FEM simulation for orthogonal cutting of Titanium-alloy considering ductile fracture to Johnson-Cook model

Makoto NIKAWA*, Hiroki MORI**, Yuki KITAGAWA** and Masato OKADA***

*Department of Mechanical Engineering, Gifu University

1-1 Yanagido, Gifu-shi, Gifu 501-1193, Japan

E-mail: mnikawa@gifu-u.ac.jp

**Student of Graduate School of Engineering, Gifu University

1-1 Yanagido, Gifu-shi, Gifu 501-1193, Japan

***Department of Mechanical Engineering, University of Fukui

3-9-1 Bunkyo, Fukui-shi, Fukui 910-8507, Japan

Received 30 September 2015

Abstract

FEM simulation for the orthogonal cutting of Ti-6Al-4V alloy was investigated. Johnson-Cook's model was used for a flow stress equation of material. Rigid-plastic analysis was carried out using DEFORM-2D and AdvantEdge which were commercial software. For the constants in this model, the initial yield strength, the strain-hardening coefficient, the strain-rate sensitivity, the strain-hardening exponent and the thermal-softening exponent were used a reported value by Meyer-Kleponis. Failure accumulation in the Johnson-Cook model was considered by applying the Cockcroft & Latham law to the failure condition of materials. Some constants of material model and fracture limit value were estimated from the orthogonal cutting test. The friction between the chip and cutting tool was assumed the Coulomb friction $\mu=0.382$. The friction coefficient that applied to simulation was calculated by the results of the cutting test. The validity of the calculation results were considered by comparing with the experimental results that were the cutting force, tool temperature and chip shape. When a ductile fracture condition was not considered ($D_f=0$), the chip shape was calculated the flow type, the characteristic saw-tooth type in titanium alloy was not calculated. The chip shape was varied according to a limit value of the ductile fracture. The calculation result of the tool temperature was approximately accorded with an actual value. It was found that the cutting simulation of the titanium alloy was possible by the Johnson-Cook model that applied a ductile fracture condition as $D_f=0.1$.

Key words : Cutting, FEM, Titanium-alloy, Johnson-Cook model, Ductile fracture condition

1. Introduction

FEM simulation is a strong means to the creation of a new processing method and the optimization of the existing processing method. There are various reports about the simulation of the cutting (Obikawa and Matsumura, 2009), (Ohnishi, 2010), (Xi, et al., 2014). The simulation was actively utilized in the field of plastic working such as the forging and the sheet metal forming, it had become indispensable tools for manufacturing (Kim, 2010), (Wang and Yoshikawa, 2014). However, the simulation was not utilized enough in the field of the cutting. The reason, it is difficult to actually measure the phenomena during cutting due to the severe environments of high temperature, high pressure and high strain rate.

Johnson-Cook model was generally used for a constitutive equation of the numerical analysis of the cutting phenomenon (Shinozuka, 2007). The constants in this equation were determined by a high-speed compression test such as the split Hopkinson pressure bar test (Yamashita and Sato, 2007). But, the strain-rate during cutting was higher than the high-speed compression test (Neugebauer, et al., 2011). Therefore, it was difficult to determine the constitutive equation of materials. Furthermore, the general Johnson-Cook model cannot consider a deformation history by the strain, the strain rate and the temperature. So, it was necessary to consider the failure mechanism due to the

compression test. This calculation technique that introduced the failure condition to Johnson-Cook model was tried (Lesuer, D. R., et al., 2001).

FEM simulation for the orthogonal cutting of Ti-6Al-4V alloy in consideration of a ductile fracture condition was investigated in present study. The cutting force, tool flank temperature, and dimension of the chip after cutting were measured by cutting test, and the constants values of flow stress equation and the limit value of ductile fracture condition for the simulation were determined.

2. Cutting tests

2.1 Milling test

Titanium alloy (Ti-6Al-4V) of t 3 x 100 mm was used as workpiece. Cutting tests of the workpiece were carried out with a NC (Numerical Control) milling machine (KE-55, Makino Milling Machine Co., Ltd.) by dry cutting. Cutting direction was performed by a down-cut. The milling test conditions were shown in Table 1. The tool used in the tests was a one flute throw-away end mill. The cutting forces (F_H , F_V) were measured with a three-component dynamometer. The cutting force in this study was obtained the maximum cutting pulse. The tool flank temperature during cutting was measured using a two-color pyrometer with an optical fiber (Okada, et al., 2014).

Table 1 Milling test conditions.

