3D Finite Element Modeling of Milling of Titanium

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Abstract
This paper analyses the FEM simulation of the slot milling of Titanium, considering the three-dimensional geometry of insert cutter. The high temperature in a concentrated zone at the tool tip and segmented chip formation are two major factors that limit the machinability of Titanium. Hence it is crucial to predict the influence of cutting parameter in order to prevent several experimental test. The FEM simulation is carried out with commercial code. Machining experiments are conducted. The measured cutting forces are compared to finite element modeling. Results of this research help to guide the design of new cutting tool materials and coatings to further advance the productivity of titanium machining.

1 INTRODUCTION

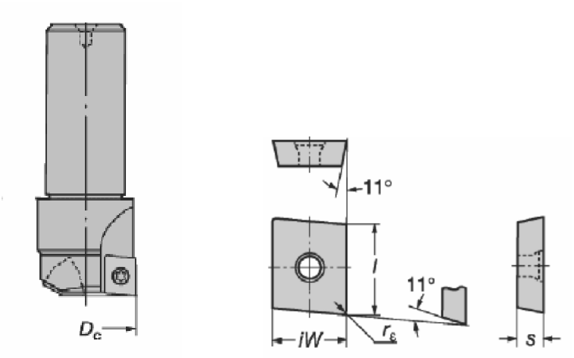
The prediction of the performance of cutting process and the influence of the process parameters on the product quality is important for tool and process design.
Titanium and its alloys are lightweight, corrosion resistant and high temperature materials. Titanium has the highest strength-weight ratio of all commonly used metals up to 550 °C. Titanium and its alloys are used extensively in aerospace because of their excellent combination of high specific strength, which is maintained at elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion. They are also used increasingly in other industrial and commercial applications, such as military, racing and medical.
The machining of Ti is critical because of high temperature in a small, concentrated area at the tool tip and the segmented chip formation with adiabatic shear band due to mechanical instability. The high tool temperature produces tool diffusion wear and limits the cutting speed. The chip shear band formation creates the fluctuation in cutting forces and the associated chipping at tool cutting edges. Ti machining has been studied extensively in the past [1]
Titanium milling is widely used in the aerospace industry, i.e. pocket realization.
The finite element numeric method is capable to predict thermal, mechanical stress and cutting forces. These are important information to analyze the desired cutting operation to prevent rapid wear and select best cutting parameter.
The 2D modeling of Ti machining has been studied [2, 3, 4]. Li [5] has analyzed the 3D finite element modeling of Ti machining using a commercial code. For other materials Ceretti [6] has investigated the oblique cutting and Fang [7] adopts a thermo elastic plastic model that permits to evaluate temperature distribution. In the flat end milling there is a work of Ozel [8]; the analysis is carried out with a 2D dimensional commercial code.
In this paper, the experimental setup is first introduced. The 3D finite element modeling and comparison of cutting forces with experimental measurements are discussed.

2 EXPERIMENTAL SETUP AND DESIGN

2.1 Experimental setup

The milling experiments were conducted on MCM milling centre. The grade four commercially pure (CP) Titanium plate, 8.5 mm thickness, was the work-material used.
A Sandvik cutter body, R216.2 – 525, is used to hold a square shape inserts. The diameter D_c

is 25 mm. The coated WC-Co tool insert, Sandvik R216.2 with 0.8 mm nose radius (denoted as r_ε in Figure 1), honed cutting edge, and GC 235 grade material (TiC-TiCN-TiC coating with thickness of 2.5 μm) is used in this study. The insert dimensions are shown in Table 1.



(a) (b)

Figure 1: Cutter body (a) and insert geometry (b).

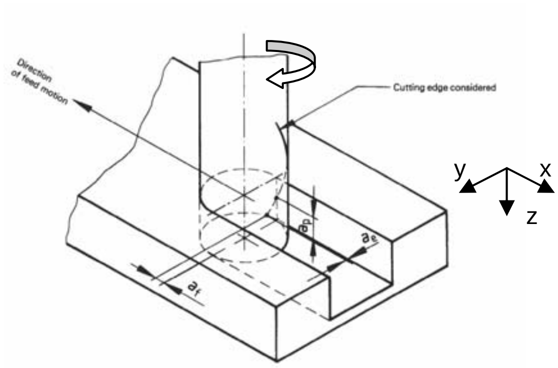


Figure 2: Schematic diagram of the milling experiments.

