International Journal of Machine Tools & Manufacture 49 (2009) 1053–1062

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Investigation of lead and tilt angle effects in 5-axis ball-end milling processes

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ARTICLE INFO

Article history:
Received 15 May 2009
Received in revised form
24 July 2009
Accepted 28 July 2009
Available online 7 August 2009

Keywords:
5-axis milling
Tool orientation
Forces
Stability

ABSTRACT

Five-axis milling is widely used in aerospace, die-mold and automotive industries, where complex surfaces and geometries are machined. Being special parameters of 5-axis milling, lead and tilt angles have significant effects on the process mechanics and dynamics which have been studied very little up to now. In this paper, first of all, effects of tool tip contact on the surface finish quality is presented, and conditions to avoid tip contact in terms of lead and tilt angles and depth of cut are stated. The effects of lead and tilt angles on cutting forces, torque, form errors and stability are investigated through, modelling and verified by experimental results. It is shown that the cutting geometry, mechanics and dynamics vary drastically and non-linearly with these angles. For the same material removal rate, forces and stability limits can be quite different for various combinations of lead and tilt angles. The results presented in the paper are expected to help understanding of complex 5-axis milling process mechanics and dynamics in a better way. The results should also help selection of 5-axis milling conditions for higher productivity and machined part quality.

1. Introduction

Manufacturing of parts with complex surfaces brings additional challenges such as tool accessibility and contouring. Five-axis milling provides much better accessibility with the help of increased tool orientation capability. However, 5-axis milling also brings extra difficulties due to the complicated process geometry and mechanics. Lead and tilt angles determine orientation of cutting tool and the engagement region, and affect the mechanics and dynamics of the process. Local chip thickness, cutting force coefficients, dynamic forces and stability are affected by lead and tilt angles. Improper tool orientation may result in decreased productivity and part quality due to higher cutting forces, surface form errors and process instability. Thus, lead and tilt angles are very important parameters in 5-axis milling processes.

Effects of lead and tilt angles on the process are not known very well, and cannot be easily estimated unlike parameters such as feed rate and cutting depths. The effects of tool orientation on the process are studied in mainly two aspects: process kinematics and process mechanics. Kinematics is the most investigated aspect [1–5] where conditions for smooth tool axis movement [2,3], gouge and collision free tool positioning [4,5] are studied by several authors. In one of the studies that consider process mechanics, Xu et al. [6] showed the effects of path increment angle on the workpiece surface in 3-axis milling which is analogous to the tilt angle is 5-axis ball-end milling. They demonstrated that path increment angle has effects on cutting forces and tool tip contact condition with the workpiece, and presented that tool tip contact can be eliminated by applying sufficient path increment angle. Radzevich [7], on the other hand, analyzed conditions of proper sculptured surface machining from workpiece orientation, surface topography and tool geometry perspectives. Lopez de Lacalle et al. [8] determined preferable local machining directions and tool orientation in finishing operations with respect to tool deflections. In another study, Lim et al. [9] experimentally investigated the effects of tool orientation and cutting directions in 5-axis milling of a turbine blade. They applied mainly 4 cutting directions with lead/tilt angle combinations of 15°, and concluded that the best strategy was machining "horizontal inward with a tilt angle". This result is specific to the cutting conditions used in the experimental set-up. The tool orientation has also considerable effect on the stability of processes; however, this effect was only investigated in few studies [10,11].

In this paper, it is proposed that the effects of lead and tilt angles on the process can be predicted in terms of cutting forces, form errors [12] and chatter stability [10,11]. Their effects on the process geometry, mechanics and dynamics are demonstrated by simulations and experiments. The presented results can be used in better understanding of 5-axis milling processes.

The paper is organized as follows. Following the introduction, the process geometry is presented in Section 2. Afterwards, the effects of lead and tilt angles on the process are explained. These

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doi:10.1016/j.ijmachtools.2009.07.013

effects are demonstrated by experimental results and simulations. Finally, the contributions and the potential applications of the presented study are summarized in the conclusions.

2. Process geometry

2.1. Coordinate systems, lead and tilt angles

The geometry of 5-axis milling operations can be modelled using three coordinate systems as shown in Fig. 1. The first one is a fixed coordinate system, MCS, formed by the (X), (Y) and (Z) axes of the machine tool. The second coordinate system is the process coordinate system, FCN, consisting of feed (F), cross-feed (C) and surface normal (N) axes. Finally, TCS is the tool coordinate system which is the rotated form of the FCN. In TCS, the tool axis is the (z) axis of this coordinate system where (x) and (y) axes are in the transversal directions of the cutting tool.

In 5-axis milling, the tool orientation is determined by lead and tilt angles which are measured with respect to the surface normal axis (N) as shown in Fig. 1. The lead angle is the rotation of the tool axis about the cross-feed axis (C) and the tilt angle is the rotation about the feed axis (F).

2.2. Engagement regions

Engagement regions where the cutting tool is in contact with the workpiece depend on lead and tilt angles, ball-end mill geometry and cutting depths. The effects of lead and tilt angles on the engagement regions are illustrated in Fig. 2 for two different lead and tilt angle combinations. Engagement boundaries can be determined using the previously developed engagement model [12].

In the engagement model three different cutting modes are considered: first cut, following cut and slotting. In the first cut, the tool cuts a non-machined surface (Fig. 2(c)) whereas in the following cut cases (Fig. 2(a) and (b)) the tool is in cut with a previously machined surface.

The cutting depth (a) is the distance between the tool's lowest point and upper surface of the workpiece in the surface normal direction (N) as shown in Fig. 2(a) and (d). For the following cut cases, step over (s) is the distance between the adjacent cutting steps in the cross-feed axis (C) (Fig. 2(a)). The "cross-feed direction" is the direction of uncut material in the (C) axis. If the uncut material is in the direction of the positive (C) axis, the cross-feed direction is positive, otherwise it is negative.

For first cut cases, the step over definition used in [12] is further simplified for better visualization. In this definition, step over is the distance in the cross-feed axis (C) from the workpiece edge to the tool's lowest point in the surface normal direction (N) (Fig. 2(d)). Hence, if the C coordinate of the workpiece edge is positive, the step over is negative (Fig. 2(d)); otherwise it's positive. In addition to the common engagement criteria that are independent of the cutting mode [12], a point on the cutting edge is in cut with the workpiece if the C coordinate of the point is higher than $-s$ for a positive cross-feed direction case, or it is smaller than $-s$ for a negative cross-feed direction case.

