Experimental Investigation of Cutting Forces in Cutter/Work-piece Engagement Initiation in Ball-End Milling

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Abstract

Five-axis machining is widely used in aerospace, automotive and biomedical industries. Cutting forces in milling have been in focus of a lot of researchers in order to strengthen the understanding of the process, improve surface quality, reduce tool wear and maximize the productivity. A lot of research has been carried out on modeling and experimental validation of cutting forces in end milling under continuous cutting conditions, i.e. conditions after the cutter has entered the work-piece. But the research on prediction of forces in special conditions like cutter/work-piece engagement initiation without any pre-drilling has been very little. Such conditions are likely to exert varying cutting forces resulting in undesirable tool deflection and chatter. Hence, understanding this transient phenomenon is very important for better dimensional accuracies and tool wear.

In this work, experiments have been performed on an aerospace alloy with different combinations of lead and tilt angles using a ball-end mill under dry conditions. The variation of cutting forces at transient cutter/work-piece engagement initiation has been analyzed and the effect of cutting angles on the forces has been studied.

Keywords: Five-axis machining, ball-end milling, cutter/work-piece engagement initiation, lead and tilt angles.

1. INTRODUCTION

Five-axis machining is one of the most versatile manufacturing processes in use today. It facilitates machining of complex geometries with precision and is extensively used in aerospace, automobile, and biomedical industries [1]. Titanium alloys are one of the most common materials used in the aerospace industry due to its mechanical characteristics such as high strength to weight ratio, retention of properties at elevated temperatures and excellent corrosion resistance [1]. But machining of titanium alloys is very difficult because of its lower stiffness, poor thermal conductivity and, high chemical reactivity. This leads to higher stresses at the cutting tool edge, excessive tool wear and hence shorter tool life. Thus, it is essential to comprehend the mechanics of machining processes for titanium alloys.

In five axis machining, the two rotational axes stretch the available process space through orientation of the tool with respect to the workpiece. These axes are defined by 'lead angle' and 'tilt angle'. Lead angle is the angle between tool axis and surface normal measured in F-N plane (Feed and Normal axes). The tilt angle is the angle between tool axis and surface normal measured in C-N plane (Cross feed and Normal axes).

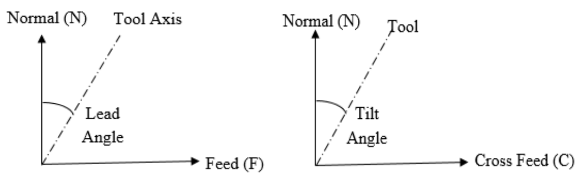

Fig. 1. Lead and tilt angles

Appropriate selection of these angles is important since they affect surface quality, cutting forces and tool life. Several researchers have modeled and experimentally investigated five axis ball end milling process. Ozturk et al. [2] studied the influence of lead and tilt angles on ball end milling process and demonstrated that to minimize the cutting torque and power, the engagement region with the workpiece should be positioned on the lower side of the tool. The authors gave qualitative comments about the effect of tool orientation on tool tip contact condition, scallop height, cutting forces, form errors and verified them by simulation and experiments. Ozturk and Budak [3] presented an analytical model to simulate effects of lead and tilt angles on cutting forces and tool deflection errors. The model was verified by machining experiments of the Ti6Al4V alloy. S.G. Han and J. Zhao [4] studied the effect of the tool inclination angle on surface topography and sub-surface properties in the high-speed milling of P20 die steel and reported that it is possible to enhance the cutting conditions and obtain better surface quality by selecting reasonable tool inclination angles and up/down milling method. Layreh et al. [5] simulated the cutting force and cutting torque for different lead and tilt angles to find the optimum tool orientation in order to consume less energy. Also by experimental investigation using aluminium 7050 alloys, the authors showed that the maximum resultant force acting on the tool can be reduced up to 22% just by appropriate selection of lead and tilt angles. A lot of research has been carried out on modeling and experimental validation of cutting forces in end milling under continuous cutting conditions, i.e. conditions after the cutter has entered the work-piece. However, the research on understanding the transient phenomenon of cutter workpiece engagement initiation, i.e. when the tool is entering or exiting the workpiece has been very little. In this paper, the effect of lead and tilt angles on cutting forces during cutter workpiece engagement initiation has been analysed.

