# 3D Finite Element Analysis of Drilling of Ti-6Al-4V Alloy

Y. Su, D.D. Chen, L. Gong
College of Mechanical Engineering
Jiangsu University of Science and Technology
China

*Abstract*——**Drilling is an important machining process. A 3D FE model of drilling titanium alloys is developed using commercial finite element software DEFORM 3D. Simulations are carried out under different feed rates and drilling speeds to investigate the effect of drilling parameters on machining performance. The simulation results indicate the influence of machining parameters on drilling force, torque, and maximum tool temperature. The optimum drilling parameters are also recommended for drilling of Ti-6Al-4V according to the FE simulations.**

*Keywords-drilling；finite element analysis；model；Ti-6Al-4V；drilling force；torque；maximum tool temperature*

## I. INTRODUCTION

With the development of machinery industry, higher requirements are put forward for the product quality and material properties. Drilling is a very important step throughout the machining process. In the past, a lot of experiments need to be conducted to obtain a series of related data during the drilling studies, which brings about huge raw materials consumption. Finite element method can make up this shortcoming. Finite element simulation can not only save the raw materials but also improve the accuracy of results. Furthermore, finite element analysis can also obtain the measured data which is difficult to obtain in experiment. Nowadays some scholars have studied drilling process based on the finite element simulation technology. For instance, F. Klocke et al. [1] introduced a three dimensional thermo-mechanical coupled finite element model for drilling AISI 4150 quenched and tempered steel by using carbide gun drills with two different diameters to predict the cutting forces as well as the temperature in gun drilling process. Y.B. Guo et al. [2, 3] investigated the burr formation using FE analysis of 3D drilling. O. Isbilir et al. [4] developed a 3D finite element model of drilling process using commercial finite element software ABAQUS/Explicit, and studied the effect of feed rate on thrust force, torque and burr height. The results indicate that the established FE model of drilling can predict changes in machining performance with respect to drilling parameters.

In this paper, a 3D finite element model of drilling of titanium alloys is first constructed, and then simulations are conducted under different drilling speeds and feed rates in order to analyze and compare the influence of drilling parameters on drilling force, torque and temperature.

## II. FINITE ELEMENT MODELLING DETAILS

### A. Geometric Model and Element Meshing

Drill is a kind of complex cutting tool. Fig. 1. shows the geometry of drill. The geometry parameters of drill used in the model are given in table 1. The workpiece is created as a cylinder in this study, whose diameter and height are 16 mm and 10 mm, respectively. And there is a centering hole on the top surface of workpiece, whose depth is set at 1.1 mm. Fig. 2. shows the geometric model of drilling process.

The drill and workpiece are divided into 25,000 and 35,000 grids, respectively. Pre-cutting region of workpiece is further subdivided so as to obtain a high simulation accuracy. Fig. 3. shows the mesh of workpiece and drill.
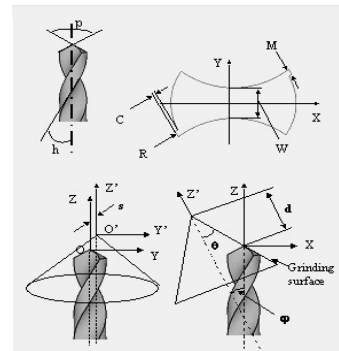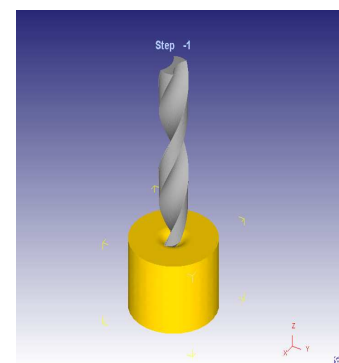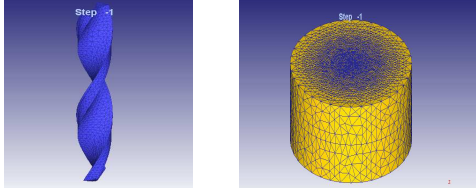


FIGURE I. DRILL GEOMETRY.



FIGURE II. GEOMETRIC MODEL.

TABLE I.        TOOL GEOMETRY PARAMETERS

| DIAMETER (MM) | P (DEG) | H (DEG) | R (MM) | Θ (DEG) | W (MM) | C (MM) | S (MM) | D (MM) |
|---|---|---|---|---|---|---|---|---|
| 6 | 118 | 26 | 3 | 35.86 | 0.9 | 4.53 | 1.19 | 3 |



(a) Drill        (b) Workpiece

FIGURE III.   MESH OF WORKPIECE AND DRILL.

