Cutting simulation of titanium alloy drilling with energy analysis and FEM

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Abstract

The drilling of titanium alloy has been increasing in airplane and implant industries. The surface quality is a critical issue in terms of reliability for the parts. Therefore, the surface finish should be evaluated for the cutting parameters in the manufacturing processes. FE analysis is effective in evaluation of not only the cutting process but also the affected layer in subsurface. However, the time for analysis depends on the computer hardware. Because the drilling analysis takes a long time on the normal performance of the computer hardware, it is actually difficult to optimize the cutting parameters and the tool geometry. The paper presents a hybrid simulation of drilling to save the time for analysis. In the hybrid simulation, the FE analysis is conducted in a 2D model determined by the energy analysis for the cutting force prediction. In the energy analysis, the 3 dimensional chip flow in drilling is modeled with piling up the orthogonal cuttings in the plane containing the cutting and the chip flow directions. Then, the FE analysis is applied to the orthogonal cutting model at the end of the lips, which control the surface quality of the drill hole. The cutting forces and the plastic strains in subsurface are shown in the hybrid analysis. The hybrid analysis is applied to drilling of titanium alloy. The hardness tests were conducted to verify the damage area simulated on a nano-indentation machine. Although the presented analysis is an approximation approach, the cutting process is evaluated in a short time in terms of the surface quality.

Keywords: Cutting; Drilling; FEM; Titanium alloy; Cutting force; Chip flow; Surface quality

1. Main text

Titanium alloys, which are lightweight and high strength materials, are used in aerospace industry [1]. Titanium alloys have also been applied to medical and dental implant parts as biocompatible materials [2]. In terms of machinability, titanium alloy is a difficult-to-cut material because of their own material properties, which are different from the conventional metals such as carbon steels. Therefore, the cutting parameters and the tool geometry should be determined properly. Many studies have been done on machining of titanium alloys [3]. The aerospace and the implant parts should be machined with high product qualities as well as high production rates. The surface integrity should also be considered in terms of reliability of the parts [4]. The strain rate and the strain hardening in Ti-6Al-4V alloy were associated with the processing parameters and the grain sizes of primary $\alpha$ phase in isothermal compression [5]. The hardness changes in subsurface were observed in drilling of titanium alloys [6]. The tool wear is also another issue as well as the surface integrity [7]. Several attempts have been tried to improve the tool life [8].

The cutting simulation has recently been used in evaluation of the cutting process. Thus, FEM has been applied to review the chip formation, the cutting force, the cutting temperature, the tool wear and the residual stress in many machining operations [9]. The serrated chip formation in cutting of titanium alloys was demonstrated in the FE analysis [10]. The temperature-dependent flow softening was considered by the modified material models [11]. However, the processing of the FE analysis still takes a long time on the present computer hardware. Therefore, the FE analysis is not effective in optimization of the cutting operations.

Based on the present situation of the FE analysis, the computational time should be reduced in terms of the optimization of the cutting process and design of the tool geometry. The paper presents a hybrid simulation of the analytical force prediction and the FE analysis to evaluate the
cutting process with the plastic strain distributions in the workpiece. An energy analysis of the force model, which is performed as the first step in the hybrid simulation, is described to predict the cutting force and the chip flow direction with the orthogonal cutting model. The simulation is verified in the cutting tests. Then, the FE analysis is conducted in the orthogonal cutting determined by the cutting force analysis. The residual strains in subsurface are evaluated using the result of the FE analysis. The effects of the wedge angle and the feed rate on the plastic strain in subsurface are discussed in the hybrid analysis.

2. Energy analysis/FEM hybrid simulation

Although the cutting process in drilling is analyzed in 3D FEM, the numerical simulation takes a long time. Therefore, faster approach is required to optimize the cutting parameters and the tool geometry. In the energy analysis, the cutting force and the chip flow direction in drilling process is predicted in a short time. 2D FEM simulation has recently been running faster owing to the technology progress in the computer hardware. The computational time, therefore, becomes short by combining the energy analysis and 2D FE analysis. A hybrid simulation model is presented to evaluate the cutting process and the surface damage in a short time. The procedure of the hybrid simulation in drilling is as follows:

1. The energy analysis is conducted to make the orthogonal cutting models in the plane containing the cutting velocities and the chip flow velocities, where the chip flow direction is determined to minimize the cutting energy.
2. The cutting force is predicted with the chip flow direction.
3. 2D FEM simulation is conducted in the orthogonal cutting model at the end of the lips, which is determined in the energy analysis.
4. The plastic strain distribution in subsurface is extracted to evaluate the surface damage. The residual strains are estimated in the depth from the workpiece surface.

