Cutting Force Prediction in Drilling of Titanium Alloy*

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Abstract
Cutting force in drilling of Ti-6Al-4V is studied with simulation based on a predictive model. In the force model, three-dimensional chip flow is made by piling up the orthogonal cuttings in the planes containing the cutting velocities and the chip flow velocities, where the cutting model in each plane is made using the orthogonal cutting data. The chip flow direction is determined to minimize the cutting energy. The cutting force is predicted in the determined chip flow model. The force model is verified in comparison between the predicted and the measured cutting forces. In the rolled titanium alloy, anisotropy is observed in the cutting force. Because the cutting edges rotate in drilling, the cutting force changes periodically with the cutting direction with respect to the rolling direction. Hardness change in subsurface is also measured with a nano indenter. The hardness of the titanium alloy increases around 10 µm underneath the machined surface. Meanwhile, hardness of 0.50% carbon steel does not change. The strain hardening effect is considered by the shear stress on the shear plane in the orthogonal cutting data in the force model.

Key words: Drilling, Titanium Alloy, Cutting Force, Simulation, Chip Formation, Anisotropy, Nano Indentation, Strain Hardening

1. Introduction
Titanium alloys, which are lightweight and high strength materials, are used in aerospace industry(1)(2). Manufacturing of the aircraft parts requires large removal volumes at high production rates. The surface integrity is also critical issue to be considered in terms of reliability of the parts(3). Titanium alloys is also applied to medical and dental implant parts as human adaptive materials(4)(5). Although the medical implant parts are relatively small compared to the aircraft parts, the high product qualities are required with high removal rates.

Many studies have been made on not only cutting but also forming of titanium alloys so far. The major interests are tool wear and surface integrity in cutting of titanium alloy(6). Several attempts have been tried to improve the tool life. The tool lives of cemented carbide and cBN materials for cuttings of titanium alloys were discussed in turning, where the continuous cutting was normally performed(7)(8). In end milling, the tool wears of cBN and PCD were also investigated(9)(10)(11).

Recently the chip formation in cutting has been scientifically discussed in FEM
simulation. The studies on the FEM simulation in cutting were reviewed by Mackerle \cite{12}. When carbon steels are machined, continuous chip formations are normally observed. Meanwhile, in cutting of titanium alloys, serrated chips are formed due to thermal softening and low thermal conductivity \cite{13}. The FEM analysis demonstrated the change in the chip formation with the different material properties \cite{14,15}. In terms of reliability of the product, the residual stress in subsurface after machining was also discussed with changing the cutting parameters. Although many studies on the titanium alloy machining have been done with the FEM analysis, most of them have discussed in the orthogonal cutting.

In manufacturing of the titanium alloy parts, a huge number of drilling operations are performed for their assembly. The chip control, the tool wear and the burr formation are the technical issues to be considered for determination of cutting parameters and design of the tool geometry \cite{16,17}. Because the tool wear is associated with the stress and the temperature on the tool face, predictions of the cutting force and the temperature are required for evaluation of the tool life.

The paper studies the cutting processes in drilling of titanium alloys with the simulation based on a predictive force model. The cutting force is predicted with making three-dimensional chip flow model in drilling using the orthogonal cutting data. The cutting forces of Ti-6Al-4V are measured in the cutting tests. Then, anisotropy of titanium alloy is discussed with observing the dynamic component in the cutting force. The effect of the feed rate on the cutting force of titanium alloy is compared with that of carbon steel. The hardness in subsurface of titanium alloy is measured to estimate strain hardening with a nano-indentation hardness tester. The strain hardening effect of titanium alloy is considered in the orthogonal cutting data in the force model.

2. Predictive Force Model in Drilling

An analytical model is applied to predict the cutting force with the chip flow direction in drilling. The chip flow 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. 1. The cutting edges are divided into small segments to consider the change in the tool geometry. The orthogonal cutting model in each segment is made by Eq. (1), which is acquired in the orthogonal cutting tests:

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

(1)

where $\phi$, $\tau_s$ 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.
Because the cutting velocity \( V \) is the sum of the rotation speed of the edge and the feed rate \( f \), \( V \) is given by:

\[
V = \sqrt{(R_e \omega)^2 + f^2}
\]  

(2)

where \( \omega \) and \( R_e \) are the angular velocity and the radius at a position \( P \) on an edge. Because the cutting direction is inclined at an angle of \( \tan^{-1}(f/R_e \omega) \), the axial rake angle during cutting is regarded as \( \alpha'_a = \alpha_a + \tan^{-1}(f/R_e \omega) \), where \( \alpha_a \) is the nominal angle given by the tool geometry. When a chip flow angle \( \eta_c \) on the rake face is assumed, as shown in Fig. 1, the orthogonal cutting model is made by Eq. (1) with the effective rake angle \( \alpha_e \).

