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Tool Orientation Effects on the Geometry of 5-axis Ball-end Milling

Erdem Ozturk, Erhan Budak*
Manufacturing Research Laboratory, Sabanci University, Istanbul, Turkey
*Tel: +90 216 483 95 19, Fax: +90 216 483 95 50

Abstract. 5-axis ball-end milling has found application in various industries especially for machining of parts with complex surfaces. Additional two degree of freedoms, namely, lead and tilt angles make it possible to machine complex parts by providing extra flexibility in cutting tool orientation. However, they also complicate the geometry of the process. Knowledge of the process geometry is important for understanding of 5-axis ball-end milling operations. Although there are considerable amount of work done in 3-axis milling, the literature on 5-axis ball-end milling is limited. Some of the terminology used in 3-axis milling is not directly applicable to 5-axis ball end-milling. Hence some new process parameters and coordinate systems are defined to represent a 5-axis ball end-milling process completely. The engagement zone between the cutting tool and the workpiece is more involved due to the effects of lead and tilt angles. In this paper, effects of these angles on the process geometry are explained by presenting CAD models and analytical calculations.

Keywords: 5-axis, ball-end milling, lead and tilt angles, process geometry

1. Introduction

5-axis milling is a geometrically complex process since there are two additional rotational degrees of freedom, namely lead and tilt angles, compared to 3-axis milling. They define the cutting tool orientation with respect to surface normal direction.Visualization of their effect on the process geometry is not straightforward; however, the understanding of the process geometry is a very important step in process modeling. Hence, in this paper, the effects of lead and tilt angles on the proces geometry are presented.

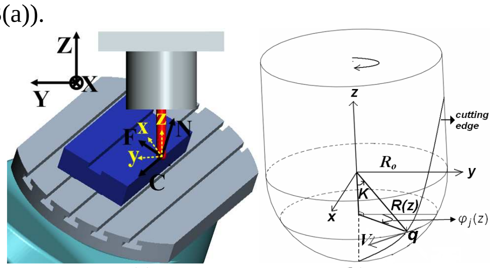
There have been considerable amount of work done on modelling of sculptured surface geometry in 3-axis ball-end milling. Although rotational degrees of freedoms are not available in 3-axis ball-end milling, there may be inclination in both feed and cross-feed directions due to CNC interpolations on the sculptured surface. Geometry of these processes is similar to the 5-axis ball-end milling geometry. Imani et al. [1] presented machining cases with up-hill angle in 3-axis ball-end milling which corresponds to application of positive lead angle in 5-axis ball-end milling. For different up-hill angles they showed the calculated engagement boundaries which are determined using the ACIS geometric engine [2]. Later, Kim et al. [3] included the effect of tilt angle on the engagement region. In their notation, ramping corresponds to application of lead angle while contouring matches with the application of tilt angle. Combined effect of lead and tilt angle on the engagement region on the ball-part of the tool was shown by Lamikiz et al. [4] by cutting an inclined plane with a sloped feed direction in a 3-axis milling machine tool. Later, Fontaine et al. [5] applied the same notation with Kim et al. [3] for different machining strategies but added the effect of cross-feed direction where they refer to it as up/down milling. In this paper, the terminology in 5-axis ball end milling is introduced firstly. The process parameters and coordinate systems are defined. Then, combined and independent effects of lead and tilt angles on engagement regions between the tool and workpiece are explained by CAD models and analytical calculations. For the engagement calculations, engagement model presented by Ozturk and Budak [6] is used. In this model, the engagement regions in both ball and cylindrical zones can be calculated. Effect of lead and tilt angles on maximum uncut chip thickness is also illustrated on a representative case.

2. Terminology in 5-axis ball-end milling

In order to represent position and orientation of a cutting tool at an instantaneous point along a tool path, three coordinate systems need to be defined (Fig. 1(a)). The first one is a fixed coordinate system called the machine coordinate system (MCS). It consists of X, Y, Z axes of the machine tool, its origin is the home position. The second one is the process coordinate system (FCN). In FCN coordinate system F is the feed direction, C is the cross-feed direction and N is the surface normal direction.The origin of the FCN is at the ball-centre of the cutting tool, and thus it is a moving coordinate system. Moreover, F, C and N directions change along a tool path depending on the workpiece geometry and machining strategy selected. Tool coordinate system (TCS) is the third coordinate system and its origin is also the ball centre of the tool. x and y axes are transversal axes of the tool and z is along the tool axis direction. TCS defines the orientation of the cutting tool with respect to FCN. Lead angle defines the rotation of the cutting tool around C axis whereas tilt angle is the rotation of the tool around

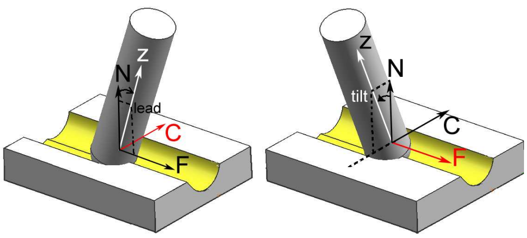
F axis (Fig.2). Therefore, TCS is the rotated form of FCN with lead and tilt angles.

