FORCE MODELING FOR OBLIQUE CUTTING ON NON-PLANAR SURFACES

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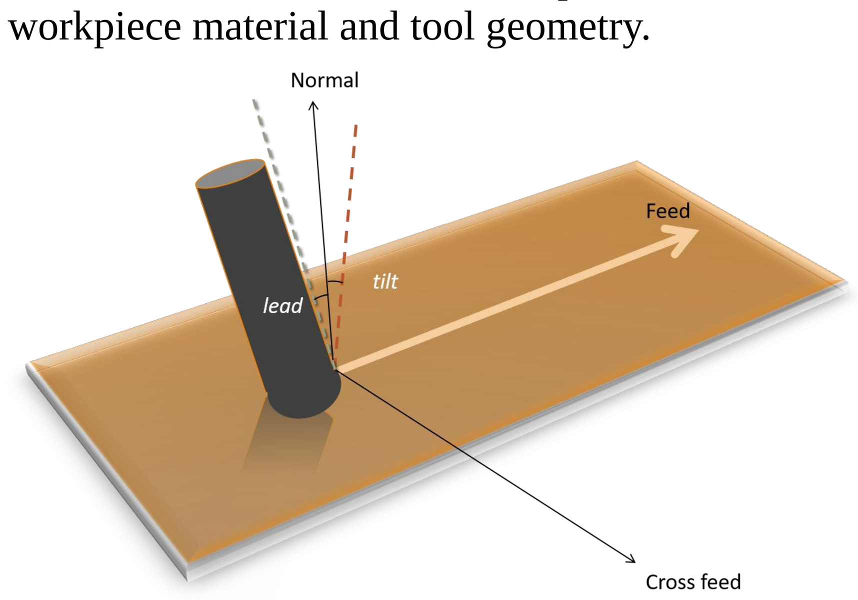
Introduction

We see technology driven changes in the manufacturing processes everyday across the globe. As technology has been continuously evolving over the last few decades, the demand and importance of lowering the tolerance limit in various industries has been increasing. Industries like aerospace, automotive and die mold machining, are demanding a very high quality of the component which essentially leads to a demand for extremely tight tolerance limit in the manufacturing processes

Manufacturing of turbine propeller and aircraft structural components are made up of high strength composites containing nickel, aluminium and titanium alloys [2]. These composites exhibit magnificent mechanical properties but conventional 3-axis milling process does not meet the required tolerance limit. This happens because the tool undergoes deflection due to high forces while cutting. Tool wear over time reduces the tool life significantly, and it essentially governs the duration for which the given tool can be used without compromising the quality (or surface roughness) and accuracy (or deviation from desired surface profile) of the machined part. Apart from tool deflection and tool wear, tool accessibility is also an important concern in free foam surfaces manufacturing. All of these shortcomings can be solved by taking the conventional milling process to the next level, by introducing two more degrees of freedom the lead and tilt angles. Lead and tilt angles determine the orientation of the cutting tool. Cutting forces experienced by the tool can be significantly reduced by the selection of appropriate lead and tilt angles under certain machining conditions. It also gives us more accessibility to cut complex shapes.

Many empirical, analytical and numerical models have been developed for the prediction of cutting forces in 5-axis milling process. All the available methods are not very generic in nature and their results are based on some specific cases of workpiece material and tool geometry.