This paper proceeds as follows: The experimental details, including workpiece material, cutting tool, cutting parameters have been provided. Cutting force variation in transient cutter-workpiece engagement initiation and the continuous cutting condition is shown. The effect of lead and tilt angles on cutting forces is studied using Root Mean Square values, maximum

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transverse force values and standard deviation. Finally, the experimental results and discussion are summarized.

2. EXPERIMENT PLAN

The workpiece material used in this study was a Ti6Al4V alloy of grade 5 which is normally used in the aerospace industry. The size of the workpiece was 80mm x 80mm x 10mm. Slot milling experiments were performed on a five-axis DMG DMC 125FD DuoBlock machine. The cutting tool selected was a solid carbide ball nose end mill (1B230-1000-XA 1630 CoroMill® Plura). It is a two fluted tool with 10 mm diameter, 30° helix angle and rake angle of 10.5°. The shank length is 53mm, with a usable cutting flute length of 19mm.

Fig. 2 Ball end mill used in analysis

The experiments were performed with a spindle speed (s) of 3000 rpm with a cutting depth (d) of 0.5 mm, a feed rate (f) of 0.08mm/tooth. These parameters were kept constant through all the experiments and the tool inclination was changed according to the lead (L) and tilt (T) angle combinations as follows. [6].

	{ (0,0),	(0,10),	(0,20),	(0,30),
(L, T) =	(0,40),	(-10,0),	(-20,0),	(-30,0),
	(-40,0),	(-10,20),	(-20,10),	(-30,20),
	(-20,30),	(-40,30),	(-30,40),	(-10,40) }

The values of lead and tilt angles were selected considering the machining envelope of the CNC machine tool and commonly used angles in multi-axis machining. To minimize the effect of tool wear on cutting forces, the tool was changed after every 4 slots. The machining was done under dry condition (no coolant). Each workpiece was mounted on a fixture and the fixture was mounted on a Kistler table dynamometer (Kistler Corporation, Model 9257A), which was used to measure the cutting forces in X, Y, Z direction. The data acquisition frequency was 1000Hz. This entire setup was rigidly clamped to the table of CNC machine.

3. RESULTS AND DISCUSSION

3.1 Initiation of cutting forces

Fig. 3(a) shows a variation of cutting forces in machine coordinate system (F_x, F_y, F_z) for slot milling with tool orientation of zero-degree lead and tilt angles. The forces F_x, Fy, F_z are cross-feed force, feed force and the normal force respectively. Positive and negative values in the graph signify the change in direction of force due to rotation of the ball end mill. The 'transient force region' is the cutter workpiece engagement initiation zone.

As clearly seen from Fig. 3 in the transient force region, the forces increase gradually from zero and after a certain duration, become almost constant in magnitude. Feed force acts in both directions (+Y and – Y) whereas cross-feed force and normal force are unidirectional. In one tool rotation of the time period 0.02s, there are 2 peaks for each of the forces since the cutting tool used is a 2-fluted symmetrical ball end mill. With the progress in cutter workpiece engagement, the peak force values are seen to gradually increase as seen in Fig. 3b. Initially, there is a small portion of zero force between each consecutive peak. This gap of zero force is absent in the latter portion of the force plot (Fig. 3c). The possible reason for this observation is gradual increase in angle of immersion (ø) of the cutter in transient force region from 0 to 180º. Hence, in the latter region, there is no time lag between the exit of first flute and entry of the second flute.

