

# A Study on Cutting Analysis upon Oblique Groove Processing by using an End Mill

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## Abstract

**Background/Objectives:** A representative tool end mill, and predictive studies on tool wear and tool life are in urgent need since the number of products requiring high-precision processing has been increasing recently. **Method/Statistical Analysis:** The workpiece had a size of 20mm in length, 20mm in width, and 5mm in thickness. For the tool with the outside diameter of 8mm, the radial rake angle of 5°, and the helix angle of 20°. Processing involved oblique processing at an angle of 5° so that the depth was increased as the transfer progressed. Revolution of the tool was 600RPM with the feed-rate being set at 100mm/min. **Findings:** Upon initial processing, plastic deformation can be seen to occur in a center part of the end mill also, as the depth was increased while almost no initial plasticity occurred in the center part. The maximum temperature occurs at the blade tip of tool edge part that was cut the deepest, and a high temperature of about 1334.5° C was produced. Therefore, work hardening is expected to occur upon processing due to such high temperature. After the formation of chips by processing flow, rapid cooling may be observed. While similar cutting forces for all of x, y, and z axes are acting initially, those for the x-axis and y-axis can be seen to be drastically increased in a vertical direction up to about 18kN after rotation by about 90°, despite the fact that almost no cutting force is applied. The reason is considered to be application of severe vertical loads so as to act as a compressive stress for the tool as the depth of the end mill is increased in oblique plane processing. **Application/Improvements:** Severe concentrated loads occurred at the blade tip of tool edge so that a shivering phenomenon was considered to occur. This result will be used as the basic data upon product processing.

**Keywords:** Cutting Analysis, End Mill, Finite Element Method (FEM), Forming, Milling Machine, Mises Stress

## 1. Introduction

Along with the development of precision machine tools, machining centers are being widely distributed which can process several parts with the exchange of tools even in one process by mounting tens of tools to an ATC apparatus. A representative tool mounted to this machine is an end mill, and predictive studies on tool wear and tool life are in urgent need since the number of products requiring high-precision processing has been increasing recently. However, as processing occurs while the tool is rotated at

a few hundred to a few thousand RPM, temperature variation or the chip generation process as well as workpiece deformation during processing are difficult to measure. Furthermore, observation is impossible because of the occurrence of cutting between the tool and the workpiece. Recently, cutting force and chip formation, etc. are being studied<sup>1,2</sup> for their cutting phenomenon through computer simulation by FEM<sup>3,4</sup>. However, in studies on diversified processing particularly with different depths, no useful utilizations are being made yet in the industry

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fields due to the proposed conditions and the proposed process studies<sup>5-7</sup>.

Thus, in the present study, cutting results were sought by an analytical method using a FEM method for the process of products' oblique plane processing after mounting an end mill tool to a milling machine. Cutting analysis was performed using commercial software through computer simulation. First, the tool selected was an end mill of diameter 8mm, by the use of which a model of processing planes inclined by  $5^\circ$  in depth was modeled. According to the analysis results, generation process of processing chips, 3-axis cutting forces and stresses produced in the tool, and strains in the workpiece were obtained by the FEM for analysis and discussion.

## 2. Method of Analysis

Configuration for the model employed in the present study is schematically shown in Figure 1. First, the workpiece had a size of 20mm in length x 20mm in width x 5mm in thickness, with the material being AISI404. For the tool, an end mill of 4 blades as shown in Figure 1 was used, with the outside diameter of 8mm, the radial rake angle of  $5^\circ$ , and the helix angle of  $20^\circ$  along with the detailed specifications as shown in Table 1. Material for the

tool was high-speed steel (AISI M7). Processing involved oblique processing at an angle of  $5^\circ$  so that the depth was increased as the transfer progressed. Revolution of the tool was 600 RPM with the feed rate being set at 100mm/min. As the analytical software, commercial Third Wave AdvantEdge™ was employed, which is characterized by a coupled thermo-mechanical finite element model of plane-strain orthogonal and used for processing analyses. In mesh generation for FEM, meshing was realized as triangular meshes as shown in Figure 2, and the blade tip part being densely meshed.