2.3. Scallop height

Scallop height, h_s, is a measure of surface quality for the following cut cases. In 3-axis ball-end milling, it only depends on the radius of ball-end mill and step over. However, in 5-axis ball-end milling, it may also be affected by the tilt angle while lead angle has no effect on the scallop height. If the step over s is lower than $2R_o \cos t$, the successive tool paths intersect on the parts machined by the ball sections of the tool (Fig. 3(a)). On the other hand, if step over is higher than $2R_o \cos t$, the consecutive tool paths intersect on the parts machined by the cylinder section of the tool in one pass and the ball section in the other pass as shown in Fig. 3(b). In the first case, scallop height only depends on radius of ball-end mill and step over. However, in the second case, the tilt angle also affects the resulting scallop height. Scallop heights for

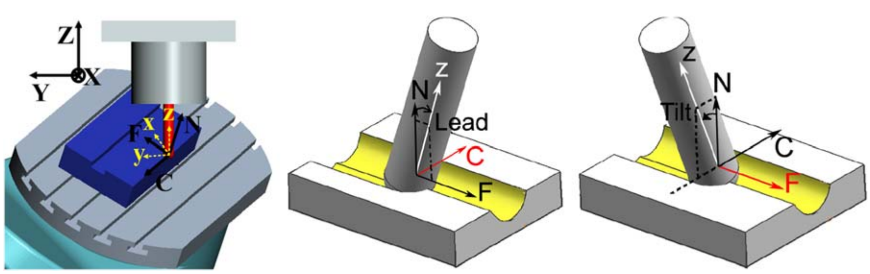

Fig. 1. Coordinate systems and lead–tilt angles.

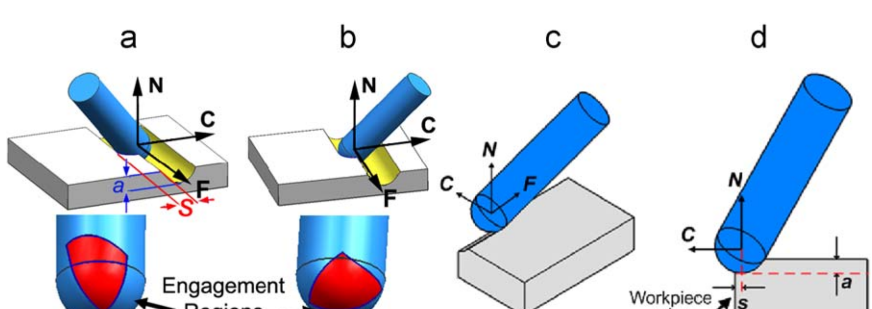

Fig. 2. (a) Engagement regions for positive lead (15°) and positive tilt (40°), (b) for positive lead (15°), negative tilt (–40°), (c) first cut cases; cross-feed direction is negative: 3D view and (d) 2D view on CN plane.

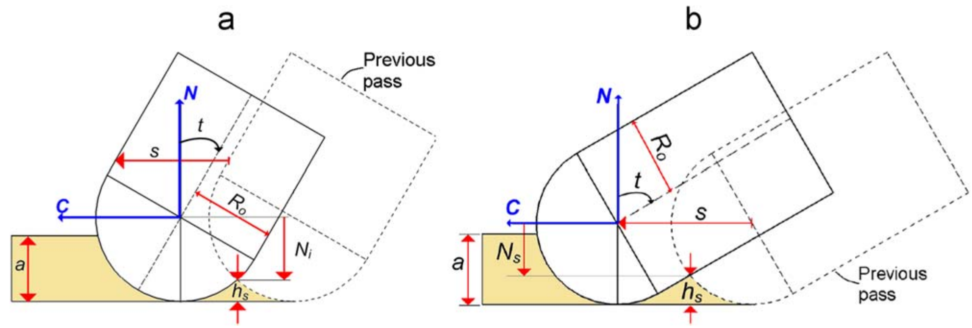

Fig. 3. Scallop height: (a) $s \le 2R_o \cos t$) and (b) $s > 2R_o \cos t$.

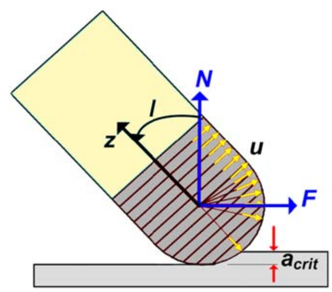

Fig. 4. Indentation case.

each case are given by the following equations:

$$h_s = \begin{cases} R_o + N_i, & \text{if } s \le 2R_o \cos t \\ R_o + N_s, & \text{if } s > 2R_o \cos t \end{cases} \tag{1}$$

where the N coordinates of the ball–ball intersection point N_i (Fig. 3(a)) and the ball–cylinder intersection point N_s (Fig. 3(b)) are calculated as follows:

$$N_i = -\sqrt{R_o^2 - \frac{s^2}{4}}$$

$$N_s = -\sqrt{R_o^2 - (R_o - s\cos t)^2}\cos t - (R_o - s\cos t)\sin|t| \tag{2}$$

In the second case, by increasing the tilt angle, larger step over values are allowed for the same scallop height requirement on the surface. As a result, total number of cutting steps can be decreased, resulting in a lower machining time.

3. Effects of lead and tilt angles on the process

Lead and tilt angles have effects on different factors such as tool tip contact with the workpiece, scallop height, cutting forces, torque, form errors and stability. Effects of lead and tilt angles on each of these are explained in this section.