The workpiece surface in the orthogonal cutting plane is inclined with respect to the cutting direction when the edge penetrates and exits workpiece. The uncut chip thickness increases or decreases with the cutter feed. Therefore, the orthogonal model in the transient cutting process is made in the coordinates system inclined at an angle \( \delta_s \), as shown in Fig. 2.

The rake angle of the cutting edge is regarded as \( \alpha'^* = \alpha_e - \delta_s \) in the model. The cutting edge removes the material in the direction of the surface inclination at a cutting velocity of \( \dot{V} = \dot{V} = V \{\cos\delta_s \sin\alpha_e \tan(\eta_c - \delta_s)\} \) in an uncut chip thickness of \( \dot{t}_1 = t_1 \sin\phi^*/\sin\phi \). Therefore, the nominal shear angle \( \phi \) is:

\[
\phi = \delta_s + \phi^*
\]  

(3)

where \( \phi^* \) is given by Eq. (1) at \( \alpha'^*_e, \dot{V} \) and \( \dot{t}_1 \). Then, the shear stress on the shear plane \( \tau_i \) and the friction angle \( \beta \) are given by Eq. (1).

The shear energy in a segmented area \( dU_s \) is:

\[
dU_s = \tau_i l_s dL_s \frac{\cos \alpha_e}{\cos (\phi^*_e + \delta_s - \alpha_e)} V
\]  

(4)

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 \( dF_f \) and the chip flow velocity \( V_c \) in the following equation:

\[
dU_f = dF_f V_c
\]  

(5)

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

\[
dF_f = \tau_i \dot{t}_1 \frac{\sin \beta}{\cos (\phi^*_e + \beta - \alpha_e)} \sin \phi^*_e dL_f
\]  

(6)

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

\[
V_c = \frac{\sin (\phi^*_e + \delta_s)}{\cos (\phi^*_e + \delta_s - \alpha_e)} V
\]  

(7)

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 \([h_{min}, h_{max}]\) in the cutting area as follows:

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

(8)

The chip flow angle \( \eta_c \) is determined to minimize \( U \) in the iterative calculation. The cutting force, then, is predicted in the model at the minimum cutting energy.
Figure 3 shows an orthogonal cutting plane with the cutting force components loaded on a point P of an edge. \( X'\cdot Y'\cdot Z' \) 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 \( dF_H \) is:

\[
(dU_x + dU_y) / V
\]

where \( \alpha_R \) is the radial rake angle of the edge viewed from the inclined direction at an angle of \( \tan^{-1}(f/R_p \omega) \) and \( \alpha_b \) is the inclination angle of the rake face with respect to \( Z\)-axis direction. The radial component \( dF_T \) and the axial one \( dF_V \) are given by:

\[
\begin{align*}
\eta_c' & = \frac{-dF \cos \alpha_e \sin \eta_c + dF \cos \alpha_b \cos \alpha_R}{dF \cos \alpha_e \cos \eta_c' - dF \sin \alpha_R} \\
\eta_c & \equiv \frac{\cos \alpha_e \sin \eta_c' + \cos \alpha_b \cos \alpha_R}{\cos \alpha_e \cos \eta_c' - \sin \alpha_R}
\end{align*}
\]

\[
\begin{align*}
\eta_c' & = \frac{-dF \cos \alpha_e \sin \eta_c + dF \cos \alpha_b \cos \alpha_R}{dF \cos \alpha_e \cos \eta_c' - dF \sin \alpha_R} \\
\eta_c & \equiv \frac{\cos \alpha_e \sin \eta_c' + \cos \alpha_b \cos \alpha_R}{\cos \alpha_e \cos \eta_c' - \sin \alpha_R}
\end{align*}
\]

The chip formations on a chisel and a lip were observed in the cutting experiments. Figure 4 shows a picture of the chips at the interruption of cutting. The picture proves that the chip is formed on the chisel as well as on the lip. However, 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 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 \([R_{min}, R_{max}]\) in the
cutting area as follows:

$$T = \int_{r_{\text{min}}}^{r_{\text{max}}} r \cdot dF_{\mu} dr$$  \hspace{1cm} (12)$$