## 3. Result of Analysis

Figure 3 shows the analysis results for the generation process of cutting chips. When Figure 3 (a) is analyzed first, plasticity begins to occur at the tips of 2 blades upon the start of initial processing since a 4-blade end mill was used, and the chips begin to form with overall crumbling in Figure 3 (b). Then, after the chips are formed linearly to the length of about 0.5 cm in Figure 3 (c), the chips can be seen to flow upward while being rolled up in Figure 3 (d). Meanwhile, upon initial processing, plastic deformation can be seen to occur in a center part of the end mill also, as the depth was increased while almost no initial

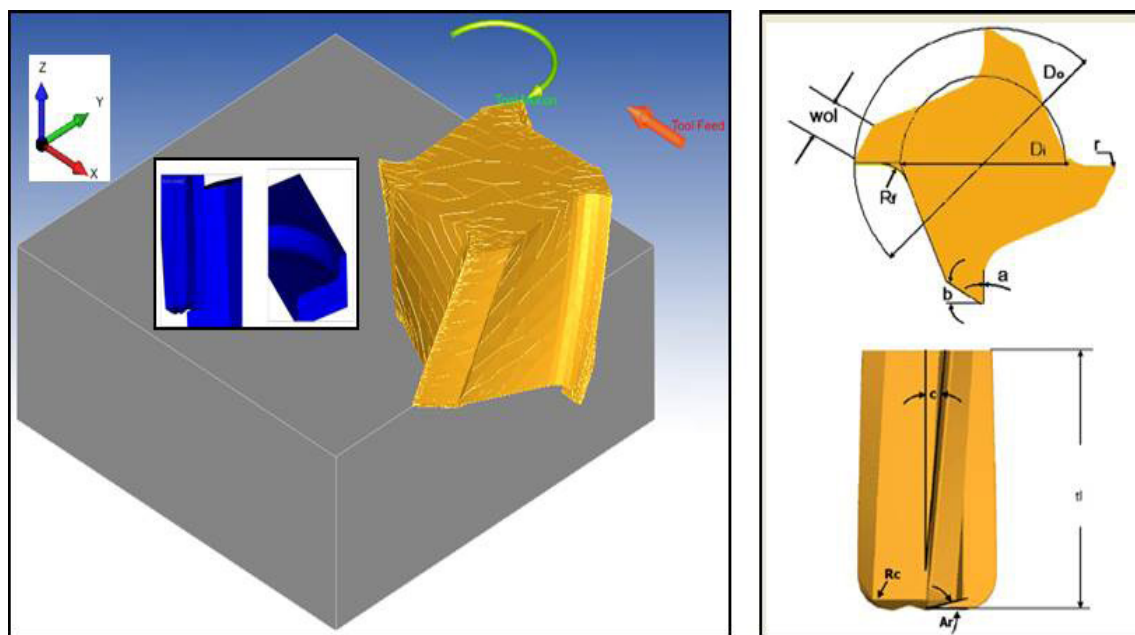
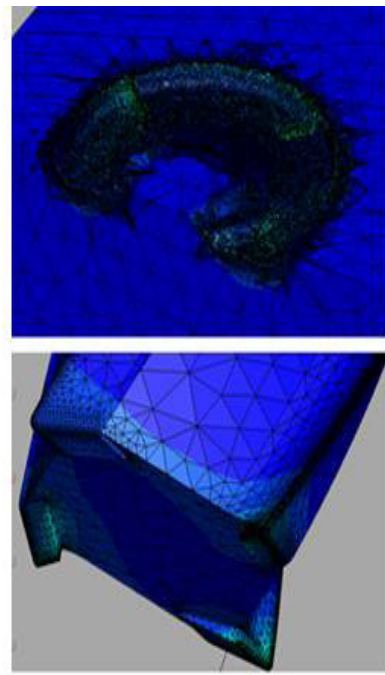
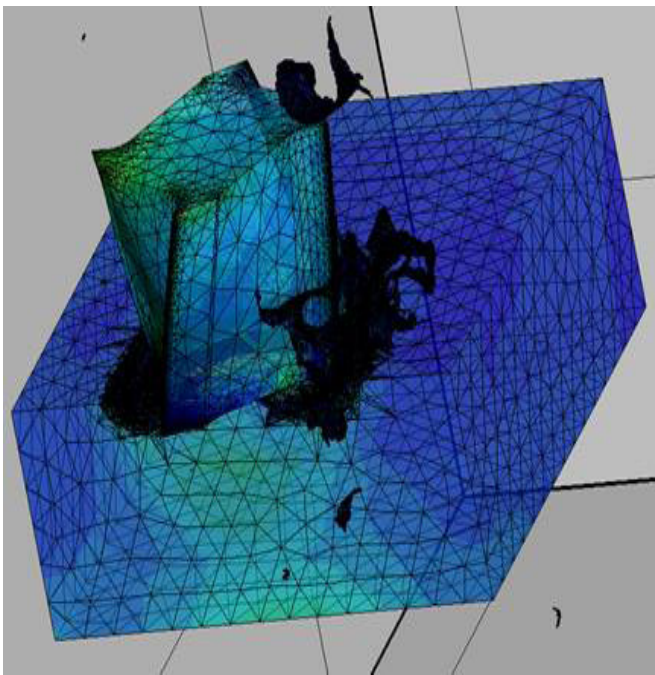
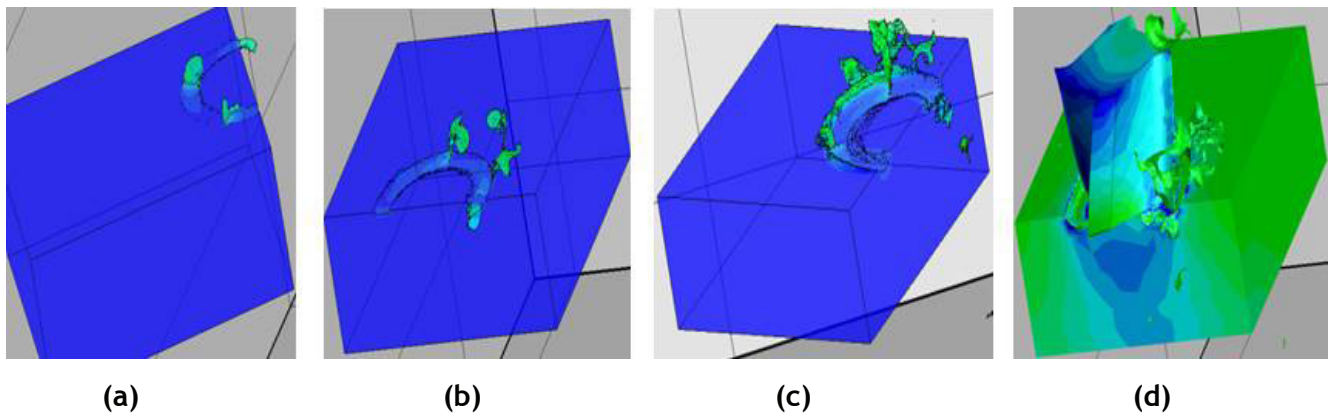