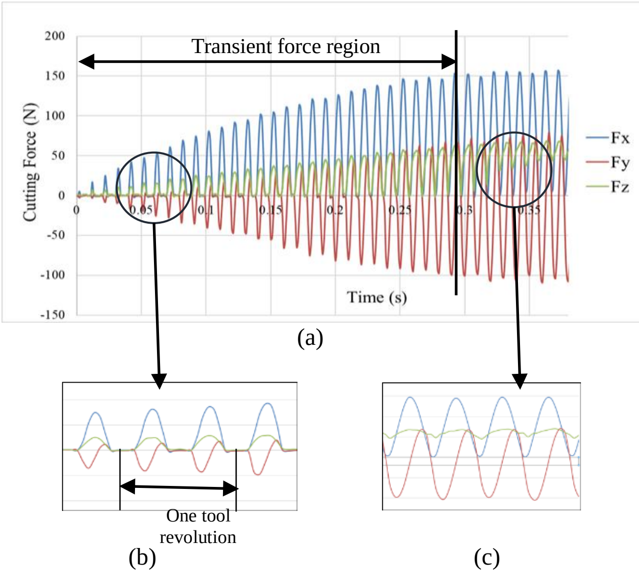


Fig. 3. Cutting forces for slot milling with zero lead and zero tilt angles (a) Plot of cutting forces measured by dynamometer (b) Detailed view of cutting forces in transient initiation zone (c) Detailed view of stabilized cutting forces

Since the feed rate was kept constant, time axis represents the length of the slot. Slot length was calculated based on feed rate and the time value of transient force region and plotted for different combinations of lead and tilt angles as shown in Fig. 4.

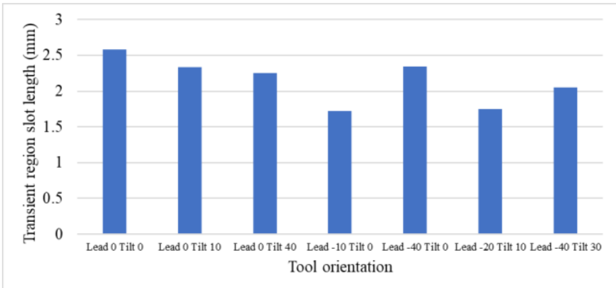


Fig. 4. Length of slot during cutter workpiece engagement initiation

It was observed that range of slot lengths in transient force region was 1.72 mm to 2.58 mm. The average duration of this region is 0.275s which correspond to 14 tool revolutions. After 15 tool revolutions (180º engagement) the nature of cutting forces become stable. Hence, in further analysis, data for first 20 tool revolutions is presented.

3.2 Variation of F_x and F_y

Fig. 5 is the plot of Root Mean Square (RMS) value of F_x calculated for all data points in one tool revolution against number of tool revolution. As the tilt angle increases, keeping zero lead angle, RMS of Fx is decreasing, whereas for a similar plot of F_y in Fig. 6, with the increasing tilt angle the variation of F_y is very less. The probable explanation for this observation can be given by the area of the tool in contact with the workpiece during machining.

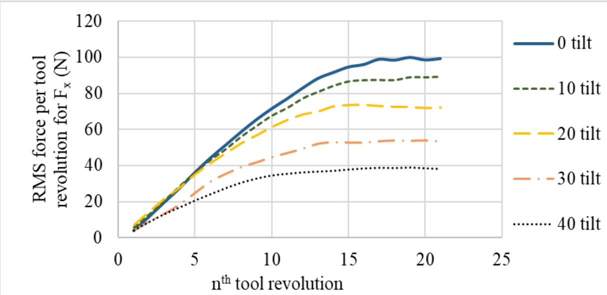


Fig. 5. RMS F_x force for each tool revolution in transient force region for varying tilt angles (degrees) with zero degree lead angle

The radius of the ball portion of the tool is 5 mm whereas the depth of cut is 0.5 mm. When tilt angle increases, area of the tool-workpiece contact zone in the Y direction (feed direction) remains same as shown in Fig.7. But the contact zone shifts its position on the tool with changing tilt angle when viewed along X-axis. Thereby, cutting velocities at different points in engagement zones are changing and hence the cutting force values, as seen in Fig.5.