## B.   Material Properties

Carbide (WC) is selected as the material of drill and Ti-6Al-4V is selected as the material of workpiece in this model. A classical Johnson-Cook model is selected as flow stress model of workpiece. This model can be represented by the following expression:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})[1 - (\frac{T - T_r}{T_m - T_r})^m]$$

(1)

where $\varepsilon$ is the plastic strain, $\dot{\varepsilon}$ is the strain rate (s-1), $\dot{\varepsilon}_0$ is the reference plastic strain rate (s-1), T is the temperature of workpiece (℃), Tm is the melting temperature of the workpiece (℃), Tr is the room temperature (℃). Coefficient A is the yield strength (MPa), B is the hardening modulus (MPa), C is the strain rate sensitivity coefficient, n is the hardening coefficient and m is the thermal softening coefficient. The Johnson-Cook parameter values of Ti-6Al-4V are presented in table 2 [5].

TABLE II.        JOHNSON-COOK PARAMETER VALUES OF TI-6AL-4V ALLOY.

| A (MPa) | B (MPa) | C | n | m |
|---|---|---|---|---|
| 782.7 | 498.4 | 0.028 | 0.28 | 1 |

## C.   Simulation Conditions

In the simulation, the workpiece is fixed in all directions. The drill rotates around Z axis and moves down along Z axis at the same time. The initial temperature and convection heat transfer coefficient of environment are set at 20℃ and 0.02 N/sec /mm/℃, respectively. As far as the friction between tool and chip is concerned, a constant shear stress model is used and the friction factor is set equal to 0.6. The drilling speed $v_c$ is set at 9.42, 11.3 and 13.19 m/min. The feed rate $f$ is set at 0.08, 0.12 and 0.16 mm/rev. Thus, 9 simulations are performed. The total simulation step is set at 10000 for each simulation.

## III.        RESULTS AND DISCUSSION

### A.   Influence of Drilling Parameters on Drilling Force

Drilling force not only determines the power consumption of drilling but also directly affects the cutting heat generated during the drilling process. Figs. 4. and 5. show the variation of axial force (Z load) with time for different feed rates and drilling speeds, respectively. It can be seen that drilling force increases when the drill cuts into Ti-6Al-4V alloy, and then reaches a steady value. After that, it fluctuates in a certain range.
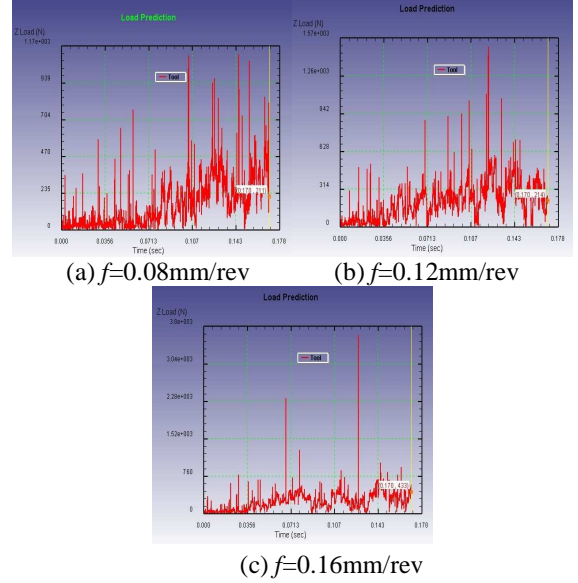


(a) f=0.08mm/rev        (b) f=0.12mm/rev



(c) f=0.16mm/rev

FIGURE IV.   AXIAL FORCE AGAINST TIME UNDER DIFFERENT FEED RATES (VC =9.42 M/MIN).