3.1. Tool tip contact conditions and avoidance

In ball-end mills, local radius is variable along the tool axis and zero at the tool tip where cutting speed is also zero. In cases where the tool tip is in contact with the workpiece, cutting cannot be performed around the tip. Instead, it indents into the workpiece and/or ploughs over the surface depending on the lead angle. When the lead angle is negative, the feed vector has a component in the outward normal vector of the tool (***u***) at the tool tip (Fig. 4). The non-cutting contact between the work material and the cutting tool tip results in extra indentation and ploughing forces. Although the tool tip is in contact with the workpiece in this case due to the negative lead angle, the tool tip is not in contact with the created surface. So, there are no tool tip marks on the resulting surface. On the other hand, when the lead angle is zero, the tool tip ploughs over the resulting surface. Ploughing deteriorates the surface quality of the part especially in relatively soft metals such as aluminium by leaving tool tip marks on the resulting surface. Consequently, considering either extra indentation/ploughing forces or tool tip marks on the resulting surface, the tool tip contact with the workpiece should be avoided wherever possible. The conditions for tool tip contact avoidance are discussed in this section.

The position vector of the tool tip (F_t, C_t, N_t) in FCN coordinate system is defined as follows:

$$\begin{bmatrix} F_t \\ C_t \\ N_t \end{bmatrix} = \begin{bmatrix} -R_o \sin l \\ R_o \sin t \cos l \\ -R_o \cos t \cos l \end{bmatrix} \tag{3}$$

where R_o is radius of ball-end mill, l is lead angle and t is tilt angle. The tip contact can only occur if the lead angle is not positive, thus non-positive lead angles must be avoided if possible. However, in some cases non-positive lead angle must be used due to the tool accessibility. Under such circumstances, the tip contact can be eliminated by keeping the cutting depth smaller than a critical cutting depth, a_{crit}, which is shown in Fig. 4. The critical cutting depth depends on the N component of the tool tip position vector, N_t, and is calculated by the following equation:

$$a_{crit} = R_o(1 - \cos t \cos l) \tag{4}$$

If the required cutting depth is greater than the critical cutting depth, the tip contact can still be avoided if the cross-feed direction, the step over, the lead angle and the tilt angle are selected properly except the slotting cases. The conditions to avoid tool tip contact for first and following cut cases are described as follows.

In first cut cases, there are two different situations depending on the cross-feed direction (Fig. 5). Fig. 5(a) shows a case where cross-feed direction is positive whereas Fig. 5(b) illustrates a case with negative cross-feed direction. In these cases, both lead and tilt angles are negative. The highlighted regions in the figures show the engagement zones of the cutting tool and workpiece. The below conditions, which are determined from the geometry, should hold in order to avoid tool tip contact in first cut cases:

$$\left.\begin{matrix} s < -R_o \sin t \cos l \\ s > -R_o \sin t \cos l \end{matrix}\right\} \begin{matrix} \text{if cross-feed direction is positive} \\ \text{if cross-feed direction is negative} \end{matrix} \tag{5}$$

In following cut cases, when the lead angle is non-positive and the cutting depth is higher than the critical cutting depth, the tool tip is definitely in contact if both of the cross-feed direction and the tilt angle are either positive or negative. Similarly, tool tip contact cannot be avoided when tilt angle is zero. In Fig. 5(c) tool tip contact is illustrated for a representative case where both cross-feed direction and tilt angle are positive. On the other hand, the tool tip can be kept out of contact if the cross-feed direction and the tilt angle have opposite signs and the step over is selected properly as illustrated in Fig. 5(d). As shown in the figure, the tip contact does not occur since the material at the tool tip location has been removed in the previous cutting pass. For such cases, if the step over is less than a critical step over value, s_{crit}, the tool tip is out of cut. The critical step over value can be calculated using the engagement model presented in [12]; it depends on the cross-feed direction, lead angle, tilt angle, step over and tool tip's N coordinate, N_t. The critical step over, s_{crit}, in terms of these parameters are given in Table 1 for different cases where tool tip contact can be avoided.

In cases where the step over is less than $2R_o \cos t$, if tool tip's N coordinate, N_t, is less than N_i, the tool tip is in contact with the workpiece; otherwise, the tip contact can be avoided by selecting the step over according to Table 1. On the other hand, if the step over is higher than $2R_o \cos t$, the tool tip is in contact with the workpiece if its N coordinate is less than N_s, if not, tool tip contact can be eliminated by adjusting the step over with respect to s_{crit} (Table 1).

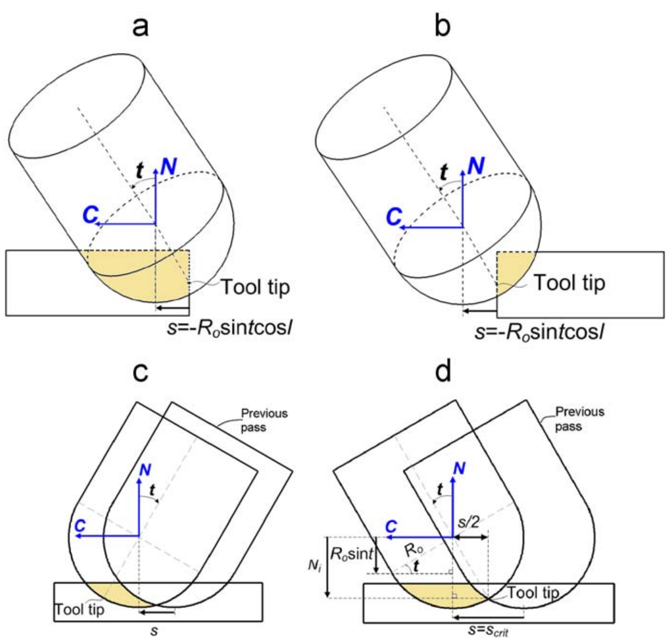

Fig. 5. (a) Tool tip contact avoidance in first cut cases, cross-feed direction positive, (b) crossfeed direction negative, (c) tool tip contact in following cut cases, cross-feed direction positive, positive tilt angle and (d) negative tilt angle.

As presented above for first cut and following cut cases, even if the lead angle is non-positive and cutting depth is higher than a_{crit}, the tool tip contact with the workpiece can be avoided by selecting step over properly when the lead and tilt angles are fixed. Alternatively, if step over is selected beforehand, the tool orientation (lead and tilt angles) can be selected accordingly considering the above conditions to prevent tool tip contact. The procedure that can be followed to prevent tool tip contact is summarized in Fig. 6.

3.2. Scallop height

In finishing operations, the step over is decided according to the allowed scallop height on the resulting surface. Given the allowable scallop height, the required number of cutting steps may decrease with increasing tilt angle under certain conditions. Therefore, it is important to identify these conditions and select the tilt angle accordingly for increased productivity, which is discussed in this section.