Tool	Cemented carbide with one flute (Non-coating)
	Diameter (mm) 16
	Tool rake angle (°) -45, -25, -9
	Tool flank angle (°) 5
	Radius of tool edge (mm) 0.02
Cutting speed, V (m/min)	100, 150, 200 (Milling)
Cutting depth to radial direction, R_d (mm)	0.1, 0.3, 0.5
Cutting feed, f (mm/tooth)	0.1
Cutting direction	Down cut
Lubrication	Dry

2.2 Turning test

Disk-like workpiece of Ti-6Al-4V with a thickness of 3mm was used. Testing machine was carried out with a non-numerical controlled lathe. The turning test conditions were shown in Table 2. Cutting speed changes momentarily, because the spindle rotating speed is constant during cutting. So, the cutting force was measured via plural cutting tests around the target cutting speed, and assumed the average value as a cutting force.

Table 2 Turinig test conditions.

Tool	Cemented carbide (Non-coating)
	Tool rake angle (°) -5
	Tool flank angle (°) 5
	Radius of tool edge (mm) 0.02
Cutting speed, V (m/min)	25, 50, 100
Cutting feed, f (mm/rev.)	0.1
Cutting depth t_1 (mm)	0.1
Lubrication	Dry

3. Computer simulation

3.1 Examination of the suitable values of Johnson-Cook model constants

AdvantEdge software was used for examination of suitable values of Johnson-Cook model (Sartkulvanich, et al., 2004) constants. The equation is expressed by eq. (1).

$$\bar{\sigma} = (A + B\varepsilon^n) \left[1 + c \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \cdot \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (1)$$

where A ; initial yield strength, B ; strain-hardening coefficient, C ; strain-rate sensitivity, n ; strain-hardening exponent, m ; thermal-softening exponent, $\dot{\varepsilon}$; equivalent strain rate, $\dot{\varepsilon}_0$; normalized with a reference strain rate, T_m ;

melting temperature of material, T_r ; room temperature.

The constants were reported by several papers (Lee and Lin, 1998), (Meyer and Kleponis, 2001), (Kay, 2003). Fig. 1 shows the flow curves when applied these constants to eq. (1). The constants that used for present study were shown in Table 3. The maximum cutting force, chip shape and the tool flank temperature during cutting were calculated from these reported constants. The dimension of calculation model was determined from the circular arc of the trochoid (Shamoto, 2011). The suitable values of Johnson-Cook model constants to use for present study, it was determined by comparing with the calculated values and the actual values. Fig. 2 shows the schematic drawing of the cutting force of the milling test and the computer simulation. The calculated cutting forces (F_X , F_Y) are direction along X - Y coordinate, different direction to the measured cutting force via milling test. Therefore, the calculated cutting forces were compared with the measurements converted by eq. (2).

$$\begin{cases} F_X = -F_{HX} + F_{VX} \\ F_Y = F_{HY} + F_{VY} \end{cases} \quad (2)$$

where F_H ; Cutting force to the X direction, F_Y ; Cutting force to the Y direction, F_{HX} ; Component force to the X direction of F_H , F_{VX} ; Component force to the X direction of F_V , F_{HY} ; Component force to the Y direction of F_H , F_{VY} ; Component force to the Y direction of F_V .

The friction law between the chip and cutting tool was not clear (Rusinek, R., et al., 2014). In this study, it was assumed the Coulomb friction. The friction coefficient that applied to simulation was calculated by the results of the turning test. The friction coefficient on the rake face is expressed in eq. (3) from the friction force and the normal force to the rake face via a geometric orthogonal cutting model.

$$\mu = \tan\beta = \frac{F_f}{F_{nf}} = \frac{F_H \tan\alpha + F_V}{F_H - F_V \tan\alpha} \quad (3)$$

where β ; Friction angle, F_f ; Friction force, F_{nf} ; Normal force, F_H ; Principal force, F_V ; Thrust force, α ; Rake angle of tool.

F_H and F_V were measured by cutting test. α was determined by tool information. Fig. 3 shows the calculated result of the Coulomb friction coefficient from cutting test. The turning test to Ti-6Al-4V was carried out in this test. The Coulomb friction coefficient was determined with 0.382 that was an average value of calculated results.

The heat transfer coefficient between the tool and workpiece was taken as a 10 kW/m²°C (Karpat, 2011).