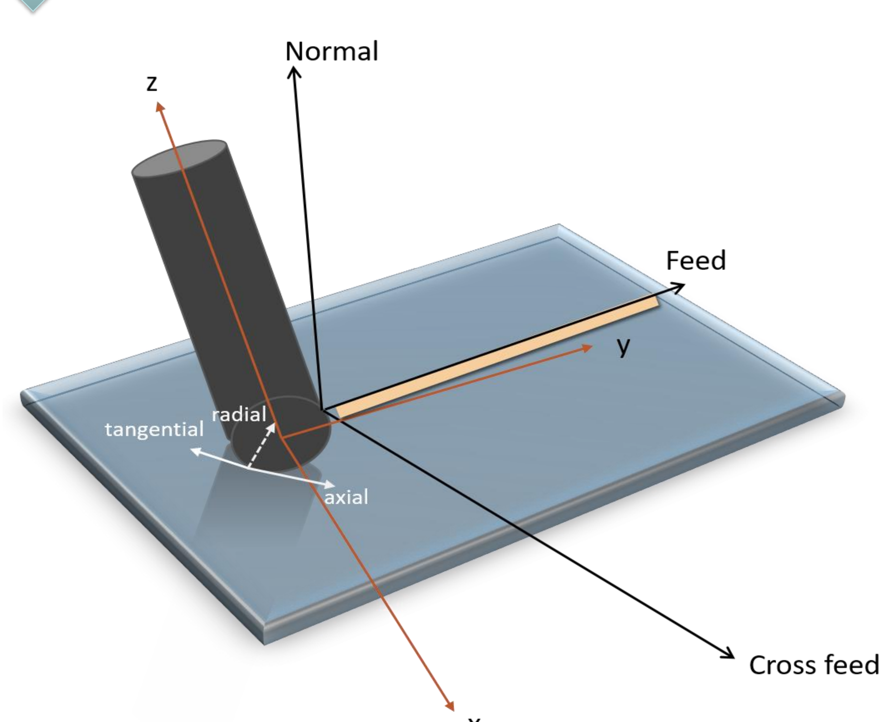


The motivation for this study comes from the fact that being a very crucial subject of study, there exists a literature and experimental gap between the research required in precision machining and research which has been done till date.

The main aim of this project is to develop and generalize the methodology to predict the cutting forces and torque experienced by the tool during the 5-axis milling process. These forces are dependent on various factors such as 1) tool geometry 2) machining parameters like tool orientation, feed, speed, cutting depth and 3) workpiece material characteristics.

Methods

- Step 1 • Establishing coordinate systems for cutting tool as well as workpiece
- Step 2 • Mathematical formulation of tool geometry
- Step 3 • Defining cutting edge parameters
- Step 4 • Discretization of surface and
- Step 5 • Identification of engagement region (cutting zone)
- Step 6 • Determining chip dimensions
- Step 7 • Determining edge and cutting force coefficients
- Step 8 • Computation of elemental forces and torques
- Step 9 • Transformation of forces and torques to TCS and then FCN



Cutting edge parameters:

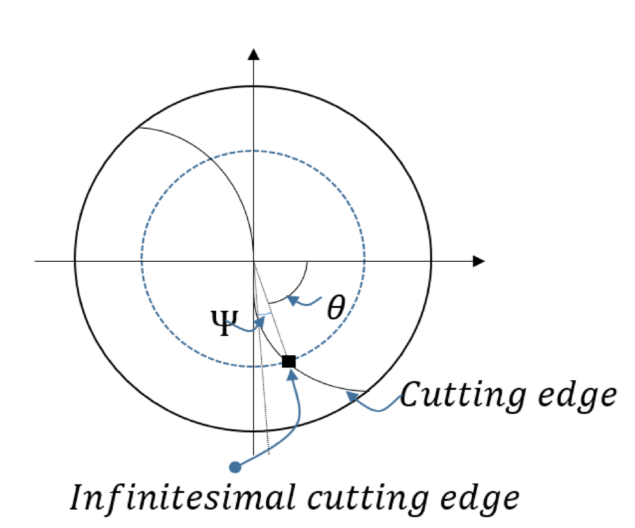
i. Distance from tool tip along tool-axis (Z)

ii. Local radius r(z)

iii. Axial immersion angle

iv. Lag angle Ψ

v. Radial Immersion angle (Φ)