Figure 1. Workpiece and tool.

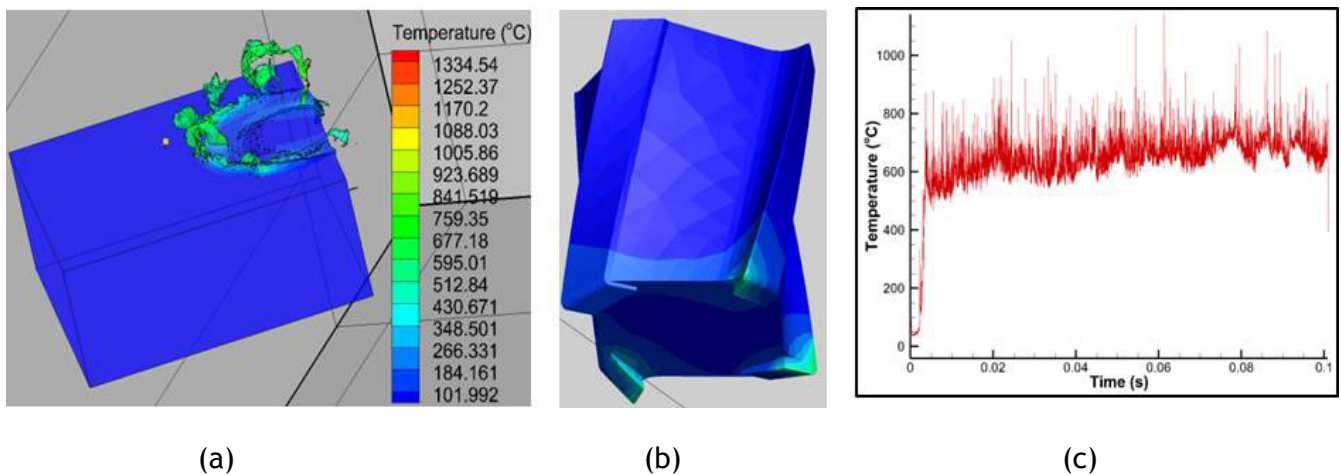
**Table 1.** Spec, of end mill & cutting conditions