3.2 Examination of the limit value of ductile fracture condition

Rigid-plastic analysis was carried out using DEFORM-2D Ver.9.0 which was commercial software. Failure accumulation in the Johnson-Cook model was considered by applying the normalized Cockcroft & Latham law

Fig. 1 Comparison of the flow curves of Johnson-Cook model for Ti-6Al-4V. The solid lines, broken lines and dashed lines were expressed the flow curves that were set to reported constants.

Table 3 Reported constants of Johnson-Cook equation.

Parameter	A (MPa)	B (MPa)	C (-)	n (-)	m (-)
Lee-Lin (Lee and Lin, 1998)	782.7	498.4	0.028	0.28	1.0
Meyer-Kleponis (Meyer and Kleponis, 2001)	862.5	331.2	0.012	0.34	0.8
Kay (Kay, 2003)	1098*	1092*	0.014	0.93	1.1

* Reported value $A=159.246$ (ksi), $B=158.376$ (ksi).

Fig. 2 Schematic drawing of the cutting force of the milling test and the computer simulation. Cutting area was determined from the quantity removed per one flute during the tool rotation.

Fig. 3 Calculated result of the Coulomb friction coefficient from turning test. Black circle dot was expressed the friction coefficient. An average value of friction coefficient was 0.382.

(Umbrello, 2008) to the failure condition of materials. The equation is expressed by eq. (4).

$$D_f = \int \left(\frac{\sigma_{\max}}{\bar{\sigma}} \right) d\varepsilon \quad (4)$$

where D_f ; fracture limit value, $\sigma_{\max}$; maximum principal stress, $\bar{\sigma}$; equivalent stress, $d\varepsilon$; equivalent strain increment.

The validity of the calculation results were considered by comparing with the experimental results that were the cutting force, tool temperature and chip shape.

4. Results and discussions

4.1 Examination of the constants of Johnson-Cook equation

The suitable constants in present study were determined via comparison of the results of milling test and the computer simulation.

Fig. 4 shows the relation between the cutting force and the rake angle. Cutting force was expressed the magnitude per a unit cutting width. The actual value of the cutting force was decreased with increasing the rake angle. The

calculated value was a similar tendency.

Fig. 5 shows the relation between the cutting force and the cutting depth. The actual value of cutting force was increased with increasing the cutting depth. The calculated value was approximately a same tendency.

Fig. 6 shows the relation between the cutting force and the cutting speed. The actual value of F_X was decrease with increasing the cutting speed. The actual value of F_Y didn't change significantly with the increasing the cutting speed in this test range. The calculated result using the all constants except Kay's constant was showed a similar tendency.

Fig. 7 shows the relation between the tool temperature and the cutting speed (Okada, et al., 2012). The actual tool temperature was increased with the increasing cutting speed, the calculated results by the constants of Meyer-Kleponis was approximately accorded.

Fig. 4 Relation between the cutting force and the tool rake angle. The white dots were expressed the actual value. The black dots were expressed the calculation value.

Fig. 5 Relation between the cutting force and the cutting depth. The white dots were expressed the actual value. The black dots were expressed the calculation value.

Fig. 6 Relation between the cutting force and the cutting speed. The white dots were expressed the actual value. The black dots were expressed the calculation value.

Fig. 7 Relation between the tool temperature and the cutting speed. The white dots were expressed the actual value (Okada, et al., 2012). The black dots were expressed the calculation value.

Fig. 8 shows the comparison of the calculated results of chip shape. The chip shapes which calculated by the reported constants of Meyer-Kleponis and Lee-Lin were approximately the same. The chip thickness which calculated by Kay's constant was large than other results. The saw-tooth type chip which was a characteristic chip shape of the titanium alloy was not able to calculate clearly in these constants.

The suitable value of Johnson-Cook equation constants for this study was examined by comparing of the cutting test and the computer simulation. The calculation results using the reported constants were qualitatively accorded for the actual results. But, there were large difference of the deviation between the actual value and the calculated value. Furthermore, the difference of chip shape was confirmed by these reported constants.

Therefore, it was considered desirable to apply a reported constant by Meyer-Kleponis to Johnson-Cook equation in this study.

Actual shape	Calculated shape (Meyer-Kleponis)	Calculated shape (Lee-Lin)	Calculated shape (Kay)

Fig. 8 Comparison of the chip shape. The left microscopic observation was expressed the chip of Ti-6Al-4V.