(a) $v_c$ =9.42m/min        (b) $v_c$ =11.3m/min
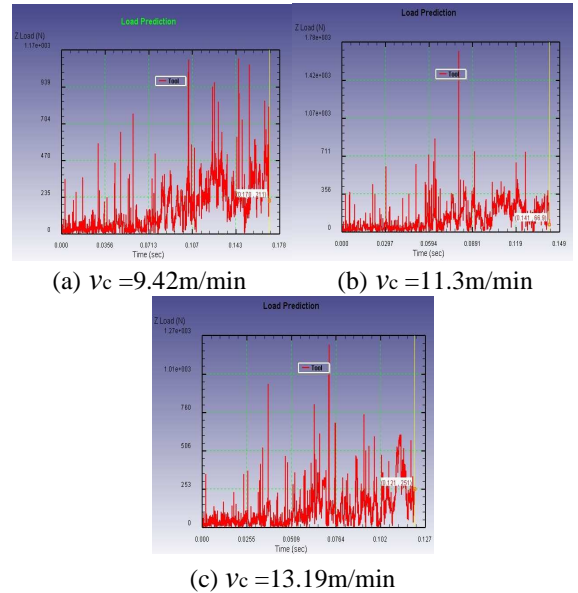


(c) $v_c$ =13.19m/min

FIGURE V.   AXIAL FORCE AGAINST TIME UNDER DIFFERENT DRILLING SPEEDS (F=0.08MM/REV).

Figs. 6. and 7. show the variation of drilling force with drilling speed and feed rate obtained from simulation,

respectively. As shown in fig. 6, when the feed rate remains at 0.08 mm/rev, the drilling force decreases with the increase of drilling speed. And it increases with the increase of drilling speed when the feed rate remains at 0.12 mm/rev and 0.16 mm/rev. Meanwhile, according to fig. 7, drilling force increases with the increase of feed rate, especially at a high drilling speed (13.19 m/min). The lowest drilling force can be obtained at the feed rate of 0.08 mm/rev and the drilling speed of 13.19 m/min. By comparing fig. 6. with fig. 7., it can be found that drilling force increases more rapidly with increasing the feed rate, indicating that feed rate has a more significant effect on drilling force than drilling speed.
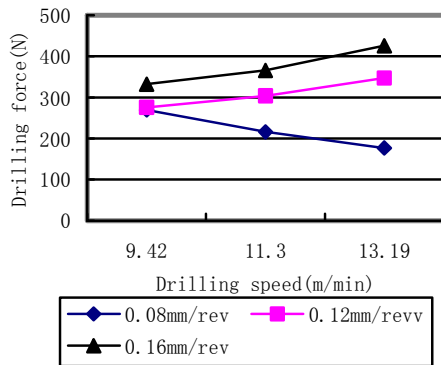


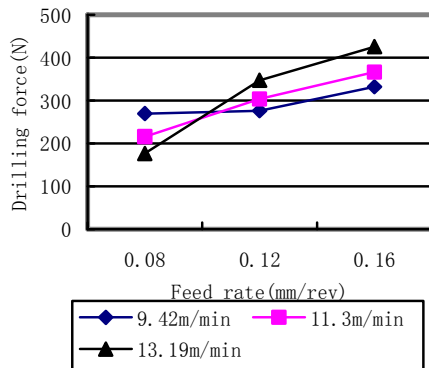FIGURE VI.  VARIATION OF DRILLING FORCE WITH DRILLING SPEED FOR VARIOUS FEED RATES.



FIGURE VII.  VARIATION OF DRILLING FORCE WITH FEED RATE FOR VARIOUS DRILLING SPEEDS.

*B.  Influence of Drilling Parameters on Tool Temperature*

The predicted distribution of temperatures in the drill for different feed rates and drilling speeds are shown in figs. 8. and 9, respectively. The maximum temperatures are indicated in each distribution. As shown in figs. 8. and 9, the maximum tool temperature appears in the vicinity of main cutting edge. Besides it, there is also high temperature in the chisel edge of drill.

Fig. 10. shows the variation of maximum tool temperature with drilling speed for different feed rates obtained from simulation. At the feed rates of 0.08 and 0.12 mm/rev, maximum tool temperature increases with increasing drilling speed from 9.42 m/min to 11.3 m/min. Further increase in drilling speed results in a little change in maximum tool temperature. However, at the feed rate of 0.16 mm/rev, maximum tool temperature increases continuously with increasing drilling speed from 9.42 m/min to 13.19 m/min. Fig. 11. shows the variation of maximum tool temperature with feed rate for different drilling speeds obtained from simulation. By comparing fig. 10. with fig. 11., it can be seen that the increase in maximum tool temperature resulting from increasing feed rate are more obvious than that resulting from increasing drilling speed.
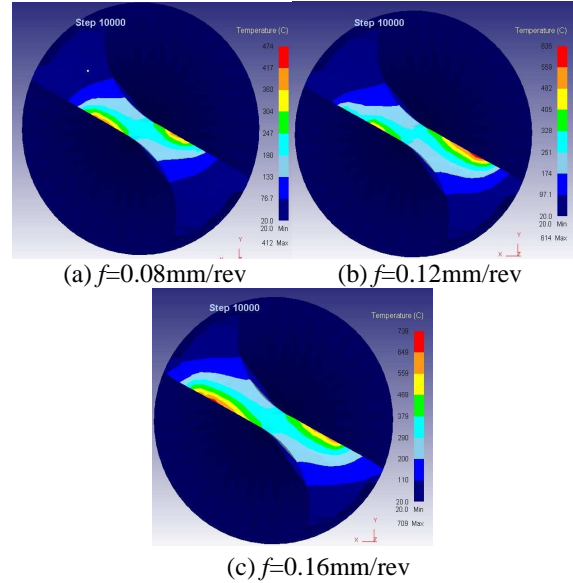