3. Force prediction of drilling in energy analysis

3.1. Force model

Because the force model for drilling was presented in Reference [12], the outline is described here. The cutting edges are divided into small segments to consider the change in the tool geometry. Fig. 1 shows a picture of the chips in drilling. The drill has a X thinning to reduce thrust with ploughing effect at the center of the tool. The picture proves that the chip is formed on the chisel as well as on the lip. Although the chip does not generate at the center of the drill and the material forms with indentation, the indentation area is relatively small in drilling with the thinning. The chip formation on the chisel is different from that of the lip. Therefore, the chip flow models are made on the chisel and the lip independently to predict the cutting forces with the chip flow directions.

The chip flow in the oblique cutting of each segment is interpreted as a piling up of the orthogonal cuttings in the planes containing the cutting velocities \( V \) and the chip flow velocities \( V_c \), as shown in Fig. 2. Although plastic deformation actually occurs in the chip flow, the interaction between each orthogonal cutting plane is ignored in the model. In analysis, the orthogonal cutting model is determined at the center of the cutting area first. The cutting models in the other areas are then determined so that the chip flows without internal plastic deformation.

The orthogonal cutting model in each segment is given by Eq. (1), which is acquired in the orthogonal cutting tests:

\[
\begin{align*}
\phi &= f(V, t_1, \alpha) \\
\tau_c &= g(V, t_1, \alpha) \\
\beta &= h(V, t_1, \alpha)
\end{align*}
\]

where \( \phi \), \( \tau_c \), and \( \beta \) are the shear angle, the shear stress on the shear plane and the friction angle. \( V \), \( t_1 \), and \( \alpha \) are the cutting velocity, the uncut chip thickness and the rake angle, respectively.

When the chip flow angle is assumed, the orthogonal cutting models in the chip flow are made by Eq. (1), where the shear angle, the rake angle and the uncut chip thickness in each orthogonal cutting model are determined as \( \phi_c \), \( \alpha_c \), and \( t_{cc} \), respectively. In the penetration and the exit processes of the edges, the inclination of the workpiece surface with respect to the cutting direction is also considered in the orthogonal cutting model. The cutting energy is consumed into the shear energy in the shear plane and the friction energy on the rake face. The shear energy in a segmented area \( dU_s \), is:
where \( l_s \) and \( dL_s \) are the length and the width of the shear plane on the segmented area, respectively.

The friction energy \( dU_f \) is given by the friction force \( dF_t \) and the chip flow velocity \( V_c \) in the following equation:

\[
dU_f = dF_t V_c \tag{3}
\]

where \( dF_t \) is given in the orthogonal cutting model as follows:

\[
dF_t = \tau_f t \omega \frac{\cos \alpha_e}{\cos(\phi_e - \alpha_s)} dL_s \tag{4}
\]

where \( dL_s \) is the width of the tool-chip contact area in the segmented edge. The chip flow velocity at the center of the cutting area removing material is:

\[
V_c = \frac{\sin \phi_e}{\cos(\phi_e - \alpha_s)} V \tag{5}
\]

The chip flow velocities in the other segmented areas on the cutting edge, in turn, are determined geometrically to be a constant angular velocity of the chip curl without plastic deformation in the chip.

The cutting energy \( U \), then, is given by the integration over the range of the height \([h_{\text{min}}, h_{\text{max}}]\) in the cutting area as follows:

\[
U = \int_{h_{\text{min}}}^{h_{\text{max}}} (dU_s + dU_f) dh \tag{6}
\]

The chip flow angle \( \eta \) is determined to minimize \( U \) in the iterative calculation. The cutting force, then, is predicted in the model at the minimum cutting energy.

