a result of the deformation process and the temperature field in the cutting process for micro-cutting of alternatively-arranged resin and metal obtained by using the developed simulation system, in the metal-cutting section, the chip shape and machined surface generation were very similar to the formation of the exit burr, which led to the exit failure of the cutting tool.

Acknowledgment
This study was partly supported by a project named “Development of an evaluation scheme by the modeling of machine tool / cutting process” sponsored by FUJITSU Ltd.. The authors gratefully acknowledge them.

References

Figure 10: Cutting force
(Alternatively-arranged resin and metal)