4.2 Examination of the limit value of ductile fracture condition

Fig. 9 shows the effect of the limit value of fracture condition (D_f). When a fracture condition was not considered with $D_f = 0$, the chip shape was calculated the flow type, the saw-tooth type chip was not calculated. When a fracture condition was considered with $D_f = 0.1$, the chip shape was calculated the saw-tooth type. However, the limit value of fracture value was increased to $D_f = 0.2$, the calculated chip shape was changed to the flow type. The chip shapes were varied according to a limit value of the fracture law.

Fig. 9 Comparison of the calculated results of chip shape. The limit value of fracture condition (D_f) of zero means that it was calculated without considering eq. (4). Cutting speed of 25m/min, Tool rake angle of 5°.

Fig. 10 shows the change of cutting force during cutting with one flute of tool by computer simulation. The cutting forces were decreased with increasing the cutting distance, because the chip thickness was gradually decreased. The F_X were approximately the same value in $D_f = 0$ and 0.2. F_Y in $D_f = 0$ and 0.2 were showed a periodic variation. However, the calculated value of F_X in D_f is 0.1, it was greatly fluctuated. F_Y in $D_f = 0.1$, showed an irregular variation. This periodical change of the cutting force was approximately accorded with the cycle of the ridge and the valley of the chip (Appendix A). These results suggested that there was the suitable value of fracture condition for computer simulation of titanium alloy.

Fig. 10 Cutting force history during cutting by computer simulation. The black arrow in the figure which showed results of $D_f = 0.1$ was expressed that the ridge of the chip had begun to be formed. The white arrow was expressed that the valley of the chip. These actual values were adopted from reported values (Okada, et al., 2012)

Fig. 11 shows the influence of the limit value of fracture on the calculated cutting force. These cutting forces were assumed the maximum calculated value in Fig. 10. The calculated value was approximately the constant value with change of the limit value of fracture. The suitable limit value of fracture condition was determined to be 0.1 from the comparison result of cutting force and chip shape.

Fig. 11 Influence of the limit value of fracture on the calculated value of cutting force.

These examinations were carried out about milling of the titanium alloy. However, there is the concern that the limit value of fracture and the constants of constitutive equation are effective for only to the present tool shape, cutting conditions and cutting method. So, we have applied the all decided numbers to computer simulation of turning.

Fig. 12 shows the relation between cutting force and the limit value of ductile fracture. The cutting force was increased with increasing the limit value, D_f value was 0.1 or more, the cutting force was approximately constant value. The calculation result of F_X was approximately 80 N lower than actual value. F_Y was approximately accorded with experiment. The calculated F_X was a large difference with the actual value. In this present study, the simulation parameters such as the constants of Johnson-Cook law and the heat transfer coefficient were used with the reported values. The approximate prediction was possible by calculation applying these values. However, it was possible to improve the calculation accuracy via detailed examination (Appendix B).

Fig. 12 Relation between the cutting force and the limit value of fracture in turning process.

Fig. 13 shows the calculated results of the chip shape with the change of limit value of fracture. The chip shape with the saw-tooth type was calculated by using $D_f = 0.1$ which was suitable limit value of fracture in computer simulation of milling.

These results suggested that the limit value of fracture and constants of constitutive equation in computer simulation of milling of Ti-6Al-4V alloy were able to apply to the turning simulation.

Fig. 13 Comparison of the calculated results of the chip shape in turning simulation. Cutting speed of 50m/min, Cutting depth of 0.1mm, Tool rake angle of -5° ,

5. Conclusions

FEM simulation for the orthogonal cutting of Ti-6Al-4V alloy in consideration of a fracture condition was investigated in this study. Johnson-Cook model was used for constitutive equation, the equation constants reported by plurality of researchers examined the suitable values for milling simulation of Ti-6Al-4V. The fracture condition was used a Cockcroft & Latham law. The results are summarized as follows:

- 1) For the constant of the Johnson-Cook model, a reported value by Meyer-Kleponis was suitable in present study.
- 2) The saw-tooth type chip was calculated by considering a fracture condition.
- 3) The ductile fracture value was estimated to be 0.1 in milling simulation.
- 4) The ductile fracture value and the constants of constitutive equation were effective for turning simulation.

Acknowledgement

The part of this study was financially supported by the Koshiyama Research Grant.

