Manufacturing of parts made out of difficult-to-cut materials presents many challenges. Reduced productivity and increased cost due to low machinability and tool life are main problems in these applications. Turn-milling may offer important advantages in solving these problems. Turn-milling combines conventional turning and milling processes providing lower cutting temperatures, higher process flexibility and productivity. Turn-milling processes have additional parameters one of which is the eccentricity between the tool and workpiece axes. The objective of this study is to develop a process model for eccentricity effects on orthogonal turn-milling operation. Process model includes chip geometry and cutting force calculations. In addition, effect of eccentricity on tool wear is also investigated in this paper. Although interrupted characteristics of turn-milling provide benefits such as lower cutting temperature and longer tool life, there are some drawbacks which have to be taken into consideration. In this direction, analytical definitions related to surface quality such as circularity, surface roughness and cusp height under the effect of eccentricity are also investigated. Experiments were carried out on a multi tasking CNC machine tool. Analytical solutions and experimental results are compared to verify the process model.

Keywords: Turn-milling; Eccentricity; Tool Wear; Surface Roughness; Circularity

1. Introduction

Market demands for higher quality, reduced leads times and cost often create need for alternative manufacturing processes. Within this context, turn-milling, which combines conventional turning and milling, may offer advantages as a promising technology. This relatively new process may provide high productivity and surface quality at the same time if the conditions are selected properly. In addition, increased tool life is another potential advantage of turn-milling especially for difficult-to-cut materials due to intermittent cutting since cutting temperatures are lower compared to the ones in conventional turning.

One of the pioneering works on turn-milling was published by Schulz et. al in 1990 [1]. They categorized turn-milling into two as co-axial and orthogonal turn-milling. Although co-axial turn-milling is suitable for both external and internal machining, orthogonal turn-milling can be applied only external surfaces. They demonstrated on machining of bearing half liners that high speed turn-milling (HSTM) provides good chip removal, high surface quality and low cutting forces. Some of the recent efforts in turn-milling research have focused on surface quality. Choudhury and Mangrulkar [2] conducted several orthogonal turn-milling experiments for two different workpiece materials and compared the results with conventional turning. They pointed out that $R_s$ value of surface roughness for orthogonal turn-milling is 10 times lower than that is obtained by conventional turning. Choudhury et al. [3] conducted another experimental study on orthogonal turn-milling where the results were this time compared with conventional milling demonstrating that the surface produced by orthogonal turn-milling was better. Savas et al. [4] investigated surface roughness in tangential turn-milling of rotationally symmetrical workpieces achieving surface quality comparable to grinding. Kopac and Pogacnik [5] analyzed eccentricity effects on surface quality in turn-milling. They observed that the roughness value $Ra_{s}$ was much...
better in eccentric turn-milling. In addition, Yuan and Zheng [6] focused on developing a geometric model for turn-milling operation in order to predict the surface roughness in an effective way. They investigated the effects of turn-milling process parameters on surface roughness. Huang et al. [7] focused on developing a geometric model for turn-milling operation in order to predict the surface roughness in an effective way. They investigated the effects of turn-milling process parameters on surface roughness. Huang et al. [7] studied optimization of turn-milling parameters in terms of tool wear. They tried to develop a cutting acreage model to observe the cutting parameters effect on tool wear. There have been also studied about turn-milling kinematics. Karaguzel et. al [8] carried out extensive amount of testing with zero eccentricity demonstrating significant increases up to 20 times in tool life using turn milling instead of conventional turning for the machining of difficult to cut materials such as waspaloy and nickel alloys.

Neagu et al. [9] pointed out that turn-milling can reach 20 times greater productivity than rough turning operation of straight shafts. Analytical cutting force models were also developed for turn-milling Filho [10] conducted experiments on a five axis machining center while measuring cutting forces, and compared them with a an analytical model. In another study, Jiang by Zhu et al. [11] investigated the process parameters effects on surface roughness by simulations.

The main objective of this paper is to develop a comprehensive geometric model for eccentric orthogonal turn-milling operations which covers tool wear and surface quality are formulated. Furthermore, material removal rate (MRR) is specified and optimized by taking into account tool wear and machined part quality.

### Nomenclature

- \( v_t \): feed speed
- \( a_p \): axial depth of cut
- \( a_c \): feed per workpiece revolution
- \( f_i \): feed per tooth
- \( z \): number of teeth
- \( n_w \): rotational speed of workpiece
- \( n_t \): rotational speed of tool
- \( r_n \): rotational speed ratio of tool over workpiece
- \( R_w \): radius of workpiece
- \( R_t \): radius of tool
- \( D_t \): diameter of tool
- \( e \): eccentricity
- \( \Phi_s \): immersion start angle
- \( \Phi_e \): immersion exit angle
- \( l_m \): minor cutting edge length of the tool insert
- \( c \): cusp height
- \( \beta \): feed mark angle
- \( \theta \): angle between facets
- \( \text{MRR} \): material removal rate
- \( a_{e\text{crit}} \): critical feed per workpiece revolution
- \( \text{circ rough} \): roughness in circumferential direction

### 2. Experimental Setup

Fig. 1a shows Mori Seiki NTX 2000 Multi-Tasking Machine on which the turn-milling experiments were conducted. In addition, the primary axes and milling spindle are shown in Fig.1b. Tool spindle can rotate around only Y axes but can move linearly along the X, Y and Z axes. As a result of this configuration turning, milling and turn-milling operations can be performed on this machine.