Fig. 3 shows an orthogonal cutting plane with the cutting force components loaded on a point P of an edge. \( X'-Y'-Z' \) is the coordinate system rotating with the cutting edge at an angular velocity \( \omega \) as shown in Fig. 3(a), where the direction of the cutter radius is defined as \( X' \)-axis. The tangential cutting force in the segmented area \( dF_t \) is:

\[
dF_{th} = (dU_s + dU_f) V \tag{7}
\]

The normal force on the rake face \( dF_n \) is given by:

\[
dF_n = \frac{dF_t}{\cos \alpha_e \cos \alpha_s} \sin \alpha_e \tag{8}
\]

where \( dF_t \) is the friction force given by Eq. (4). \( \alpha_e \) is the radial rake angle of the edge viewed from the inclined direction at an angle of \( \tan^{-1}(f/R_p, \phi) \) and \( \alpha_s \) is the inclination angle of the rake face with respect to \( Z \)-axis direction. The radial component \( dF_r \) and the axial one \( dF_a \) are given by:

\[
\begin{align*}
\{ dF_r &= -dF_t \cos \alpha_e \sin \eta_c' + dF_t \cos \alpha_s \sin \phi_e - dF_t \sin \phi_e \sin \alpha_s \\
\{ dF_a &= dF_t \cos \alpha_e \sin \eta_c' - dF_t \sin \phi_e \sin \alpha_s
\end{align*} \tag{9}
\]

\( \eta_c' \) is the projected angle of the chip flow direction onto the vertical plane including \( X' \)- and \( Z \)-axis.

The thrust force is the sum of \( Z \) components in the cutting forces loaded on all the cutting edges. Torque is given by the integration over the range of the radius \([R_{\text{min}}, R_{\text{max}}]\) in the cutting area as follows:

\[
T = \int_{R_{\text{min}}}^{R_{\text{max}}} r \cdot dF_t dr \tag{10}
\]

3.2. Validation of force prediction

The cutting tests were conducted to validate the cutting force model in drilling of titanium alloy on a 3-axis machining center (Yasuda, YBM640Ver3), as shown in Fig. 4(a). A piezoelectric dynamometer (Kistler, type 9272) was mounted on the table. A 4 mm thick plate was clamped on the dynamometer to measure thrust and torque. A drill shown in Fig. 4(b) was employed in the tests. Table 1 shows the parameters in the tool geometry. The tool material was cemented carbide coated by TiAlN thin layer. The soluble coolant was supplied during drilling.
Fig. 5 compares the predicted and the measured cutting force at a spindle speed of 1327 rpm and a feed rate of 0.1 mm/rev, where the peripheral speed is 25 m/min. The orthogonal cutting data of titanium alloy with the TiAlN coated tool are:

\[
\begin{align*}
\phi &= \exp(3000t_i + 1.005\sigma - 1.343) \\
\tau &= 1194.3 \times 10^6 \\
\beta &= \exp(-2500t_i - 0.3045\sigma - 0.311)
\end{align*}
\] (11)

The simulation is validated in agreement with the actual cutting force. The change in the cutting force of the drilling process is simulated in a few minutes, which is much faster than 3D FEM analysis. Therefore, the process and the tool engineers can review their designs to optimize the drilling operation in a short time.

4. FE analysis

2D FE analyses were conducted for the orthogonal cutting models at the end of the lips, which control the surface qualities of the holes. The cutting parameters and the tool geometries in the orthogonal cutting models determined by the energy analyses are shown in Table 2. Although the simulation performance depends on the FE software, the commercial software, AdvantEdge, was used to analyze the chip formation, the cutting temperature, the stress and the plastic strain in the model. Fig. 6 shows an example of the FE analysis in the cutting operation in Index 1 of Table 2.