For following cut cases, the tilt angle does not have any effect on the scallop height if the step over is less than $2R_o \cos t$. This is in general the case for finishing operations where s is selected low in order to achieve good surface finish. However, if step over is higher than $2R_o \cos t$, increasing tilt angle decreases the scallop heights left on the surface as shown in the following example.

In order to demonstrate the effect of tilt angle on scallop height, a following cut operation where cross-feed direction is positive and cutting depth is 5 mm is considered for different step over values, i.e., 5 and 10 mm. The cutting tool is a 12 mm diameter ball-end mill. In Fig. 7(a), the effect of the tilt angle on scallop height for the two cases is presented. When step over is 5 mm, the tilt angle does not affect the scallop height since $s \leq 2R_o \cos t$ condition holds for the given tilt angle range. However, as the step over is increased to 10 mm, $s > 2R_o \cos t$ condition is satisfied when the absolute value of tilt angle exceeds 33.6°. In Fig. 7(a), it is seen that the scallop height decreases for this case for higher absolute values of tilt angle.

The effect of tilt angle on the allowable step over values for four different scallop height constraints is shown in Fig. 7(b). It is clearly seen that increase in tilt angle causes allowable step over value to increase, resulting in less number of cutting steps to remove the required volume of material.

3.3. Cutting torque, forces and form error

Effects of lead and tilt angles on cutting force, torque or form error can only be predicted through simulations using the process model [12] due to the complex geometry of the ball-end mill and

Table 1
s_{crit} definition for following cut cases.

Cross-feed direction	Tilt angle	Step over	Tool tip's N coordinate N_t	s_{crit}
Positive	$t<0$	$s \leq 2R_o \cos t$	$N_i < N_t \leq R_o \sin t$	$R_o(\sqrt{1-\cos^2 t \cos^2 l} - \sin t \cos l)$
			$N_t > R_o \sin t$	$\frac{R_o}{\cos t}$
		$s > 2R_o \cos t$	$N_t > N_s$	$\frac{R_o}{\cos t}$
Negative	$t>0$	$s \leq 2R_o \cos t$	$N_i < N_t \leq -R_o \sin t$	$R_o(\sqrt{1-\cos^2 t \cos^2 l} + \sin t \cos l)$
			$N_t > -R_o \sin t$	$\frac{R_o}{\cos t}$
		$s > 2R_o \cos t$	$N_t > N_s$	$\frac{R_o}{\cos t}$

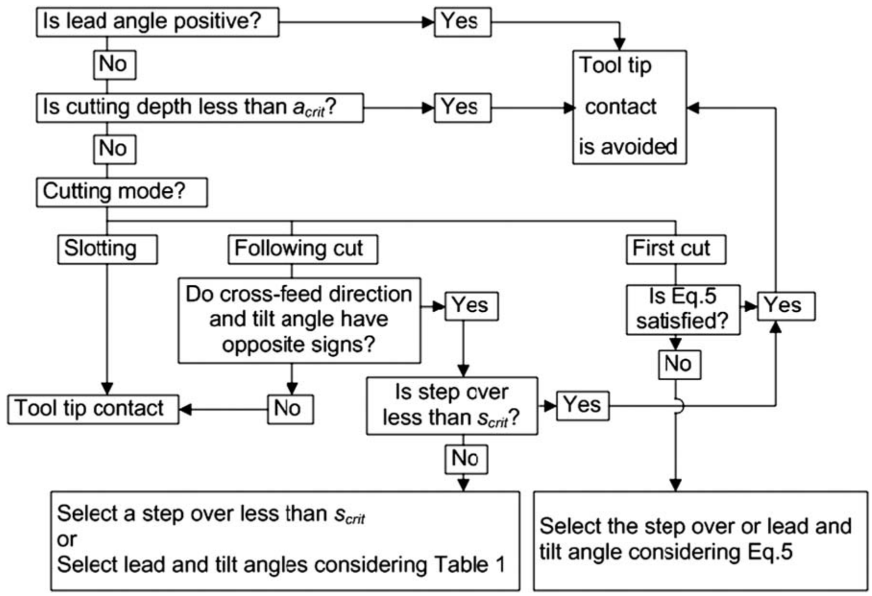

Fig. 6. Tool tip contact avoidance procedure.

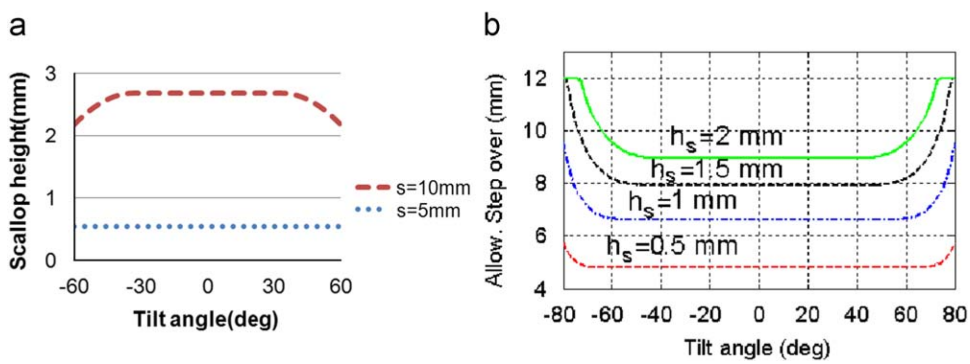

Fig. 7. Variations of (a) scallop height and (b) allowable step over with tilt angle.

non-linear variations. However, some qualitative information for the effect of the lead and tilt angles in following cut cases are given here considering the geometry and mechanics of the process for roughing and finishing operations, separately.

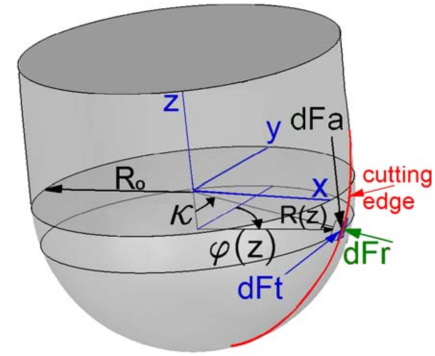

Fig. 8. Representation of local cutting forces.