(a) *f*=0.08mm/rev          (b) *f*=0.12mm/rev



(c) *f*=0.16mm/rev

FIGURE VIII.  PREDICTED TEMPERATURE DISTRIBUTION OF DRILL (VC =9.42 M/MIN).



(a) *v*c =9.42m/min          (b) *v*c =11.3m/min



(c) *v*c =13.19m/min
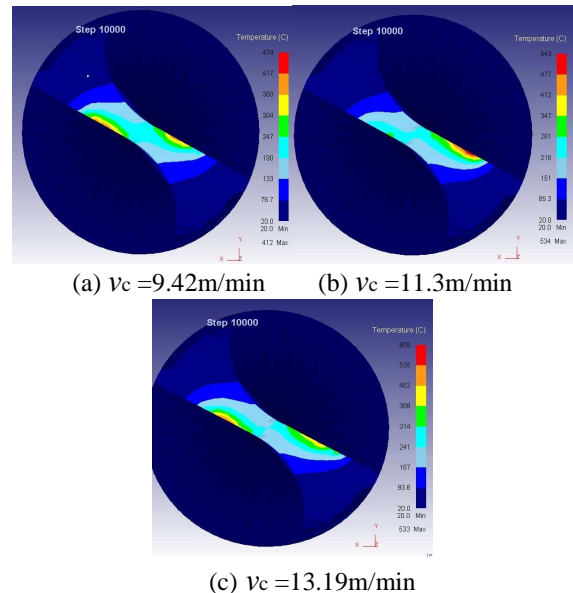
FIGURE IX.  PREDICTED TEMPERATURE DISTRIBUTION OF DRILL (F=0.08MM/REV).
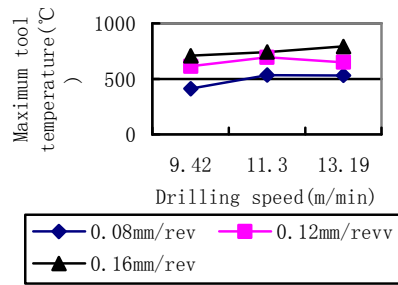
FIGURE X.   VARIATION OF MAXIMUM TOOL TEMPERATURE
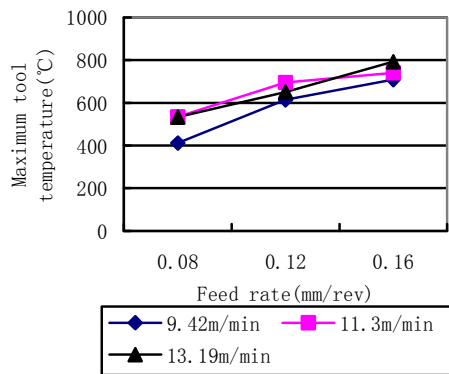WITH DRILLING SPEED FOR DIFFERENT FEED RATES.



FIGURE XI. : VARIATION OF MAXIMUM TOOL TEMPERATURE
WITH FEED RATE FOR DIFFERENT DRILLING SPEEDS.

## C.  Influence of Drilling Parameters on Torque

Drilling torque is an important parameter for drill design. Excessive torque will lead to the fracture of drill. Figs. 12. and 13. show drilling torque against time for different feed rates and drilling speeds, respectively. As shown in figs. 12. and 13, the trend of drilling torque against time is similar with that of drilling force against time.
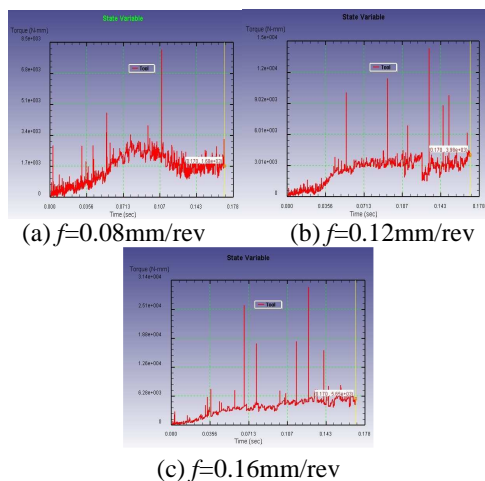