Quantity	Value
l	15.2 mm
iW	9.5 mm
D1	4 mm
s	3.97 mm
r_ε	0.8 mm

Table 1: Insert dimensions.

The three measured cutting forces on the workpiece in the X, Y, Z direction is measured with Kistler 9255B 3-axis piezoelectric dynamometer (Figure 2). The force signal was processed using the charge amplifiers and recorded by a PC-based data acquisition system.

2.2 Experiment design

A baseline-cutting test with two cutting speeds (235.5 m/min and 157 m/min) and two feeds (0.2 mm/tooth and 0.1 mm/tooth) were conducted at 1 mm depth of cut. Cutting forces were measured and compared to 3D finite element simulation results. All cutting tests were conducted dry without using coolant.

3 FINITE ELEMENT MODEL

3.1 3D Finite element simulation

The AdvantEdge 3D version 4.8 machining simulation software by Third Wave System at Minneapolis, MN was used to model the Ti milling process.

The updated – Lagrangian finite element method with continuous remeshing and adaptive meshing techniques was applied [9].

The coupling of the thermal and mechanical modeling of the tool and workpiece deformation is applied.

The 4-node, 12 degree-of-freedom tethaedral finite element was used to model the workpiece and the tool. The top and the back surfaces of the tool are fixed in all directions. The workpiece is constrained in X, Y and Z directions.

3.2 Material and friction models

The work material model in finite element analysis contains the power law strain hardening, thermal softening, and rate sensitivity [9]. The material behaviors are governed by the following equations:

$$\left(1+\frac{\dot{\varepsilon}^P}{\dot{\varepsilon}_0^P}\right)=\left[\frac{\bar{\sigma}}{g(\varepsilon^P)}\right]^{m_1}, \quad if\, \dot{\varepsilon}^P \le \dot{\varepsilon}_t \tag{1}$$

$$\left(1+\frac{\dot{\varepsilon}^P}{\dot{\varepsilon}_0^P}\right)\left[1+\frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_0^P}\right]^{\frac{m_2}{m_1}-1}=\left[\frac{\bar{\sigma}}{g(\varepsilon^P)}\right]^{m_2}, \quad if\, \dot{\varepsilon}^P > \dot{\varepsilon}_t \tag{2}$$

$$g(\varepsilon^P)=\sigma_0\theta(T)\left[1+\frac{\varepsilon^P}{\varepsilon_0^P}\right]^{\frac{1}{n}} \tag{3}$$

where $\bar{\sigma}$ is the effective Mises stress, σ_0 is the initial yield stress, ε^P is the plastic strain, $\dot{\varepsilon}^P$ is the plastic strain rate, $\dot{\varepsilon}_0^P$ is the reference plastic strain rate, $\dot{\varepsilon}_t$ is the threshold strain rate, ε_0^P is the reference plastic strain, m_1 and m_2 are the strain rate exponents, and n is the strain hardening exponent.

The $\theta(T)$ in Eq.3. is determined by:

$$\theta(T)=C_0+C_1T+C_2T^2+C_3T^3+..if\ \ T\le T_{cut} \tag{4}$$

$$\theta(T) = \theta(T_{cut}) - \left(\frac{T - T_{cut}}{T_{melt} - T_{cut}} \right) if \;\; T > T_{cut} \qquad (5)$$

where C_0, C_1,… are material constant, T_{cut} is the threshold temperature, and T_{melt} is the melting temperature.

All parameters are build-in constants in the material database of the software.

3.3 Finite element analysis

It has been carried out 2D simulation for overall conditions and a 3D simulations for milling. The objective is the comparison of the force due to the cutting process between 3D simulation and experimental results. The quantity of information obtained by 2D simulations are less than 3D; however provide results relatively faster and the comparison with 3D simulation is interesting.

4 EXPERIMENTAL VALIDATION OF FINITE ELEMENT MODELING

4.1 3D Simulation

It has been performed a 3D simulation with cutting speed of 235.5 m/min (n = 3000 rpm) and feed of 0.2 mm/tooth.

The simulation has been stopped at about 0.01 s, that corresponds at half milling turn.

In the figures below (Figure 3, Figure 4 and Figure 5) the cutting force components in x, y and z directions are shown. In the same graphs both experimental measures and finite element modeling results are reported.