3. Cutting Experiments

The cutting forces in drilling were measured on a 3-axis machining center, as shown in Fig. 5. A piezoelectric dynamometer was mounted on the table. The workpiece was clamped to measure thrust and torque on the dynamometer (Kistler type9272). A drill was clamped on the spindle with the tool shank interface.
Figure 6 shows the drill employed in the cutting experiments. The geometrical parameters defined as Fig. 7 are shown in Table 1. The tool material is carbide tool coated by TiAlN thin layer. The workpiece is Ti-6Al-4V, which is commonly used in the aerospace, the medical, the marine, and the chemical processing. It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen and the remainder titanium. 8 mm drill holes were machined at cutting speeds of 25, 50 and 75 m/min and feed rates of 0.1 and 0.2 mm/rev. The spindle speeds were 995, 1990 and 2985 rpm.

Figure 8 shows the measured cutting forces. The horizontal axis is adjusted with the cutting time corresponding to the feed rate. Because the drill consists of the chisel and the lips, the drilling process changes as follows:

1. The chisel penetrates the workpiece. The cutting area on the chisel increases with the cutter feed (Process O-A in Fig. 8).
2. The chisel and the lips remove the material. The cutting areas on the lips increase with the cutter feed (Process A-B in Fig. 8).
3. The steady cutting process continues with the constant cutting areas on the chisel and the lips (Process B-C in Fig. 8).
4. The chisel exits the workpiece. The cutting area on the chisel decreases with the cutter feed (Process C-D in Fig. 8).
5. The cutting areas on the lips decrease with the cutter feed (Process D-E in Fig. 8).

Thrust and torque change with the cutter feed in the above steps. The cutting force increases rapidly at engagement of the chisel and increases gradually in penetration of the lips. The cutting force does not change when all part of the chisel and the lips remove the material. The cutting force drops after exit of the chisel and then decreases gradually with the cutter feed.

Figure 9 shows the thrust force and torque in the steady cutting processes (Process B-C in Fig. 8). The cutting force does not change remarkably with the cutting speed. Therefore, the effect of the cutting speed on the cutting force is little in the tested conditions.

It is noted that periodical change in the cutting force is observed with the cutting time, as shown in Fig. 8. Figure 10 shows the power spectrums of the thrust force in the steady process. When the cutting speed is 25 m/min, a prominent component is observed at a frequency of 33 Hz, which is associated with twice the frequency of a cutter rotation.
Furthermore, the frequency does not change with the feed rate. The prominent components are 66 Hz at 50 m/min and 99 Hz at 75 m/min. The component increases with the spindle speed. Because the employed titanium alloy is formed into the plate specimen in rolling, anisotropy appears in the parallel and the perpendicular directions to rolling. Consequently, the cutting force changes periodically with the cutting direction with respect to the rolling direction.

4. Cutting Force of Titanium Alloy

4.1 Validation of Force Model

The cutting forces were predicted in the force model described in Chapter 2. The orthogonal cutting were prepared for the combination of the workpiece and the tool material in the cutting tests. The shear angle $\phi$ [rad], the shear stress on the shear plane $\tau_s$ [Pa] and the friction angle $\beta$ [rad] are associated with the cutting velocity $V$ [m/s], the uncut chip thickness $t_1$ [m] and the rake angle $\alpha$ [rad] in cutting of Ti-6Al-4V with carbide tool coated by TiAlN thin layer:

$$
\begin{align*}
\phi &= \exp(4263t_1 + 0.6742\alpha - 1.070) \\
\tau_s &= \exp(-2451t_1 - 0.9542\alpha + 21.27) \\
\beta &= \exp(-1763t_1 + 0.3710\alpha - 0.1670)
\end{align*}
$$

Because the cutting force does not change with the cutting speed, as shown in Fig. 9, the influencing parameters of the cutting speed were not included in Eq. (13). Although the cutting force of the titanium alloy periodically changes due to anisotropy in the rolled workpiece, the force model predicts the mean value of the cutting force.

Figure 11 shows examples of comparison between the predicted and the measured cutting forces at a cutting speed of 25 m/min. The predicted cutting forces also agree with the measured ones in the other cutting conditions. Figure 12 shows the changes in the cutting force during penetration and exit of the cutting edges at a cutting speed of 25 m/min and a feed rate of 0.1 mm/min. The increase of the cutting force in the prediction agrees

![Graphs showing cutting forces at different feed rates](https://example.com/force_graphs.png)
with that of measured cutting force, as shown in Fig. 12(a). However, in Fig. 12 (b), a little prediction error is observed during exit of the cutting edges from the workpiece though the decreasing rate predicted is nearly equal to the measured rate. When the cutting edges exit from the workpiece, conical chip forms at the end of the workpiece, as shown in Fig. 13. As a result, the measured cutting force is larger than predicted one.