3.3.1. *Roughing operations*

For roughing operations, constraints such as cutting forces, torque, and power, and tool breakage are taken into account. F_{xy} is the resultant transversal force acting on the tool in *xy*-plane, and is responsible for bending stresses which may cause tool-shank breakage. Cutting power is proportional to cutting torque which can be calculated by integration of product of local radius $R(z)$ and local tangential force (dFt) on differential elements (Fig. 8) over the engagement zone. In ball-end mills, local radius increases along the tool axis direction (z) up to the cylindrical part. Lead and tilt angles affect cutting power and torque as they change the engagement region and local radius $R(z)$. In order to illustrate this, a lead and tilt angle combination where engagement region is on the upper side of the tool along the tool axis and another lead and tilt combination which positions the engagement zone on the lower side of the cutting tool along the tool axis are presented in Fig. 2(a) and (b), respectively.

Lead angle can be selected as slightly positive in order to avoid tool tip contact while keeping the cutting torque, thus power, lower at the same time. If the cross-feed direction is negative, the tilt angle should be selected as negative so that the tool axis points toward the workpiece as illustrated in Fig. 2(b). In this case, the engaged region is kept on the lower side of the cutting tool along the tool axis as shown in Fig. 2(b). As a result, the local radii in the engaged region, and consequently cutting torque and power are kept minimum. However, if the tilt angle is selected as positive, tool is inclined towards the workpiece and the engaged region shifts to the upper parts of the cutting tool as shown in Fig. 2(a) resulting in higher local radii in the cutting zone and higher cutting torque. Similarly, if cross-feed direction is positive, for the aforementioned reason, tilt angle should be selected as positive. Nevertheless, accurate values of preferable lead and tilt angles can only be selected by running simulations based on the process model. Such information may be useful in selection of the tilt angle in roughing operations where cutting depth, step over and feed are already set. For example, if ball-end mills having large diameters are used with high chip loads, cutting torque and power may increase close to the spindle limits. Under such circumstances it may be required to maintain lower cutting torque and power in order to achieve safe cutting conditions.

3.3.2. *Finishing operations*

In finishing operations, one of the most important limitations is the form error left on the part. It is defined as the dimensional error along the surface normal direction (N), which includes tool and workpiece deflections. Since the workpiece deflection is application specific, only the tool deflection is considered in this paper.

In general, cutting tools are much stiffer in the tool axis direction (z) than (x) and (y) directions (Fig. 8). For that reason, if the tool axis (z) is oriented in the surface normal direction (N) of the workpiece (lead $= 0^\circ$ and tilt $= 0^\circ$), tool deflection along the surface normal direction becomes minimum. However, in this case tool tip is in contact with the finished surface. As a result, the finished surface may not be of good quality especially in cutting operations of relatively softer metals such as aluminium.

An important consideration in selection of the tilt angle is overcutting. If cutting tool starts cutting from the finished surface, depending on the magnitudes and directions of the cutting forces at the instant of surface generation, the cutting tool can deflect into the workpiece surface. This is the case when tilt angle is selected negative for a clockwise rotating cutting tool. Since over cut cannot be corrected, negative tilt angle should be avoided for such tools in finishing operations. Similarly, for counter-clockwise rotating tools negative tilt angle should be preferred to avoid over cut.

Consequently, although the quantitative effect of lead and tilt angles on the tool deflection in the surface normal direction can only be predicted through simulations using a process model [12], it can be concluded that for a clockwise rotating tool, using slightly positive lead and tilt angles would be better to obtain smaller deflections and to avoid tool tip contact.

3.4. *Stability*

Lead and tilt angles have effects on the directional coefficient matrix, which defines the relation between dynamic displacements and dynamic cutting forces [13], since they change engagement region between cutting tool and workpiece. The stability limits are determined by solution of the following eigenvalue problem [11]:

$$[\boldsymbol{F}]e^{i\omega_c t} = \Delta a(1 - e^{-i\omega_c \tau})(\sum_{l=1}^{m} \boldsymbol{B_o^l})[\boldsymbol{G}(i\omega_c)]\,[\boldsymbol{F}]e^{i\omega_c t} \tag{6}$$

Depending on the kinematic configuration of machine tools, lead and tilt angles may also have effects on the transfer function matrix $\boldsymbol{G}$ in Eq. (6). This effect is seen when the rotational axes of the machine tool are on the table side (Fig. 9) and the measured transfer functions of the cutting tool in two orthogonal directions, i.e., (X) and (Y) directions, are not the same. In this case, feed direction depends on lead and tilt angles.

For a sample 3-axis ball-end milling case, feed direction with respect to the workpiece is presented in Fig. 9(a). It coincides with the $-Y$ direction in the machine coordinate system, which is an inertial reference system. However, when lead and tilt angles are applied on the process, in order to satisfy the same feed direction with respect to the workpiece, the feed direction with respect to the machine coordinate system has to change as shown in Fig. 9(b). This is particular to the considered machine tool configuration where rotational axes are on the table side. In order to take this change into consideration in the stability formulation, the measured transfer function matrices need to be oriented accordingly. The measured transfer function matrix $\boldsymbol{H}$ can be oriented using a transformation matrix $\boldsymbol{T_G}$ as follows [10]:

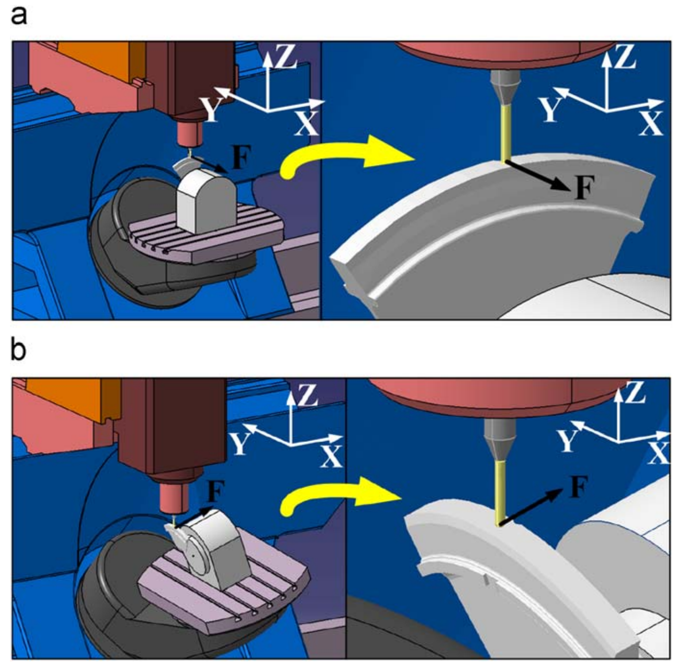

Fig. 9. Effect of lead and tilt angle on feed direction: (a) 3-axis milling and (b) 5-axis milling.

$$\boldsymbol{G} = \boldsymbol{T_G^T H T_G} \tag{7}$$

As a result, due to their effects on the directional coefficient and oriented transfer function matrices, lead and tilt angles can change the stability limits of processes considerably. This effect is demonstrated through simulations and experiments in the next section.