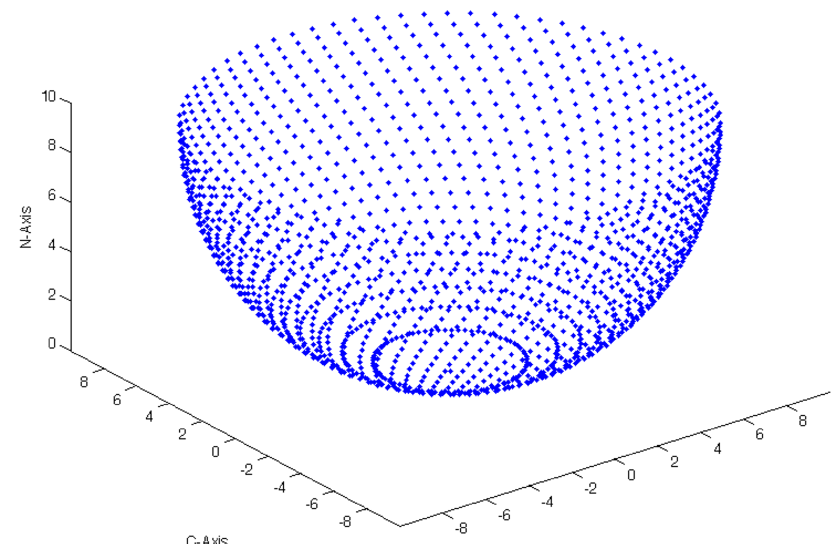


In Tool Coordinate System:

i. $xx_{tcs}(z) = r(z) * \sin\Phi(z)$

ii. $yy_{tcs}(z) = r(z) * \cos\Phi(z)$

iii. $zz_{tcs}(z) = z$



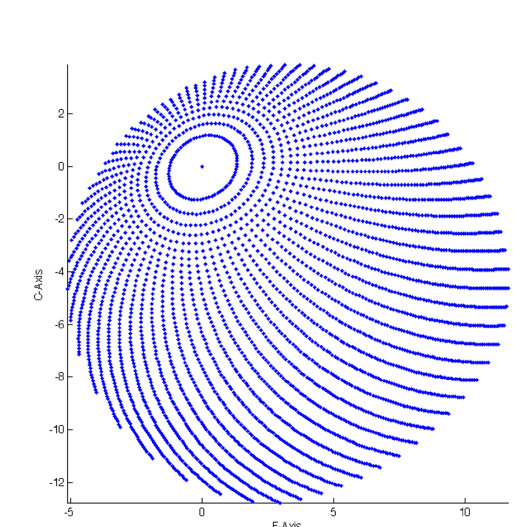
Cutting Zone:

Identified by removing two sets of points from the set of cutting points:

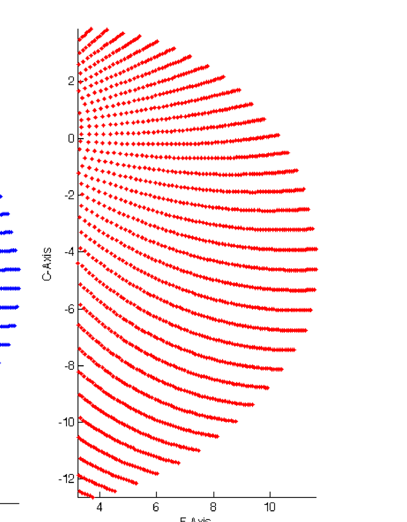
i. Points above the cutting depth

ii. Points lying opposite to the direction of the feed in FCN coordinate system

$$P(i,j) = (\, z(i,j) > cutting\ depth) \,\&\&\, (\overrightarrow{feed}.\overrightarrow{OX}(j,i))$$



Top view of discretized points below the cutting depth for 20^0 lead 30^0 tilt



Top view of discretized points in the cutting zone for 20^0 lead 30^0 tilt

Chip Dimensions:

There are three geometric parameters which are as follows:

i. **Chip thickness:** $t_n(S_t, \Phi, K) = S_t \sin\Phi \sin K$

ii. **Chip width:** projected length of an element in the direction of cutting velocity: $db = \frac{dz}{\sin K}$

iii. **Chip length:** distance between two adjacent cutting points: $ds = \sqrt{(\vec{X}(j,i) - \vec{X}(j-1,i))^2}$

Edge Forces:

- Rubbing of the tool against the workpiece material
- For Ti6Al4V, finding a regression model using experimental results

Cutting Forces

- Shearing of the workpiece material in the shear zone
- Coefficients are defined forces per unit chip area

The forces calculated on every cutting element are defined in Local Coordinate System. They have to be transformed into Tool Coordinate System to determine the forces and torque acting on the tool using a transformation matrix A. Matrix A is essentially considering the effect of axial immersion angle and radial immersion angle and rotating LCS two times.

$$\begin{Bmatrix} dF_x \\ dF_y \\ dF_z \end{Bmatrix}_{TCS} = [A] \begin{Bmatrix} dF_t \\ dF_r \\ dF_a \end{Bmatrix}_{LCS}$$