4.2 Cutting Force of Titanium Alloy

In order to discuss the typical cutting force of titanium alloy, the cutting forces were compared with those of 0.50% carbon steel in the simulation. The following orthogonal cutting data were used for prediction of cutting force of carbon steel:

\[
\phi = \exp(0.05870V + 1040t + 0.6742\alpha - 1.239) \\
\tau_r = \exp(0.005900V - 424.6t - 1.500\alpha + 21.31) \\
\beta = \exp(-0.05460V - 885.6t - 0.2388)
\]

Figure 14 compares the predicted and the measured cutting forces. The cutting tests were conducted in the cutting conditions, in which the cutting operations were normally performed in the machine shops. Based on agreement of the predicted and the measured cutting forces, the force model is applied to prediction of the cutting force of carbon steel in drilling.
Figure 15 compares the effect of the feed rate on the cutting force in cutting of titanium alloy with that of carbon steel. In cutting of carbon steel, the cutting force decreases with the feed rate corresponding to the uncut chip thickness. Meanwhile, the cutting force of titanium alloy does not decrease remarkably with the feed rate. The different effect of the feed rate on the cutting force will be discussed later.

Figure 16 shows the hardness change in subsurface after machining, where the hardness is measured with nano-indentation hardness tester (Elionix ENT-1100a). The measuring points are shown in Fig. 16(a), which is a cross section underneath the machined surface. Hardness of carbon steel does not change with the depth from the surface. Meanwhile, hardness of titanium alloy increases near the surface. According to the nano indentation tests performed in Reference (18), hardness in subsurface of the hole machined in drilling is larger than the bulk material hardness at 4–5 GPa. Although the hardness change depends on the cutting conditions, the increase of hardness appears around 10 µm from the surface in Fig. 16(b). Then, the hardness near the surface becomes about 9 GPa. The plastic deformation in subsurface during machining promotes strain hardening.

When the uncut chip thickness is small during a rotation of cutter, the hardened material volume is relatively large compared to the material removal volume in cutting of titanium alloy. It brings about increase of the specific cutting force, the cutting force per unit area. As a result, the cutting force does not become small even though the feed rate is low. The force model considers the strain hardening effect in the orthogonal cutting data. The parameter of uncut chip thickness associating with the shear stress on the shear plane mainly depends on the material properties. Because the parameter is -2451 in cutting of titanium alloy in Eq. (13), the shear stress on the shear plane changes sensitively in response to the uncut chip thickness, as shown in Fig. 17(a). The specific cutting force, then, increases largely when the uncut chip thickness reduces. Consequently, the cutting force does not decrease linearly with the feed rate. In cutting of carbon steel, the parameter of uncut chip thickness, -425, in Eq. (14) is not large and the sensitivity of the shear stress on the shear plane to the uncut
chip thickness is less than that of titanium alloy. Therefore, the shear stress does not change remarkably with the feed rate, as shown in Fig. 17(b). Then, the change in the cutting force corresponds to the material removal volume.

5. Conclusions

A predictive force model based on the minimum cutting energy was applied to simulation of cutting force of Ti-6Al-4V. Three-dimensional chip flow model is made with piling up the orthogonal cuttings in the planes containing the cutting velocities and the chip flow velocities, where the chip flow direction is determined to minimize the cutting energy. Then, the cutting force is predicted in the determined chip flow model. Some conclusions on the typical cutting force of titanium alloy and prediction of the cutting force are summarized as follows:

1. Anisotropy in the material properties appears in the parallel and the perpendicular to the rolling direction. Because the cutting edges rotate in drilling, the cutting direction with respect to the rolling direction changes. Therefore, the periodical oscillation was observed in the measured cutting force.

2. The force model predicts the change in the cutting force without the periodical oscillation. The cutting forces of drillings of titanium alloy are predicted not only in steady processes but also in edges’ penetration and exit processes.

3. The increase of hardness was observed near the surface of titanium alloy due to strain hardening in the nano indentation tests. When the uncut chip thickness is small during a rotation of cutter, the hardened material volume is relatively large compared to the material removal volume. Therefore, the cutting force does not reduce remarkably with the feed rate in drilling of titanium alloy.

4. The force model considers the strain hardening effect in the parameters associating the shear stress on the shear plane with the uncut chip thickness. Because the parameter of titanium alloy is a large negative value, the shear stress becomes large at a low feed rate in cutting of Ti-6Al-4V.

References