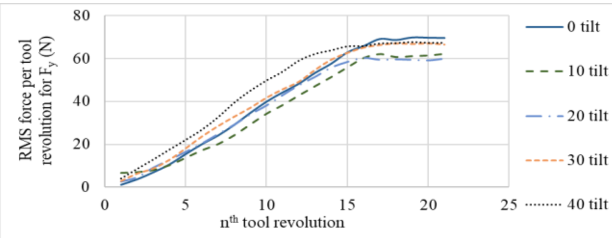


Fig. 6. RMS F_y force for each tool revolution in transient force region for varying tilt angles (degree) with zero-degree lead angle

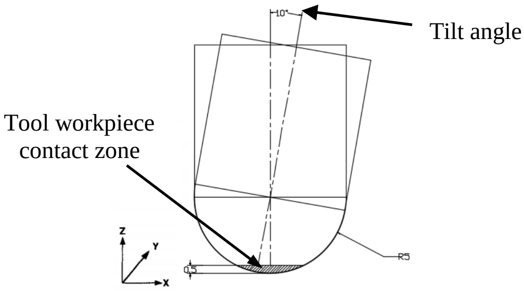


Fig. 7. Tool-workpiece contact area for zero lead and 10º tilt

Fig.8 also shows RMS plot of F_y, but for combinations of tilt angles along with negative lead angles. The maximum value of RMS force in this figure is less than that in Fig.6 which is the case of tilt angles only. The nature of the force variation with respect to tool orientation is not following any single pattern. This might be due to complexity in variation of tool-workpiece engagement zone, tool tip contact due to negative lead angle.

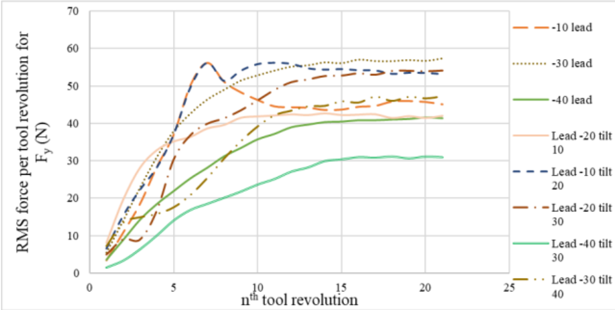


Fig. 8. RMS F_y force for each tool revolution in transient force region for varying tilt and lead angles

3.3 Variation of F_{xy}

In Fig.9, maximum F_{xy} force (resultant force of F_x and F_y) for each tool revolution in transient force region for different lead and tilt angles has been plotted against the number of tool revolution. F_{xy} is the bending force acting on the tool.

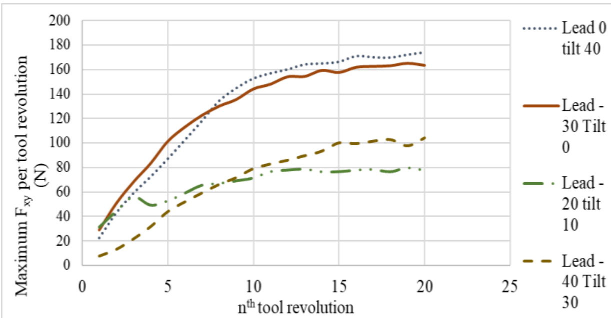


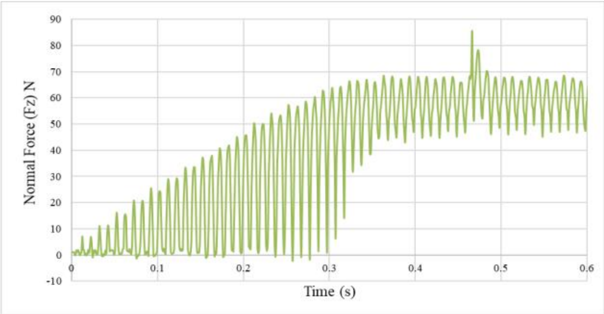
Fig. 9. Maximum F_{xy} force for each tool revolution in transient force region for varying Lead and Tilt angles

In this chart, only two maximum and two minimum curves have been shown, the rest of the combinations of the tool orientation lie between these extremes. It is observed that the difference between extreme curves is approximately 110% of the lowest curve. Thus, lead and tilt angles largely affect the bending force on the tool in cutter workpiece engagement initiation region.