4. Experimental and simulation results

The effect of lead and tilt angles on tool tip contact, overall machining time, cutting forces and cutting torque, and stability are investigated through simulations, and the results are verified by a series of cutting tests.

4.1. *Tool tip contact*

The effect of tool tip contact on the resulting surface is demonstrated through two cutting tests in following cut mode. The cross-feed direction is selected as negative in the tests, where 12 mm diameter ball-end mill is used. The test conditions are given in Table 2.

In test 1 lead and tilt angles are selected to be zero. Hence, tool tip is in contact with the created surface and leaves tool tip mark on the surface as shown in Fig. 10(a). In test 2, a positive lead angle is applied and tool tip contact is avoided. As presented in

Table 2
Conditions for the tool tip contact tests.

Test	Lead (deg.)	Tilt (deg.)	s (mm)	a (mm)	Tip contact
1	0	0	6	1.5	Yes
2	10	0	6	1.5	No

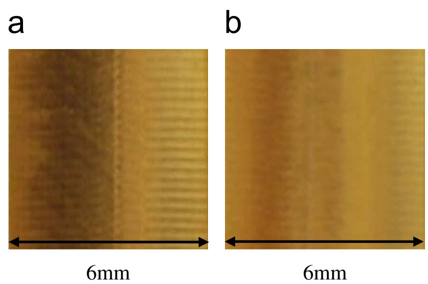

Fig. 10. Resulting surfaces after the tests.

Table 3
Effect of tilt angle on allowable step over while scallop height is fixed.

	Case 1	Case 2	Case 3	Case 4
Scallop height limit (mm)	2	2	1	1
Lead, tilt (deg.)	10, −35	10, −71	10, −35	10, −75
Allowable step over (mm)	8.94	11.28	6.63	7.84
Number of cutting steps	12	9	16	13

Fig. 10(b), the tool tip mark observed in test 1, does not exist on the surface for the test 2.

4.2. Scallop height

As mentioned previously, the number of required cutting steps subject to a scallop height limit can be decreased by changing the absolute value of the tilt angle, resulting in lower cycle time. The effect of tilt angle on cycle time is demonstrated in this section. The tilt angle value leading to higher allowable step over while satisfying the same scallop height limit is determined. Then, the resulting cycle time is compared with the case, where the tilt angle is not selected accordingly.

In the first two cases the scallop height limit is 2 mm, whereas it is 1 mm in the last two cases. The workpiece has planar surface with 100 mm of length in the feed and cross-feed directions. The cutting tool is a 12 mm diameter ball-end mill. The conditions of each case are given in Table 3. In case 1 and case 3, the tilt angle is selected randomly. In case 2 and case 4, the tilt angle is selected considering the allowable step over value according to Fig. 7. Then, the calculated allowable step over values for case 1 and case 3 are compared with the values calculated for case 2 and case 4, respectively. It is shown that the allowable step over value can be increased by changing the tilt angle from −35 deg. to −71 deg. in case 2 and by changing it from −35 deg. to −75 deg. in case 4.

From Table 3, it is seen that the total number of cutting steps can be decreased by 25% and 19% in case 2 and case 4, respectively. It can be concluded that machining time can be decreased significantly by only changing the tilt angle when possible.

4.3. Cutting force, torque and form error

Effects of lead and tilt angle pairs are demonstrated by roughing and finishing examples in this section. The variation of cutting torque and maximum F_{xy} force with lead and tilt angles are demonstrated in the roughing examples while the effect of lead and tilt angles on form error is presented for a finishing case (Fig. 11).

The first roughing case is a following cut operation where the cutting depth and the step over are 5 mm, the feed rate is 0.05 mm/tooth, the spindle speed is 1000 rpm and cross-feed direction is negative. The cutting tool is a 12 mm diameter, 2 fluted ball-end mill with 30° helix angle and 8° rake angle. It is a clockwise rotating tool. The workpiece material is Ti6Al4V which is commonly used in aerospace industry. The cutting force coefficients are calculated using *mechanics of milling method* as presented in [14].

Using the process model [12], the variation of maximum cutting torque is calculated and plotted for different lead and tilt angle combinations in Fig. 11(a). Since negative lead angles are generally unfavourable due to tool tip contact, negative lead angle cases are not included in the figure. As it can be seen from the figure, cutting torque is less for negative tilt angles. In order to verify these predictions, three points were selected on Fig. 11(a) and cutting tests were performed. Measurement and simulation results for maximum resultant lateral force F_{xy} in these cases are tabulated in Table 4. It is seen that force predictions are in good agreement with the measurements. Moreover, simulated variation of maximum resultant lateral force F_{xy} for different lead and tilt combinations is also shown (Fig. 11(a)). Comparing the figures for maximum torque and maximum force F_{xy}, it is seen that variation of maximum torque and maximum resultant lateral force F_{xy} with lead and tilt angles have a similar trend.

Fig. 11(a) reveals that low lead angles and negative tilt angles are favourable for decreased maximum resultant lateral force F_{xy} and cutting torque when cross-feed direction is negative. Hence, the qualitative remarks made about effects of tilt angle in Section 3.3, are verified by simulations and experiments in Fig. 11(a). For this case, in order to keep cutting torque and resultant lateral force F_{xy} low, and also to avoid tool tip contact, lead angle should be selected slightly positive and tilt angle should be negative. As a result, lead and tilt angle combination of (5°, −40°) can be a good selection for this case.