Some of the terminology in 3-axis milling is not directly applicable to 5-axis milling for definition of the process parameters. Due to the effects of lead and tilt angles, the tool axis is not parallel to the surface normal (Fig.2). Hence, the cutting depth term (*a*) is used to define the depth removed from the workpiece in the surface normal direction instead of the axial depth term (Fig. 3(a)).



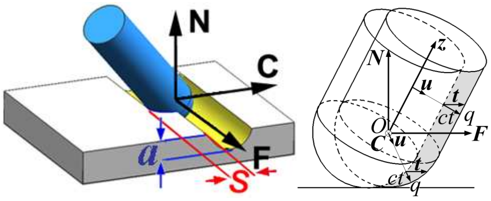
(a) (b)

Fig. 1. (a)Coordinate systems (b) Ball-end mill geometry.



(a) (b)

Fig. 2. (a)Lead angle (b) Tilt angle.



(a) (b)

Fig. 3. (a)Cutting depth *a*, step over *s* (b)Uncut chip thickness *ct*

Radial depth term is replaced with step over term as radial depth expression may result in confusion due to the effects of ball-end mill geometry, lead and tilt angles on radial directions.The step over *s* is the distance between the adjacent tool paths in C axis as shown in Fig. 3(a). Milling mode, i.e. up and down milling, definitions can be ambiguous for 5-axis ball-end milling due to the complex engagement regions. Because of the effects of tool geometry, lead and tilt angles, there may be two different immersions zones which cannot be represented with a start and exit angle pair. For that reason, another parameter, cross-feed direction is used in order to define the direction of the uncut material. If uncut material is in the positive C axis with respect to the milling tool, the cross-feed direction is positive, and vice-versa. For example, in cases presented in Fig.2 and Fig. 3(a), the cross-feed direction is negative. Cases with positive and negative cross-feed direction are analogous to up and down milling in 3-axis end milling, respectively, in the sense of the uncut material direction. After lead, tilt angles, cutting depth, step over and cross-feed direction parameters are defined at an instant, the instantaneous relative position and orientation of cutting tool with respect to workpiece are completely defined. Uncut chip thickness *ct* (Fig. 3(b)) is varible along the cutting edge locally in both tangential and axial directions. Local uncut chip tickness depends also on lead and tilt angles as formulated in [6].

3. Engagement regions and uncut chip thickness under the effects of lead and tilt angles

The visualization of effects of lead and tilt angles on the engagement regions between the tool and workpiece is not very easy in 5-axis ball-end milling. In this section, their effects are shown by CAD models and simulations. For calculation of engagement regions, a previously developed engagement model [6] is applied on representative cases. In the example case, cutting depth, step over and radius of the ball-end mill are 6 mm. Helix angle on the clockwise-rotating tool is 30^o and cross-feed direction is negative.

In the absence of lead and tilt angles, CAD model of the process is shown in Fig.4. In this case, TCS and FCN coincide. The projection views of the 3D engagement region in two orthogonal planes namely, CN and CF planes, are also presented in Fig.4. It's seen that the engaged region is variable along the tool axis. The variation of engagement boundaries along the tool axis is plotted in Fig.4 where φ_{st} and φ_{ex} represent start and exit angles, respectively. There is 180^o immersion close to the tool tip (z=-6mm) while the immersion width decreases for the higher z positions. As the name implies, immersion width is defined as the amount of angular immersion at a z-level.

When lead and tilt angles are applied on the cutting tool, the shape of the engagement region changes. This is illustrated for application of 30^o lead and tilt angles in Fig. 5 where the calculated engagement boundaries are also presented. In this case, it's seen that both ball and cylinder zones of the cutting tool are in contact with the workpiece.

Positive lead angle shifts the engagement region to the higher positions along the tool axis while negative lead angle moves the engagement to the lower sides of the tool. Moreover, lower immersion widths takes place with positive lead angles with respect to negative lead angle cases. In order to justify these comments, effect of lead angle on the immersion width on different z-coordinates is presented in Fig. 6 for the example case. Since it is a 3D surface, the 2D projections of the surface in two orthogonal planes are also plotted in the figure to show the variation with more detail. Norm_z is the ratio of z-coordinate with respect to ball-end mill radius. It is seen that the comments about the effect of lead angle and observations from the Fig.6 match well. Although not presented here, the similar effects are also seen for lower and higher cutting depth and step over cases.