AISI 1050 Steel was chosen as workpiece material both for force and tool wear experiments. In tool wear experiments 32 mm Seco Micro-Turbo 217.69-03 milling tool with three cutting teeth was used with MP2500 grade inserts. Cutting conditions used in orthogonal turn-milling experiments are as follows: 300 m/min cutting speed, 0.15 mm/tooth feed, 1 mm depth of cut and 8 mm feed per workpiece revolution. Eccentricity is another important parameter in orthogonal turn-milling and it can be defined as the Y offset according to the workpiece rotation angle (Fig. 2).

Because of the tool rotational and workpiece axial simultaneous movements, there are two different feeds in turn-milling process. The effect of the eccentricity parameter was investigated for four different values (0mm, 10mm, 21mm, 25mm) by using a 50mm diameter Seco milling tool with four teeth.

The effect of eccentricity on both tool wear and surface roughness were investigated for different cutting conditions. In order to measure tool wear, Nanofocus \( \mu \)surf 3D profilometer is used at regular time intervals.

![Fig. 1. (a)Mori Seiki NTX 2000 multi tasking machine; (b) possible axes on the machine tool.](image)

![Fig. 2.(a) 3D schematic representation; (b) concentric (eccentricity=0) case; (c) eccentric case of orthogonal turn-milling.](image)

![Fig. 3. (a)Nanofocus \( \mu \)surf; (b) Nanofocus image of cutting insert](image)
In all measurements after a certain cutting period, the inserts were chosen randomly and placed on measuring device to determine the flank wear (Fig. 3).

Mitutoyo portable surface roughness tester is used to measure the surface roughness of workpiece. In order to obtain reliable measurements, specimens were clamped on a chuck and the measurements were taken at different locations on the workpiece. The measurement devices and the set-up are illustrated in Fig. 4.

3. Eccentricity Effect on Chip Formation

Chip formation is crucial from the point of cutting mechanics, heat generation and stability. Eccentricity in orthogonal cutting changes engagement boundaries, and in turn, the chip thickness as well. Analysis of chip formation including eccentricity effects show that chip formation can be separated into three cases. For all cases $h$ represents the chip height in $Z$ direction with respect to $x$. In addition, $x$ represents the incremental length on the X axis.

If $0 < x < x_2$

$$h = \tan(\theta) \times (x - x_1)$$  \hspace{1cm} (1)

If $x_2 < x < x_3$

$$h = \sqrt{R_e - (x - 2)^2} - (R_e - a_e)$$ \hspace{1cm} (2)

Fig. 6 represents the chip formation in Case 2. When eccentricity is increased, there is no more uncut chip beyond the tool axis and governing equations become as follows:

If $x_3 < x < x_4$

$$h = \tan(\theta) \times (x - x_3)$$ \hspace{1cm} (3)

If $x_4 < x < x_5$

$$h = \sqrt{R_e - (x - 2)^2} - (R_e - a_e)$$ \hspace{1cm} (4)

Fig. 7. Cross section of uncut chip in Case 3.

Beyond a certain value of eccentricity, chip is formed only by the side of the cutting tool.

$$h = \sqrt{R_e - (x - 2)^2} - (R_e - a_e)$$ \hspace{1cm} (5)

Considering all three cases, one can obtain a general expression for the uncut chip geometry including eccentricity effect. Fig. 8 shows uncut chip area with respect to immersion angle for different eccentricity values under the cutting conditions of $R_t=4$ mm, $a_e=1$mm, $\theta=1^\circ$ and $R_w=45$ mm. Although $\Phi_s$ depends on the $R_t$ and $a_e$, $\Phi_{es}$ is always $180^\circ$.