It remarks that the x-direction cutting force is underestimated about 48% (relatively to the maximum value); however, the trend is estimated.

For y-direction and z-direction cutting forces: the graphs show a shift of the cutting forces. The shift of the cutting force is likely due to not worked surface that meets the insert; this condition is different from the real one.

The maximum value of Fy is underestimated about 17 %, and Fz about 3%. The discrepancy is likely due to the simplified friction model.

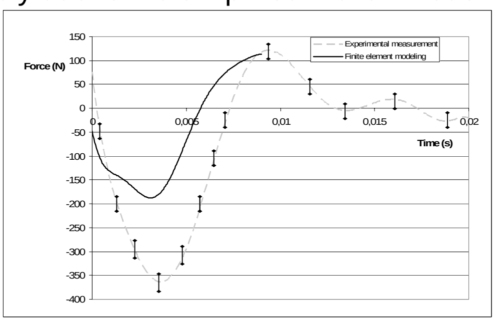


Figure 3: Fx cutting force with cutting speed 235.5 m/min, feed = 0.2 mm/tooth.

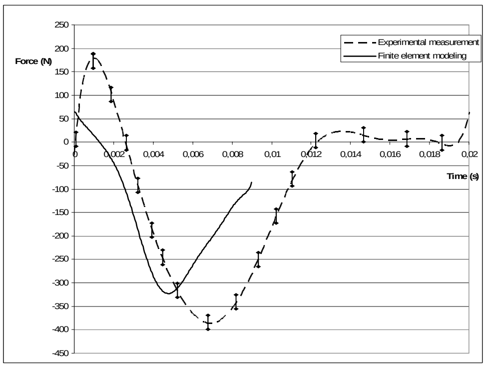


Figure 4: Fy cutting force cutting speed 235.5 m/min, feed = 0.2 mm/tooth.

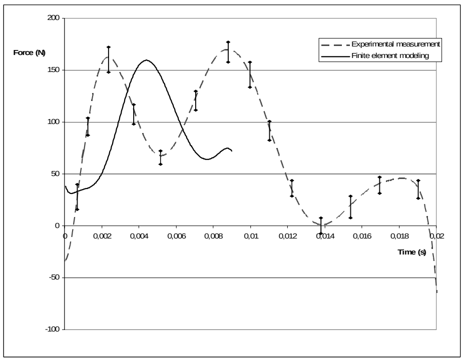


Figure 5: Fz cutting force with cutting speed 235.5 m/min, feed = 0.2 mm/tooth.

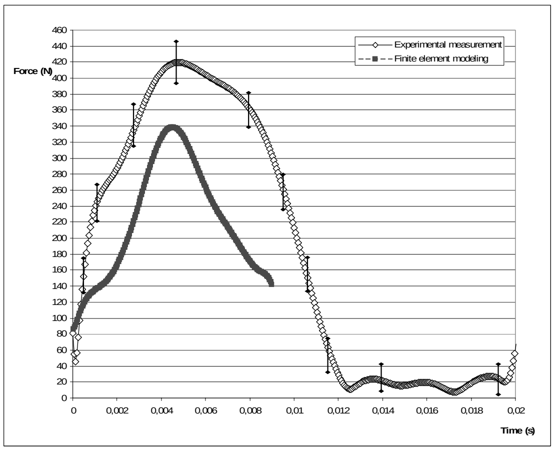


Figure 6: Resultant cutting force with cutting speed 235.5 m/min, feed = 0.2 mm/tooth.

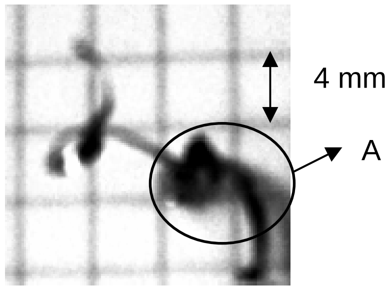


Figure 7: Chip shape.