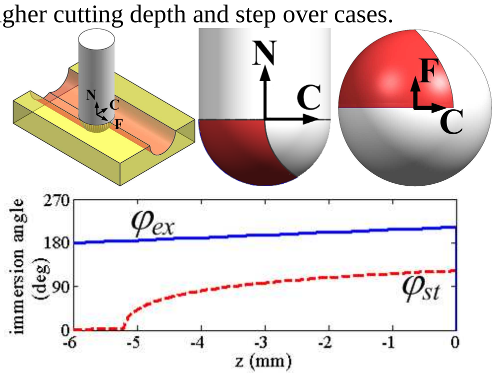


Fig. 4. Engagement region (lead,tilt=0°)

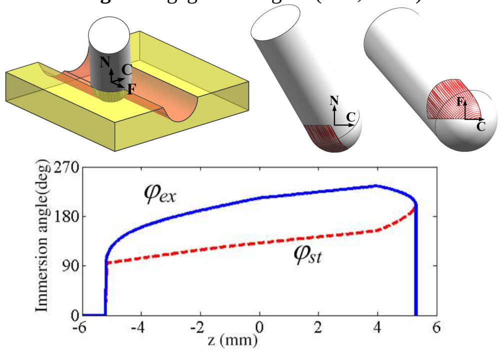


Fig. 5. Engagement region for the example case (lead,tilt=30°)

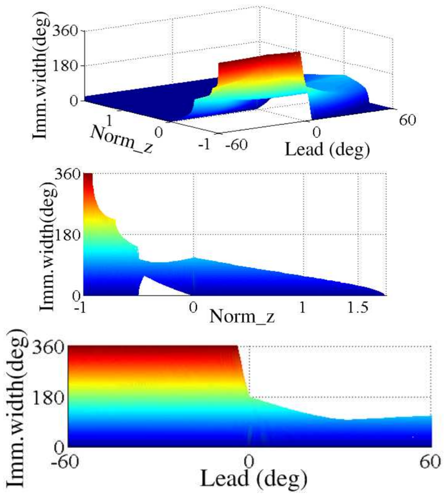


Fig. 6. Effect of lead angle on immersion width (tilt=0°)

Local radius *R*(*z*) increases as the z-coordinates of the engagement region increases (Fig.1 (b)). This results in higher cutting speed values in the engagement region. Since cutting speed increases tool wear, the engagement regions with higher z coordinates cause higher tool wear. Moreover, resulting cutting torque and power due to each cutting flute increases because of higher local radii and higher cutting speed. On the other hand, immersion widths decrease with higher z coordinates. In this case, the probability of having more than one flute in cut decreases since pitch angle between the flutes might be higher than immersion widths at these locations. As a result, it's difficult to derive a general conclusion about the required cutting torque and power since there are two contradicting effects.

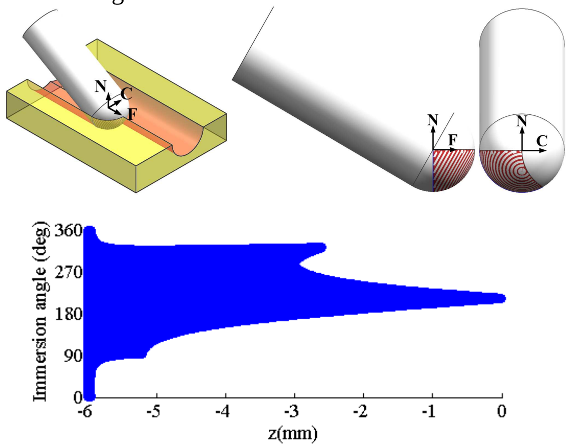


Fig. 7. Engagement region (lead=-60°,tilt=0°)

In order to show the effect of lead angle on the engagement in more detail, for a large negative lead of -60°, 3D and 2D views of the engagement regions are presented in Fig. 7. In this case tilt angle is 0°. Calculated engagement region is also demonstrated. In this case, it is seen that in regions close to the tool tip, the immersion width is 360° which means that there is full immersion in this zone. Tool-tip contact with the workpiece is generally not preferred due to additional ploughing/indentation forces and resulting tip marks on the finished surface. It is seen from Fig. 7 that for higher values of z coordinates, the immersion width decreases. It is interesting to note that between z=-3 mm and z=-2.6mm positions, there are two start and exit angles, i.e. the tool engages and disengages with the workpiece two times at these z positions. In this case, this zone on the tool stays behind the finished surface for a short duration but then tool engages with the workpiece again. This occurs depending on the step over and cutting depth for negative lead angles.