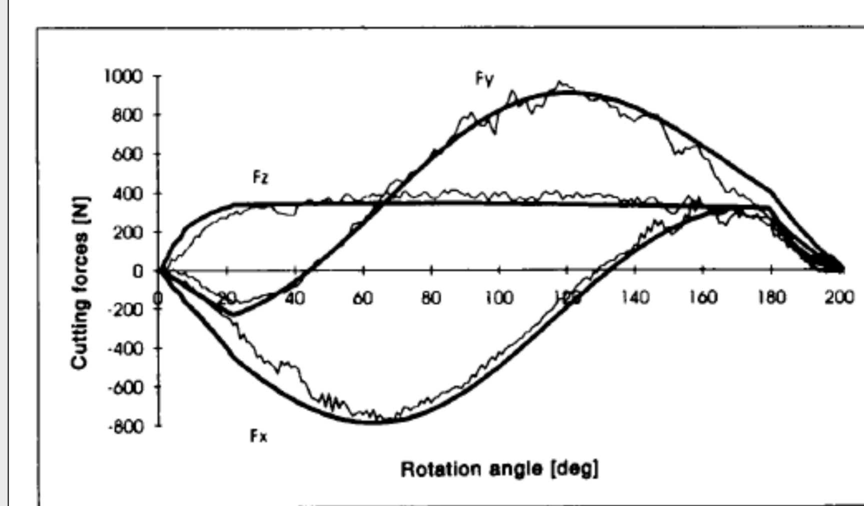
Where,

$$[A] = \begin{bmatrix} -\sin K \sin\phi & -\cos\phi & -\cos K \sin\phi \\ -\sin K \cos\phi & -\sin\phi & -\cos K \cos\phi \\ \cos K & 0 & -\sin K \end{bmatrix}$$

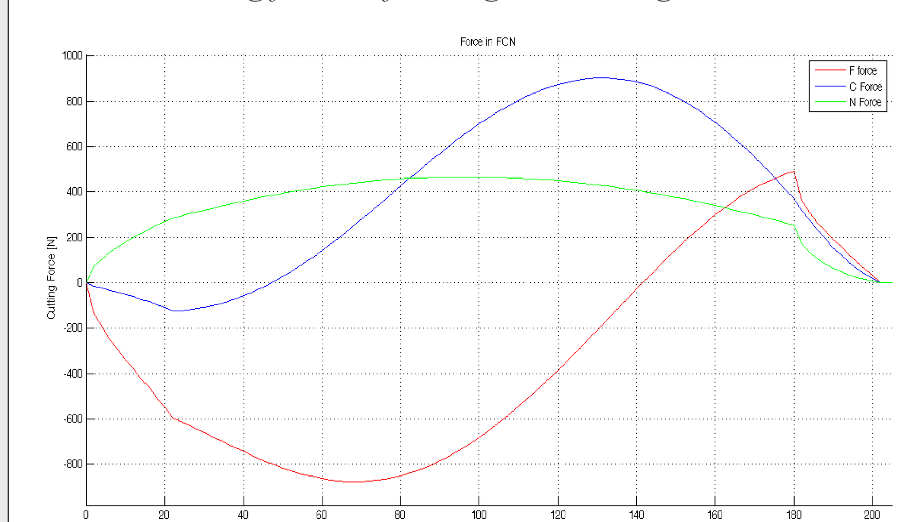
The total cutting force experienced by the ball-end tool is calculated by adding up all the differential forces exerted on each elemental cutting edge.