In the second roughing example, all the process parameters are the same with the previous case except the cross-feed direction, which is positive. Simulated variation of the maximum torque and maximum F_{xy} force with lead and tilt angles is plotted in Fig. 11(b). As presented in Section 3.3.1, it is seen that slightly positive lead angles and positive tilt angles are favourable. Therefore, for this case lead and tilt angles can be selected as 5° and 40°, respectively.

The last example is a finishing example where cross-feed direction is negative. Cutting depth and step over are both 1 mm and the other process parameters are same with the previous examples. As expected, the minimum tool deflection in the surface normal direction results when the tool axis is aligned with surface normal direction of the workpiece (point 1 in Fig. 11(c): lead and tilt angles are both zero). However, in this case, the tool tip is in contact with the finished surface and it may result in poor surface quality. Positive lead angles are favourable to avoid tool tip contact. On the other hand, in order to avoid overcut from the surface, positive tilt angles are preferred as presented in Section 3.3.2. In Fig. 11(c), it is shown that negative tool deflections in the surface normal direction are possible for some negative tilt angles. As a result, the lead and tilt angle pair of (5°, 5°) can be selected for this case.

4.4. Stability example

Effects of lead and tilt angles on absolute stability limits are presented on an example case in this section.The example case is a

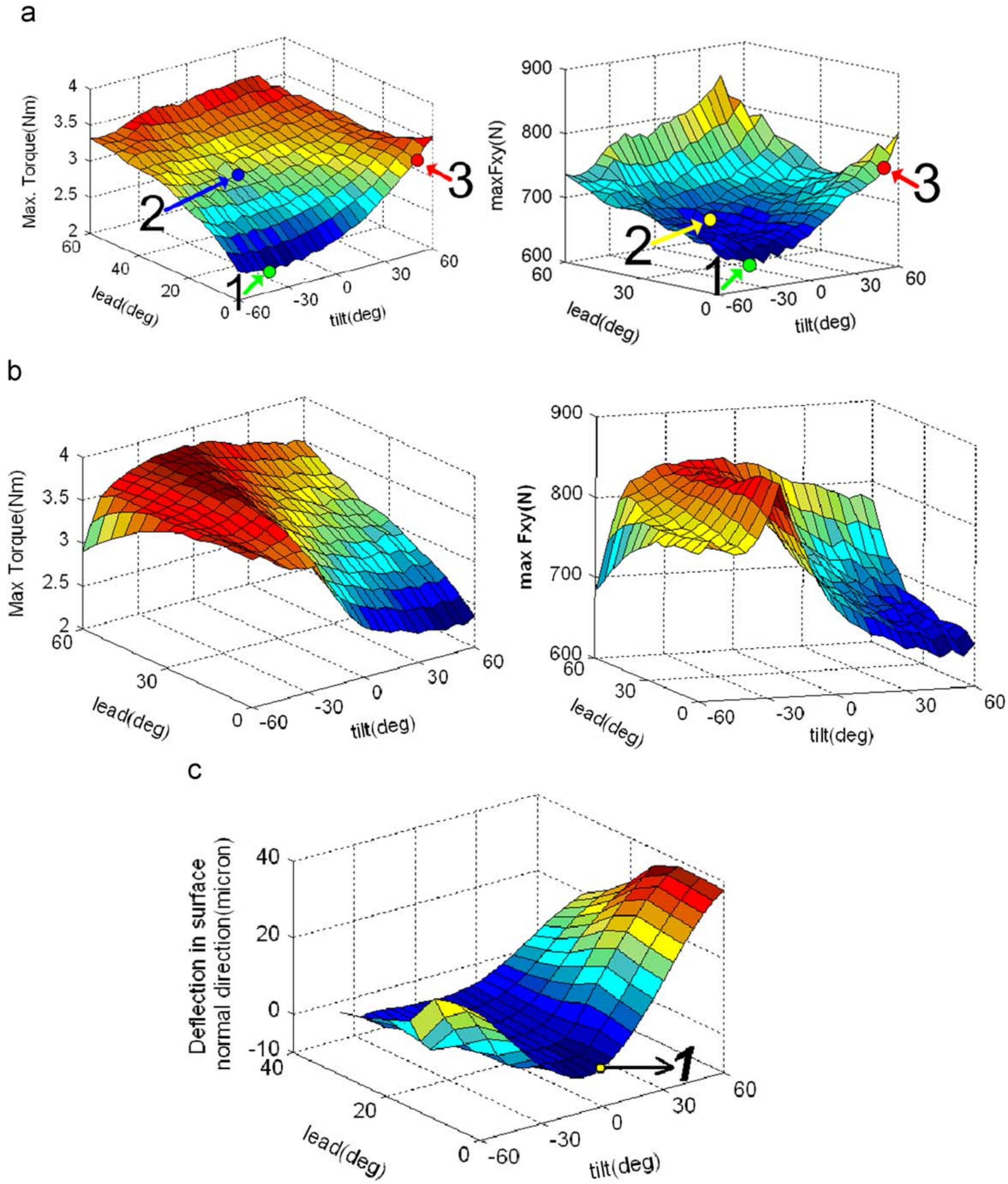

Fig. 11. Effects of lead and tilt angles on (a) maximum torque, maximum F_{xy} force for case 1 ,(b) case 2 and (c) tool deflection in the surface normal direction for case 3.

Table 4
Simulation and measurement comparison for the example case 1.

Point	lead, tilt (deg.)	Simulated maximum F_{xy}(N)	Measured maximum F_{xy}(N)
1	0, −40	637	600
2	30, −15	672	652
3	0, 50	752	712

following cut operation where step over is 2 mm and cross-feed direction is negative. The cutting tool is a 16 mm diameter ball-end mill with 2 flutes that has 8° rake angle and 30° helix angle. The machining center is DMG 50 Evolution where 2 rotational axes are on the table side, and the workpiece is a rectangular block of 1050 steel that is clamped directly to the rotary table. Only the flexibility of the cutting tool is considered and the measured frequency response functions in (X) and (Y) directions are presented in Fig. 12. In the same figure, simulated effects of lead and tilt angles on the absolute stability limits are presented. It is seen that lead and tilt angles affect absolute stability limits considerably. In order to verify this observation, the absolute stability limits were determined experimentally for six different combinations of lead and tilt angles which are also shown in the same figure. Overall, there is a reasonable agreement between the model predictions and the experimental results.