| Spec. of End mill       | Unit    | Cutting Conditions      | Unit              |
|-------------------------|---------|-------------------------|-------------------|
| Cutter Diameter [Do]    | 8 mm    | Work piece Size (W*H*D) | 20mm * 20mm * 5mm |
| Core Diameter [Di]      | 6 mm    | Rotationalt Speed       | 600 RPM           |
| Number of Flutes        | 4       | Feed rate               | 100mm/min         |
| Radial Rake Angle [a]   | 5 deg   |                         |                   |
| Helix Angle [c]         | 20 deg  |                         |                   |
| Radial Relief Angle [b] | 30 deg  |                         |                   |
| Axial Relief Angle [Ar] | 10 deg  |                         |                   |
| Corner Radius [Rc]      | 0.2 mm  |                         |                   |
| Edge Radius [r]         | 0.04 mm |                         |                   |
| Flute Radius [Rf]       | 0.8 mm  |                         |                   |
| Width of Land [wol]     | 1.5 mm  |                         |                   |
| Tool Length [TL]        | 6 mm    |                         |                   |

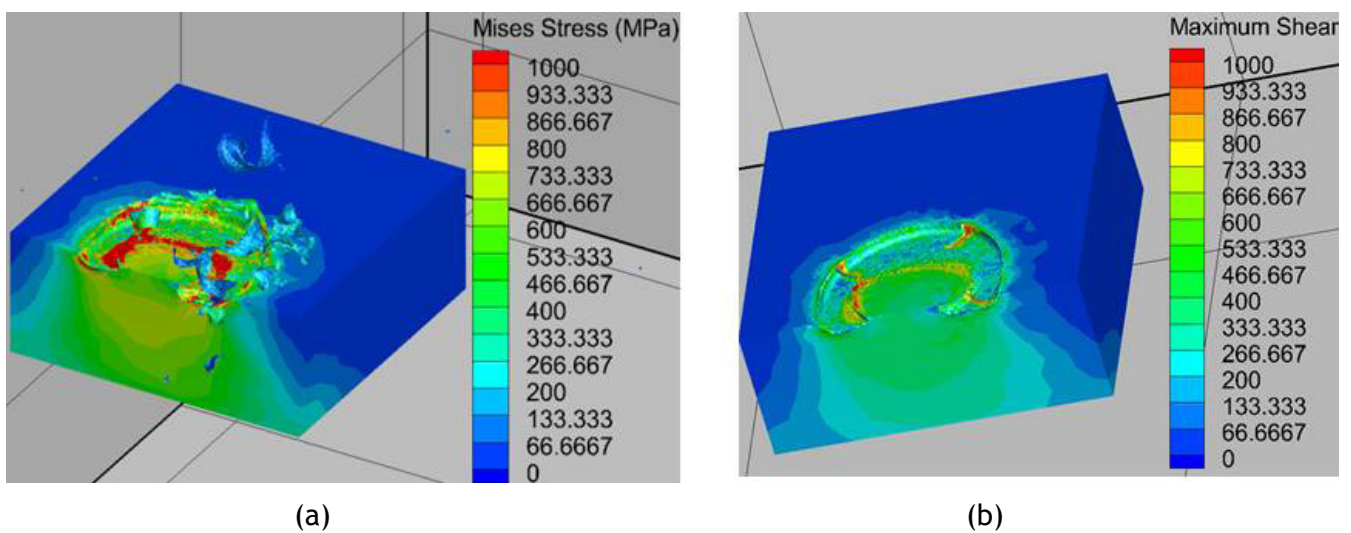
**Figure 2.** Meshing for F. E. M.