Effect of tilt angle is very much dependent on the cross-feed direction. If tilt angle and cross-feed direction have the same sign, the tool axis is oriented away from the uncut part of the workpiece. In this case, tilt angle decreases the z-coordinates of the engagement region. On the other hand, if tilt angle and cross-feed direction have opposite signs, tool axis is oriented through the uncut part of the workpiece and z-coordinates of the engagement region increase (Fig.2 (b), Fig.3 (a)). As can be seen from these figures, positive tilt angle results in engagement regions with higher z coordinates. Effect of tilt angle on immersion width on different z coordinates is presented in Fig.8 for the example case. As expected, z-coordinates of the engagement region are lower when tilt angle is negative since cross-feed direction is negative in the example case. At the same time, immersion width is higher in these cases. Similar effects are seen in calculations performed for cases with lower and higher step over and cutting depth values.

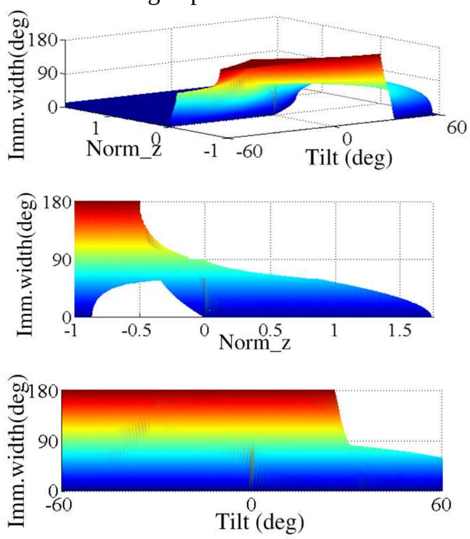


Fig. 8. Effect of tilt angle on immersion width (lead=0°)

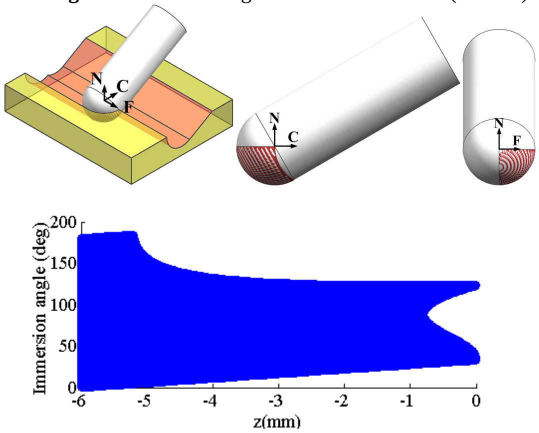


Fig. 9. Engagement region (lead=0°,tilt=-60°)

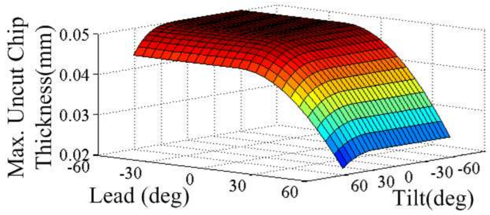


Fig. 10. Lead and tilt angle effect on maximum uncut chip thickness.(s=6mm,a=6mm,R_o=6mm, feed per tooth=0.05mm)

Tilt angle effect on the engagement region is presented on the example case with application of 0° lead and -60° tilt angle in Fig. 9. In this case, there is 180° immersion in the regions close to the tool tip and it decreases for higher z coordinates. Two different immersion zones on the same z-position presented in the previous negative lead case, are also seen in this example between z=-0.8mm and z=0mm.In this case, the tool loses contact with the workpiece due to the material removed by the previous pass and gets into contact again which is shown better in the CN plane view of the engagement region in Fig. 9. Negative tilt angle has an effect similar to the up-milling effect in 3-axis flat-end milling for a clock-wise rotating tool. In other words, the tool starts cutting from the final surface which may result in poor surface finish quality. On the other hand, positive tilt angle has a similar effect for counter-clockwise tools.

Lead and tilt angles also affect the local uncut chip thickness values on the cutting edge. The effect of lead and tilt angles on maximum uncut chip thickness is presented in Fig. 10 on a representative case. Espacially when the cylindrical part of the ball-end mill is in cut, positive lead angle results in a considerable decrease in maximum uncut chip thickness since lead angle defines the inclination of the tool in feed direction. However, in cases where ball region of the tool is incut only, lead and tillt angles do not change the maximum chip thickness. They only change the location where maximum chip thickness is reached.

4. Conclusion

In the paper, the effects of lead and tilt angles on the process geometry are shown.Their effects on the the engagement regions between the cutting tool and workpiece and maximum uncut chip thickness values are shown to be very significant. An interesting phenomena where there are more than one immersion zone on the same z position was presented on two example cases. The authors believe that the presented results help visualization of 5-axis ball-end milling process geometry which is very important for modeling the mechanics and dynamics of these processes.

5. References

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