(a) f=0.08mm/rev       (b) f=0.12mm/rev



(c) f=0.16mm/rev

FIGURE XII.   TORQUE AGAINST TIME UNDER DIFFERENT FEED
RATES (VC =9.42 M/MIN).



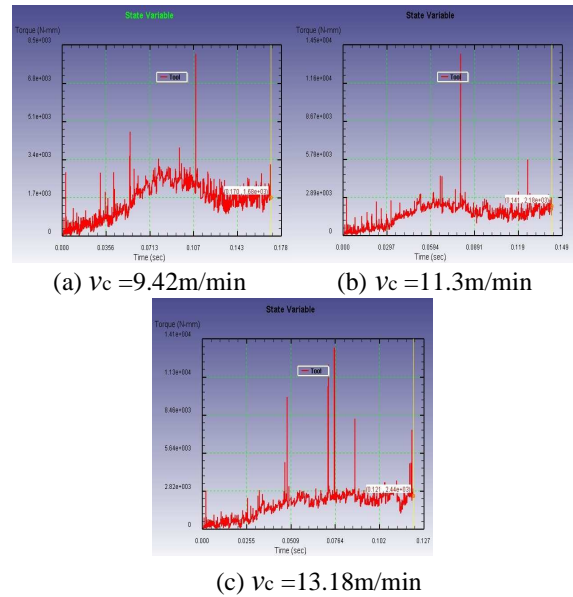(a) vc =9.42m/min          (b) vc =11.3m/min



(c) vc =13.18m/min

FIGURE XIII.  TORQUE AGAINST TIME UNDER DRILLING
SPEEDS (F=0.08MM/REV).

Figs. 14. and 15. show the variation of drilling torque with drilling speed and feed rate obtained from simulation, respectively. It is illustrated in fig. 14. that drilling torque decreases with the increase of drilling speed when feed rate remains at 0.16 mm/rev, and it increases slowly with the increase of drilling speed when feed rate remains at 0.08 mm/rev and 0.12 mm/rev. It can be seen from fig. 15. that drilling torque increases rapidly with the increase of feed rate, regardless of drilling speed.
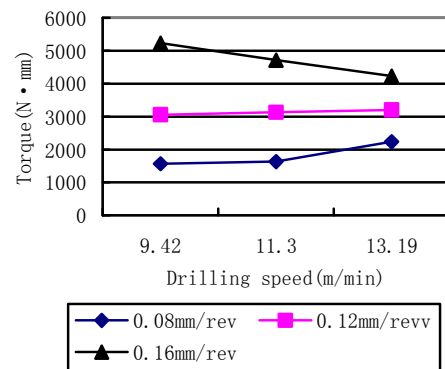


FIGURE XIV.  VARIATION OF TORQUE WITH DRILLING SPEED
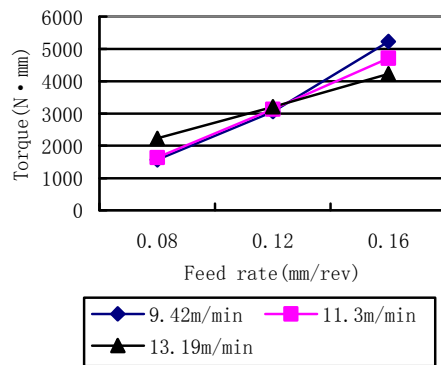FOR DIFFERENT FEED RATES.

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FIGURE XV. VARIATION OF TORQUE WITH FEED RATE FOR DIFFERENT DRILLING SPEEDS.

## IV. CONCLUSIONS

A 3D finite element model of drilling of titanium alloys is presented. A total of 9 simulations are performed to study the effect of drilling parameters on drilling performance. Simulation results suggest that feed rate has greater influence on the drill force, maximum tool temperature and drilling torque than drilling speed. In addition, based on the simulation results, the combination of low feed rate (0.08 mm/rev) and high drilling speed (13.19 m/min) is recommended for the drilling process of titanium alloys in order to obtain good machining performance and high productivity.

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