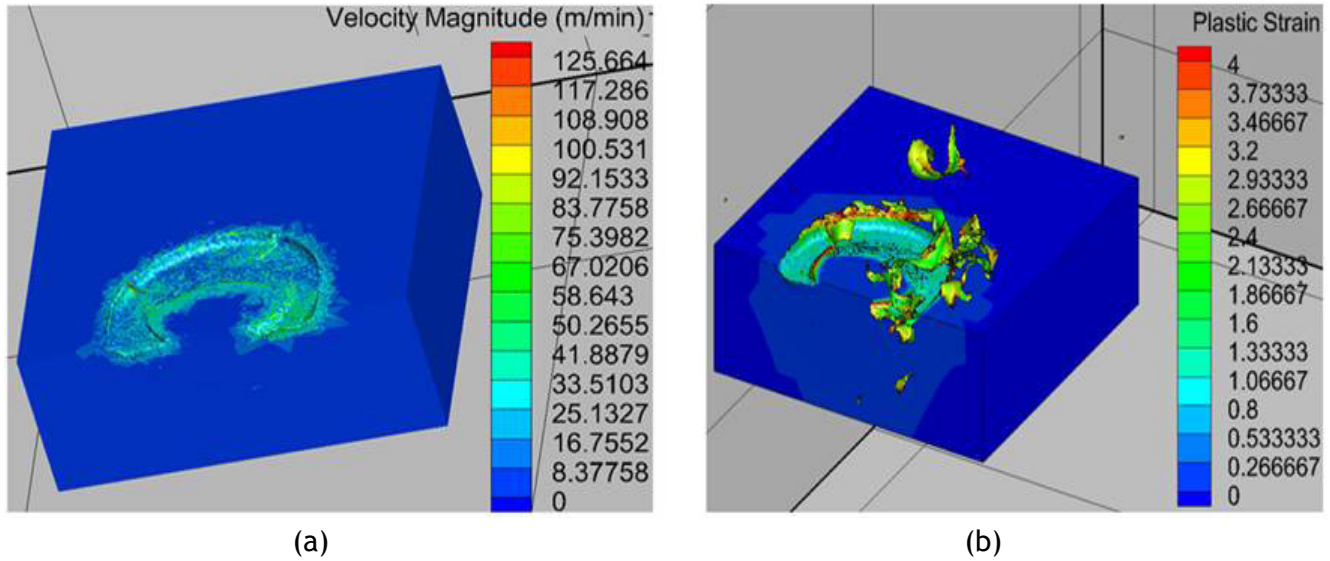
**Figure 3.** Deformation of chip flow.



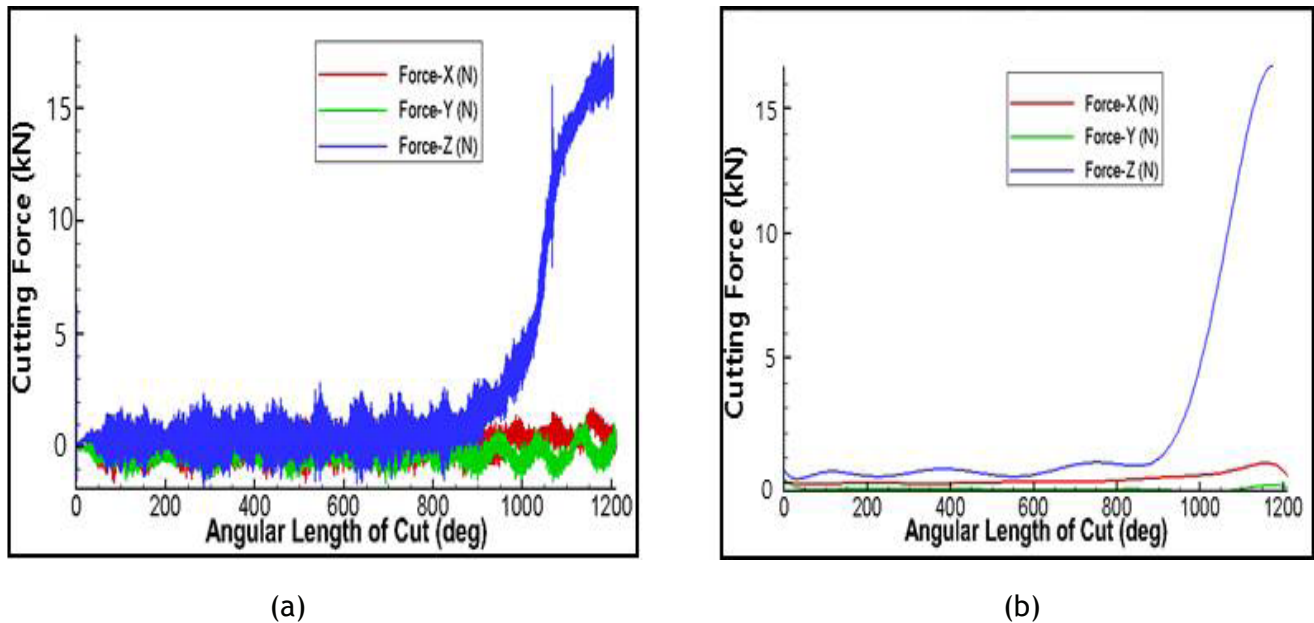
**Figure 4.** Temperature distribution during cutting process. (a) Workpiece. (b) Tool. (c) Temperature vs. cutting time.