According to the stability predictions shown in Fig. 12, for lead and tilt combination of (0°, 0°) at 2 mm cutting depth and at 9000 rpm, the process is expected to be unstable which was verified experimentally. The chatter effect on the resulting surface quality is presented in Fig. 12 where the effect of the tool tip

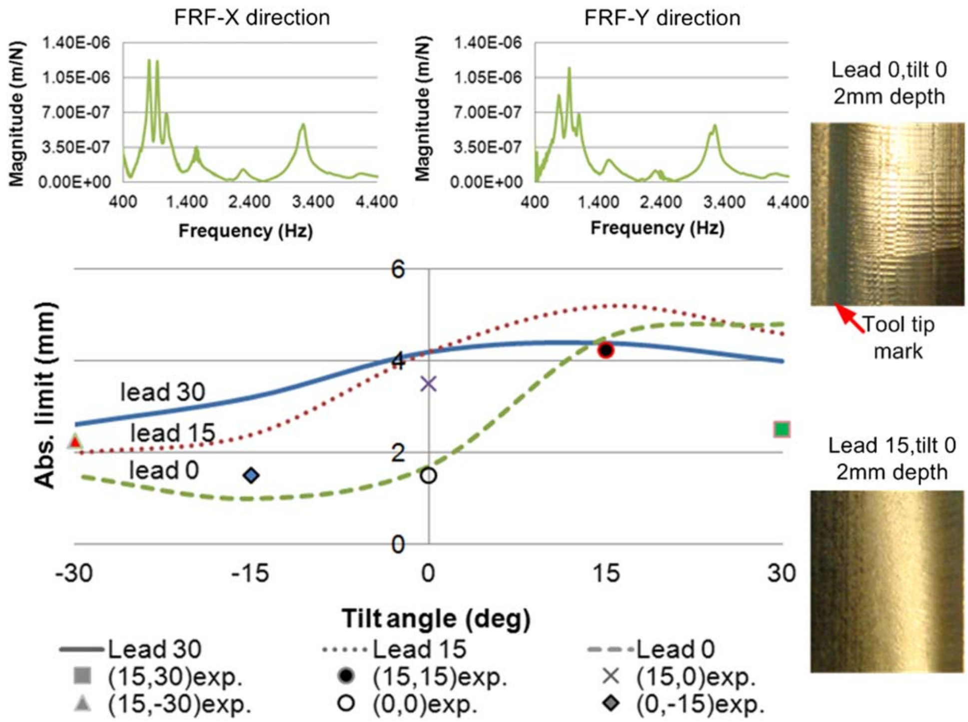

Fig. 12. Effect of lead and tilt angles on stability.

contact is also observable on the surface. For the same cutting depth and spindle speed, the surface obtained wih $(15^\circ, 0^\circ)$ combination is also shown in the figure. In this case, the process is stable as predicted, and the tool tip contact is avoided with the application of 15° lead angle.

5. Conclusion

Lead and tilt angles increase the capability of 5-axis ball-end milling in terms of enhanced accessibility and complex surface generation. However, their effect on process geometry, mechanics and dynamics are not well known which is the subject of this study. This paper presents a detailed analysis of lead and tilt angle effects on 5-axis ball-end milling operations. These effects are summarized below briefly.

Lead and tilt angles affect the tool tip contact condition which is an undesirable situation due to additional ploughing, indentation forces and tool tip marks generated on the resulting surface. If the lead angle is positive or cutting depth is less than a critical cutting depth a_{crit}, tool tip contact is always avoided which is also demonstrated experimentally. For other cases, conditions for lead and tilt angles, and other process parameters are presented to avoid tool tip contact.

For cases where step over s is higher than $2R_o \cos t$, tilt angle affects the scallop height left on the surface where increase in absolute value of the tilt angle decreases scallop height. Thus, higher step over can be used for a given scallop height limit which in turn results in less number of cutting steps. Finally, an increase in absolute value of tilt angle results in decreased machining time which is also demonstrated with experiments.

Lead and tilt angles strongly affect cutting forces, torque, power and form errors since they change the geometry and mechanics of the process. It is demonstrated that in order to minimize the cutting torque and power, the engagement region with the workpiece should be positioned on the lower side of the tool which is particularly important for roughing operations with relatively large diameter tools where the available torque and power can be the process limitation. Although exact values of the required lead and tilt angles to minimize these parameters can only be determined by running the process model [12], some qualitative guidelines can be suggested. Tilt angle should be selected such that it has the same sign with the cross-feed direction. On the other hand, lead angle should be kept at a slightly positive value since application of higher positive lead angles shifts the engagement region to the upper parts of the cutting tool and negative lead angles may result in tool tip contact. These qualitative comments are verified by simulations and experiments for two representative cases.

Form error due to tool deflections is an important factor for finishing operations. For minimum form error, lead and tilt angles could be selected as zero; however, this would result in tool tip contact marks with the created surface. For that reason, lead angle should be selected slightly positive. For the selection of tilt angle, overcutting is an important consideration. For clockwise rotating tools, when tilt angle is negative, the cutting tool starts cutting from the finished surface. In such a case, depending on the direction of cutting forces, the tool may deflect into the workpiece resulting in overcut. The opposite is true for counter-clockwise rotating tools. Hence, negative tilt angles should be avoided for clockwise rotating tools while use of positive tilt angles should be prevented for counter-clockwise rotating tools where possible.

Lead and tilt angles also affect the dynamics of 5-axis ball-end milling. They change the chatter behavior and stability limits not only due to their effect on the directional coefficient matrix, but also on the feed direction and oriented transfer function matrix depending on the machine tool configuration. For a representative test case, it is demonstrated that combined effect of lead and tilt angles may provide 4 times increase in absolute stability limit.

The presented results in this paper are believed to be useful for enhancing the understanding of lead and tilt angle effects on 5-axis ball-end milling operations. Moreover, they can also be used to increase the productivity and surface quality in 5-axis ball-end milling processes.

Acknowledgement

The authors acknowledge Scientific and Technical Research Council of Turkey (TUBITAK) for its support in this research.

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