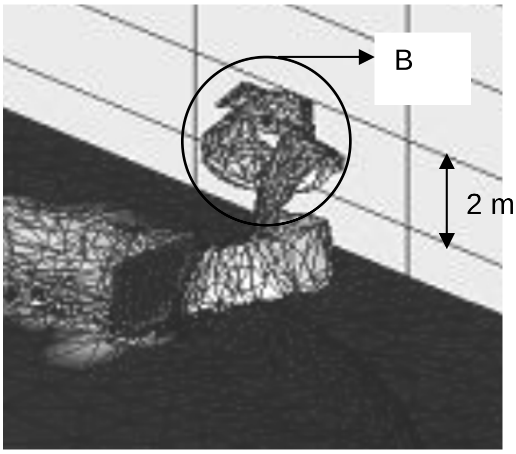


Figure 8: Chip formation in the 3D simulation.

Resultant force is shown in Figure 6; this is underestimated about 20%.

Figure 7 and Figure 8 show experimental and finite element modeling of chip shape in milling of CP Ti with 1 mm depth of cut, 235.5 m/min cutting speed, 0.2 mm/tooth feed, and 0.8 mm tool nose radius. On a quality level the formation of chip with high curvature is remarked (see A and B in respectively Figure 7 and Figure 8).

Finally the temperature distribution at the maximum chip thickness is shown (Figure 9).

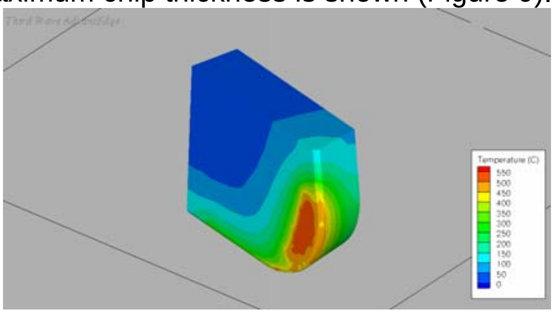


Figure 9: Temperature distribution on the insert.

4.2 2D Simulation

Further simulations have been performed using 2D simulation. In this case it is impossible know the axial component, but the calculation time is less. To execute 2D simulations is necessary to choose an angular position of the milling tool. The position where the chip thickness is maximum (90°) has been selected. The cutting length simulated is 4.5 mm. The depth of cut considered in the analysis is 1.25 mm; this value includes the real depth of cut of 1 mm and the quote of 25% relatively to increase of the cut length due to the nose radius. In Figure 10 and Figure 11 the results are reported.

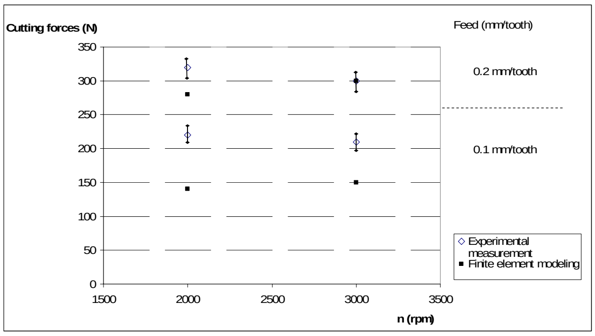


Figure 10: Tangential force cutting.

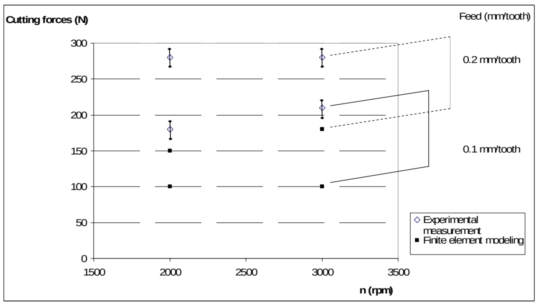


Figure 11: Radial force cutting.

The discrepancy is likely due to the simplified geometry model. To resolve this problem it can increase the length of cut.

5 CONCLUSIONS

The 3D finite element simulation of milling the CP Ti was validated by the comparison of cutting forces with reasonable agreement. It has been remarked that 3D simulation estimates cutting force better than the 2D simulation; for 2D simulation, the definition of length of cut is not ease, being the insert with three-dimensional shape.

Through FEM simulation is possible to obtain the stress and temperature field on the workpiece and on the insert providing useful information about tool life. In this case the tangential cutting force is important. Another industrial application of the FEM simulation is the optimization study, where comparative analyses have been performed to maximize tool life and cutting velocity.

The finite element modelling can assist the development of new tool materials and coatings for Ti milling.

6 REFERENCES

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