**Figure 5.** Mises stress & shear distribution during cutting process. (a) Mises stress. (b) Shear stress.



**Figure 6.** Velocity & plastic strain during cutting process. (a) Velocity. (b) Plastic strain.



**Figure 7.** Cutting force during cutting process. (a) Real time data. (b) Curve fitting of cutting forces.

plasticity occurred in the center part. Next, Figure 4 schematically shows temperatures produced in the tool as well as the workpiece upon processing. For the tool in Figure 4 (b), the maximum temperature occurs at the tip of 4 blades of the end mill, and it can be seen to be raised up

to the maximum of 850°. Also, in the workpiece of Figure 4 (a), the maximum temperature occurs at the blade tip part that was cut the deepest, and a high temperature of about 1334.5° was produced which almost reached melting point. Therefore, work hardening is expected to occur

upon processing due to such high temperature. After the formation of chips by processing flow, rapid cooling may be observed. Figure 4 (c) shows graph conversion of temperature rise data as a function of time variation upon rotation of the initial tool, where the temperature was raised instantaneously from 600° to 700°. Temperature rise at the blade tip of the tool is shown in the graph with the temperature rise being calculated for a very short time from the start to 5 revolutions, where the temperature was drastically affirmed to be raised to 0.4ms, reaching the maximum temperature. Next, analysis results of Mises stress and Shear stress to which the tool and the workpiece are subjected upon processing are shown in Figure 5 (a) and Figure 5 (b). Considerable stresses can be affirmed to be concentrated at the blade tip of the tool. In particular, as shown in Figure 5 (a), the maximum stress of 1,000 Mpa is produced at the blade tip so that wear of the end mill blade is considered to occur upon use over a long period. Meanwhile, in Figure 6 (a), plastic flow rate of the material during processing is schematically shown, where flow at a high rate of about 200m/min is observed in the case of the tip of a chip, while the maximum value of a plastic strain can be seen to occur in the part being cut according to Figure 6 (b). Meanwhile, the cutting force applied to the tool during end mill cutting is schematically shown in Figure 7. Figure 7 (a) represents a real time domain showing cutting forces produced in 3 axes as a function of increase in rotation angles of the tool, the results of curve fitting for which are shown according to the least square method in Figure 7 (b). While similar cutting forces for all of x, y, and z axes are acting initially, those for the x-axis and y-axis can be seen to be drastically increased in a vertical direction up to about 18kN after rotation by about 90°, despite the fact that almost no cutting force is applied. The reason is considered to be application of severe vertical loads so as to act as a compressive stress for the tool as the depth of the end mill is increased in oblique plane processing. This showed an agreement with the occurrence of severe stresses in the inside red part of Figure 5 (a). According to the present analysis results, when an oblique plane was processed rather than a planar groove was processed, severe concentrated loads were produced at the blade tip so that a shivering phenomenon of the tool was considered to occur.

## 4. Conclusions

The present study is represented as an article on the process of planar processing of products after mounting the end mill tool to a milling machine, where cutting results were obtained by an analytical method using the FEM method, and the following results have been obtained.

First, according to the results of analyzing the generation process for cutting chips, it can be seen that plasticity begins to occur initially at 2 blade tips, followed by the formation of chips of about 0.5 cm and subsequent flow upward with the chips being rolled up. Meanwhile, plastic deformation can be seen to also occur in the center part as the depth is increased after almost no plasticity occurred in the center part of the end mill upon initial processing.

Next, according to the results of analyzing temperatures produced in the tool, the temperatures can be seen to be raised to the maximum of 850° at the blade tip of the end mill. Meanwhile, a high temperature almost reaching the melting point was produced in the processed part of the workpiece, which suggested the occurrence of work hardening in the workpiece.

Lastly, according to the results of analyzing cutting forces applied to the tool during end mill cutting, application of a large cutting force in a vertical direction of the tool was affirmed, and severe concentrated loads occurred at the blade tip so that a shivering phenomenon of the tool was considered to occur. This result will be used as the basic data upon product processing or machine tool design.

## 5. Acknowledgement

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