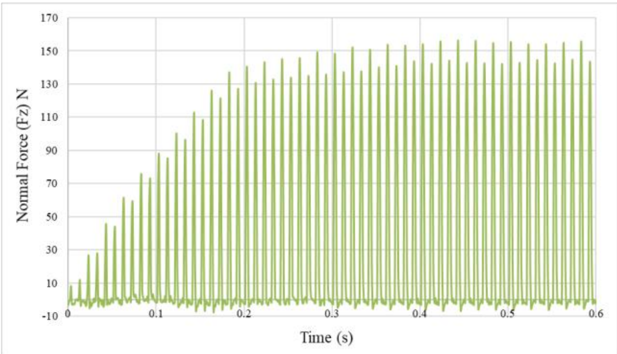
3.4 Variation of F_z

F_z is the normal force acting on the workpiece. Fig.10 shows variation of F_z for two different tool orientations. In Fig.10a, the tilt angle is minimum (zero) and in Fig. 10(b), it is maximum (40º). This varying nature can be analyzed better by using standard deviation in the measured forces.

Fig. 11 shows variation of the standard deviation of F_z force values for each tool rotation for varying tilt angle and zero lead angle. It is observed that initially the standard deviation increases in each revolution for the first 15 revolutions (at 0.3s), after which it starts to decrease. The increase in standard deviation signifies that the data points are moving away from the mean. This indicates that maximum F_z force is increasing in each revolution. The mean force increases continuously from the beginning of the cut and after 20 revolutions (0.4s) becomes constant.



(a)



(b)

Fig.10 (a) Variation of F_z for zero lead and zero tilt angle (b) Variation of F_z for zero lead and 40° tilt angle

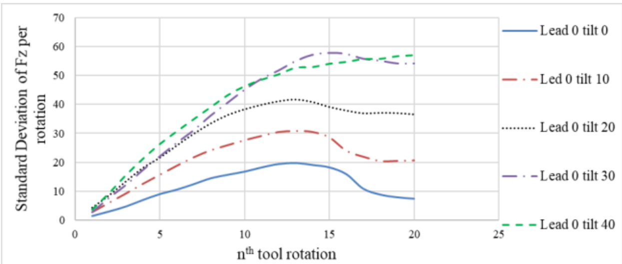


Fig.11 Standard deviation of F_z in transient force region for each tool revolution for varying tilt angles

The drop in standard deviation for tilt angles zero through 30° can be explained by referring to Fig. 10. The following explanation is applicable to the tilt zero case, but the same can be extended to other tilt angles. The standard deviation initially increases up to 15 revolutions (0.3s) because the peak force is increasing monotonically from zero before attaining a steady state of approximately 70N. After 15 revolutions (0.3s) the standard deviation drops till about 20 revolutions (0.4s) after which it remains constant. This is because the variation between the peak force and the minimum force about the mean is reduced. Simultaneously there is also a rise in the minimum force from zero to approximately 48N which subsequently remains constant after 20 revolutions. The rise and fall in the minimum force values can be attributed to the effect of the helix angle of the tool and its tilt angle on the orientation and motion of the cutting edges within the tool-workpiece engagement zone.

4. CONCLUSIONS

In five axis machining process, lead and tilt angles significantly affect the variation of cutting forces in cutter workpiece engagement initiation zone. The gradual increase in tool-workpiece contact zone is reflected in the variation of cutting forces. Similar results may be obtained when the ball end mill encounters a step in the workpiece while machining. The variation in the magnitude of the forces with lead and tilt angle could be attributed to the change in the position of the cutter-workpiece interaction zone on the tool. The instantaneous cutting velocity in the zone changes as its position on the tool changes. A detailed study of the gradual increase in cutter workpiece contact zone is required to thoroughly understand the beginning of engagement process. Also since the variation of forces is different in different tool orientations, tool chatter, tool life and surface finish will be affected.

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