$$F_x(\theta) = \sum_{j=1}^{L_p} dF_x\,(\theta, z)$$

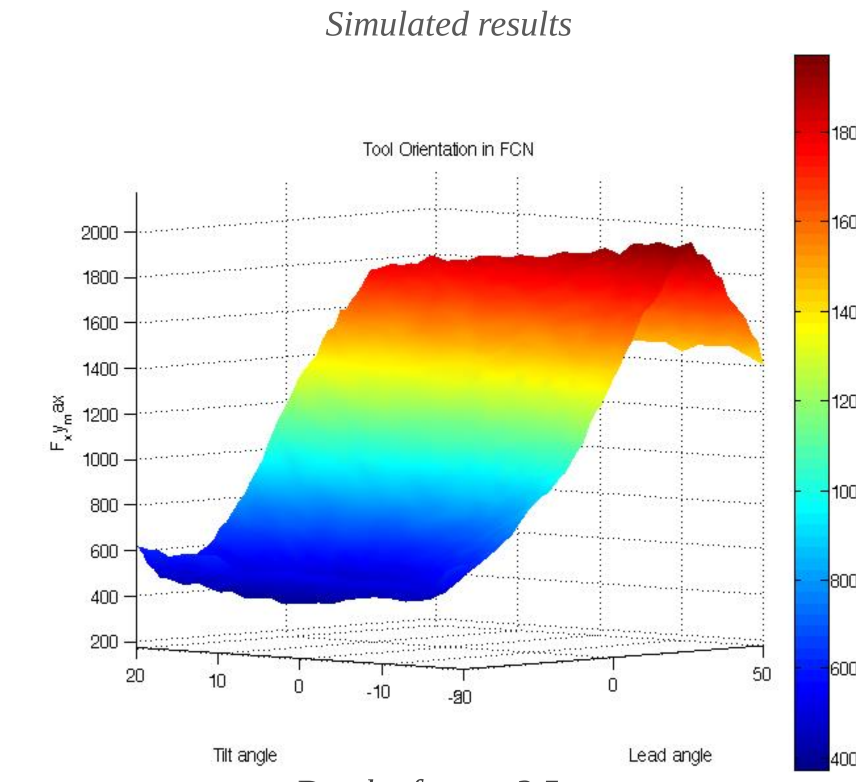
Results



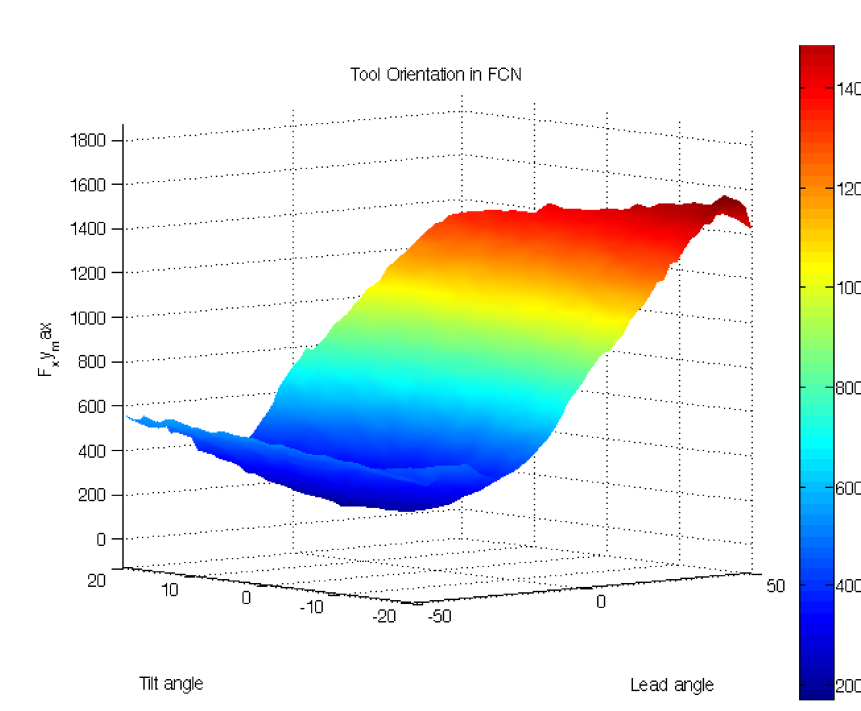
Ref: P. Lee and Y. Altintas, "Prediction of ball end milling forces of orthogonal cutting data"



Simulated results



Depth of cut = 2.5mm
Lead and tilt angles for minimum force on the cutting tool are -20^0 and 4^0 respectively.



Depth of cut = 5mm
Lead and tilt angles for minimum force on the cutting tool are -34^0 and 8^0 respectively.

As we increase the depth of cut, the lead and tilt angles also need to be increased (magnitude) to get the minimum value of Fxy_max

References

1) E. Budak and E. Ozturk, "Modeling of 5-axis Milling Processes" 2007

2) Y. Altintas, "Metal Cutting Mechanics, Machine Tool Vibrations and CNC Design" Second edition, p. Chapter 2