In order to evaluate the residual strain in subsurface, the nodal data were extracted from the numerical result. Fig. 7 shows the nodes in the model, where the surface finish is designated in the area more than 5 mm in X-axis and less than 2.952 mm in Y-axis. Fig. 8(a) shows the residual strains in

| Table 2. Cutting parameters and tool geometries in orthogonal cuttings. |
|-----------------------------|-------------|-------------|
| Index 1 | Index 2 | Index 3 |
| Wedge angle deg. | 120 | 120 | 90 |
| Cutting parameters in drilling operation |
| Spindle speed rpm | 50 | 50 | |
| Feed rate mm/rev | 0.1 | 0.05 | 0.1 |
| Uncut chip thickness mm | 0.048 | 0.024 | 0.044 |
| Rake angle deg. | 29.8 | 31.1 | 34.8 |
| Orthogonal cutting model at end of lips |
| Cutting speed m/min | 50.0 | | |

Fig. 5. Cutting force in drilling.
The subsurface of the workpiece from 5.2 mm in X directions, where the strain at each position along X-axis is plotted as a circle. The uniform distribution in the residual strain is confirmed in subsurface.

Fig. 8(b) shows the residual strain distribution less than 2.952 mm in Y directions. Large residual strains appear around the surface; the strain decreases in the depth from the workpiece surface; and, consequently, becomes 0 around a depth of 2.8 mm. Therefore, the thickness of the damage layer is estimated as 0.152 mm.

Because the positions and the values of the strains are scattered with the nodes in FEM model, the strain data are averaged to clear the change in the residual strain. The subsurface area is divided into 0.01 mm segments in the Y direction. Then, the strain values are averaged in each segment. Fig. 9 shows the strain distribution in the Y direction, which corresponds to the result of Fig. 8(b). The change in the...
strain in the depth from the workpiece surface is confirmed more clearly by averaging. Because the residual strain is analyzed in the orthogonal cutting plane containing chip flow direction on Line OA in Fig. 10(a), the depth in OA is transferred to that of OB, as the depth from the surface of the hole. Fig. 10(b) shows the residual strain distribution in Line OB, where the average chip flow angle is 5.4 degrees. The thickness of the damage layer is estimated as 0.015 mm.

In order to verify the analysis result, the hardness in subsurface were measured by nano-indentation hardness tester (Elionix ENT-1100a). The measuring points are shown in Fig. 11(a), which is a cross section underneath the machined surface. According to the hardness distribution in subsurface shown in Fig. 11(b), the thickness of hardened area is regarded as 0.010-0.015 mm, which is the same thickness of the residual strain distribution in Fig. 10(b). Although the residual strain distribution in the FE analysis depends on the mesh size, the edge roundness and the friction coefficient on the tool face, the damage area in subsurface is estimated by the strain distribution analyzed in the hybrid simulation.

5. Effect of wedge angle and feed rate on residual strain

The distributions of the residual strain in the depth from the machined surface are simulated for the orthogonal cutting parameters shown in Table 2. Fig. 12(a) compares the residual strain distributions of cuttings with the drills at wedge angles of 90 and 120 degrees, where the depth from the surface on Line OB in Fig. 10(a) is designated in X-axis. Although the difference is little, the strains in cutting at a wedge angle of 90 degrees are lower than those of 120 degrees. Because the rake angle in the orthogonal cutting model at the end of the lips becomes large at a wedge angle of 90 degrees, the plastic strain reduces with the force loaded on the surface.

Fig. 12(b) compares the strain distributions at feed rates of 0.05 and 0.1 mm/rev. The distributions are nearly the same each other. The effect of the feed rate on the residual strain is small. When the feed rate is reduced, the effect of the edge roundness becomes relatively large. Therefore, the damage area is not suppressed even though the feed rate is small.

6. Conclusions

This study presented the hybrid simulation of the energy and the FE analyses to evaluate not only in the cutting process but also the surface quality. Because 3D FE analysis takes a long time, the time for analysis should be saved to optimize the cutting operations. In the presented simulation, the chip flow model in drilling is made by piling up the orthogonal cutting model first. Then, 2D FE analysis is conducted in the orthogonal cutting determined by the energy analysis. In the energy analysis, the cutting force is predicted with the chip flow direction in a short time. Then, the processing time for 2D FE analysis does not take a long time.

The strain distribution in subsurface is acquired in the FE analysis in the plane containing the chip flow direction. The effect of the cutting parameters and the tool geometry on the residual strain is evaluated by the hybrid simulation.

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