References

- Karpat, Y., Temperature dependent flow softening of titanium alloy Ti6Al4V: An investigation using finite element simulation of machining, *Journal of Materials Processing Technology*, Vol. 211(2011), pp.737-749.
- Kay, G., Failure modeling of titanium 6Al-4V and aluminum 2024-T3 with the Johnson-Cook Material Model, Lawrence Livermore National Laboratory Final Report, (2003), DOT/FAA/AR-03/57.
- Kim, S. Y., Recent trend of CAE in forging process design of automotive part, *Journal of the Japan Society for Technology of Plasticity*, Vol. 51, No. 589(2010), pp. 106-110 (in Japanese).
- Lee, W. and Lin, C., High-temperature deformation behavior of Ti6Al4V alloy evaluated by high strain-rate compression tests, *Journal of Materials Processing Technology*, Vol. 75(1998), pp.127-136.
- Lesuer, D. R., Kay, G. J. and LeBlanc, M. M., Modeling Large-Strain, High-Rate Deformation in Metals, Third Biennial Tri-Laboratory Engineering Conference Modeling and Simulation, Pleasanton, CA, November 3-5, 1999 (2001), Paper No. UCRL-JC-134118.
- Meyer, H. W. and Kleponis, D. S., Modeling the high-strain rate behavior of titanium undergoing ballistic impact and penetration, *International Journal of Impact Engineering*, Vol. 26(2001), pp.509-521.
- Neugebauer, R., Bouzakis, K.-D., Denkena, B., Klocke, F., Sterzing, A., Tekkaya, A. E. and Wertheim, R., Velocity effects in metal forming and machining processes, *CIRP Annals-Manufacturing Technology*, Vol. 60(2011), pp.627-650.
- Obikawa, T. and Matsumura, T., Cutting theory and simulation – State of the art of the prediction of cutting performances, *Transactions of the Japan Society of Mechanical Engineers, Series C*, Vol. 75, No. 757(2009), pp. 2379-2386 (in Japanese).
- Ohnishi, Y., Finite element analysis software of cutting, *Journal of the Japan Society for Precision Engineering*, Vol. 76, No. 8(2010), pp.857-860 (in Japanese).
- Okada, M., Hosokawa, A., Asakawa, N., Fujita, Y. and Ueda, T., Influence of minimum quantity lubrication on tool temperature in end milling of difficult-to-cut materials having low thermal conductivity, *Transactions of the Japan Society of Mechanical Engineers, Series C*, Vol. 78, No. 792(2012), pp.3093-3103 (in Japanese).
- Okada, M., Hosokawa, A. and Asakawa, N., End milling of stainless steel and titanium alloy in an oil mist environment, *The International Journal of Advanced Manufacturing Technology*, Vol. 74(2014), pp. 1255-1266.
- Rusinek, R., Wiercigroch, M. and Wahi, P., Modelling of frictional chatter in metal cutting, *International Journal of Mechanical Sciences*, Vol. 89(2014), pp. 167-176.
- Sartkulvanich, P., Koppka, F. and Altan, T., Determination of flow stress for metal cutting simulation - a progress report, *Journal of Materials Processing Technology*, Vol. 146(2004), pp. 61-71.
- Shamoto, E., Mechanism and suppression of chatter vibrations in cutting, *Denki Seiko*, Vol. 82, No. 2(2011), pp.143-155 (in Japanese).
- Shinozuka, J., FEM simulation technique on metal cutting processes, *Denki Seiko*, Vol. 78, No. 3(2007), pp.233-240 (in Japanese).
- Umbrello, D., Finite element simulation of conventional and high speed machining of Ti6Al4V alloy, *Journal of Materials Processing Technology*, Vol. 196(2008), pp. 79-87.
- Wang, Z. and Yoshikawa, Y., A new forming method of triple cup by plate forging, *Procedia Engineering*, Vol. 81(2014), pp. 389-394.
- Xi, Y., Bermingham, M., Wang, G. and Dargusch, M., SPH/FE modeling of cutting force and chip formation during thermally assisted machining of Ti6Al4V alloy, *Computational Materials Science*, Vol. 84(2014), pp. 188-197.
- Yamashita, M. and Sato, H., Relationship between commencement time of impact compression and commencement time of observed stress pulses - Study of standardization of impact compression test by split Hopkinson pressure bar technique with the aid of numerical simulation I, *Journal of the Japan Society for Technology of Plasticity*, Vol. 48, No. 558(2007), pp. 635-639 (in Japanese).

Appendix A

Fig. A Calculation results of the generation process of the saw-tooth type chip during milling of Ti-6Al-4V. Cutting speed of 25 m/min, Tool rake angle of 5° , Ductile fracture limit value of 0.1.

Appendix B

Fig. B Examination of the improvement of the calculation accuracy. There results were compared with actual value and the calculation value in turning of Ti-6Al-4V.