4. Eccentricity Effect on Turn-Milling

4.1. Material Removal Rate

Material removal rate (MRR) determines the productivity in a machining process. MRR is proportional to the axial and radial depth of cuts similar to the conventional milling process. Actually $a_e$ in this equation has the same role of radial depth of cut in conventional milling, and should be used as such in the MRR calculation.

$$MRR = v_f \times n_f \times f_z$$ \hspace{1cm} (6)

$$v_f = z \times n_t \times f_z$$ \hspace{1cm} (7)

MRR in turn-milling can be limited due to surface finish quality. Both tool and workpiece simultaneous rotations result in polygon shape cross section which named as circularity through this paper. The polygon shape containing facets are a result of simultaneous tool and workpiece rotational...
The time between subsequent cutting tool engagements with workpiece is the main parameter which directly affects the number of facets on the machined surface. In orthogonal turn-milling, as the cutting edge engages with the work while it rotates, the work surface also moves due to the workpiece rotation. It results in a certain time period where there is no contact between the cutting edge and the finished surface until the next tooth reaches to the finished surface. The period between these two contact instants of the subsequent teeth with the finished surface determines the facet width, and thus the number of facets on the periphery of the cylindrical workpiece. Equation 8 illustrates the geometrical implementation of \( \theta \) angle, which represents the angle between subsequent facet middle points and related to number of facets.

\[
\theta = \frac{360}{2 \times \frac{a_e}{f_z}} \quad (8)
\]

As it can be understood from the equation above, number of facets is independent from eccentricity parameter. Cusp which is another circumferential form error in orthogonal turn-milling and shown in Fig. 9, is the height of remaining material during tool motion and directly associated with the tool, workpiece diameter and step over. Step over can be defined as the size of the cutter’s diameter that is engaged in a cut. The optimum eccentricity is \( e=R_aL_n \). In this case because of maximum contact length between tool and workpiece is obtained, highest \( a_e \) can be defined without observing cusp. The geometrical representation of cusp height is;

\[
ch = \left( \frac{R_e - a_e}{2} \right)^2 + \left[ \frac{c + (R_e - a_e) \times \tan \left( \frac{180}{2 \times \frac{a_e}{f_z}} \right)}{2} \right] - (R_e - a_e) \quad (9)
\]

\( a_e \) can be increased up to the critical value without producing any cusp. As a result, MRR can be increased without sacrificing surface quality in circumferential direction.

The effect of \( a_e \), \( n_z \), \( R_e \), and \( R_t \) on cusp height as shown in Fig. 10a. Furthermore, increasing \( r_n \) improves MRR. From Fig. 10b it can be seen that the tool radius has bigger influence on the cusp height compared to the workpiece radius where the cusp height increases with decreasing tool radius.

The effects of both \( a_e \) and eccentricity on the cusp height by using equation 9 is shown in Fig. 11a.

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The circumferential surface roughness is indirectly affected from angle $\beta$. During the measurement of circularity or circumferential roughness, a probe or a needle contacts the workpiece at desired number of points along the full circle. These desired and well-distributed points are located at the same distance from the base plane. $\beta$ angle affects the slope of the feed marks on workpiece. Therefore, the distribution of the cusps along the full circle is changed.

\[ \beta = \arctan \left( \frac{a_e}{4(R_e - a_e)} \right) \]  

(10)

In order to formulate the circumferential surface roughness the workpiece in cylindrical direction divided into two parts which are indicated with three points as shown in Fig. 14. Between point A and B, the surface roughness can be defined with the circularity form error. Point B represents the transition point in terms of circumferential surface roughness from circularity to cusp height. After point B, cusp height effect is included in the surface roughness calculation. In addition, from the point B to the C, the cusp height is increased continuously up to maximum value that’s why circular roughness equation contains weighted average. Equation 12 is derived based on this approach. At the half of the peripheral path cusp height takes its maximum value. If the $a_e$ is chosen less than or equal to $a_{e\text{crit}}$ only circularity will be observed as circumferential form error. In other words, $a_{e\text{crit}}$ is the limit value for producing surfaces without any cusp height.

\[ c = \frac{90 + \alpha - \arctan \left( \frac{a_e}{2(R_e - a_e)} \right)}{180} \times (R_e - a_e) \times \frac{90 - \alpha}{180} \times \frac{ch}{2} \]  

(11)

\[ c_{\text{circ}} = \left[ \frac{90 + \alpha - \arctan \left( \frac{a_e}{2(R_e - a_e)} \right)}{180} \times (R_e - a_e) \times \frac{90 - \alpha}{180} \times \frac{ch}{2} \right] \]  

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As it is represented in Fig. 15a, increasing in $r_n$ and decreasing $a_e$ reduce surface roughness in the circumferential direction. In addition, effects of $r_n$ and $a_e$ on the circumferential surface roughness are similar to those on the cusp height. On the other hand, there is a linear relationship between tool and workpiece and circumferential surface roughness as shown in Fig. 15b. Furthermore, conversely to the Fig. 15a, radius of workpiece effect on circular form error is bigger than radius of the tool.
number of wiper insert on the face mill tool must be increased. As illustrated in Fig. 17 increasing eccentricity eliminates wiper insert’s positive effect on the surface roughness since the engagement length between the tool and the workpiece is reduced by increasing eccentricity. Although wiper insert’s positive effect on the surface roughness is decreased with increased eccentricity, surface roughness is still better compared to standard insert except when the eccentricity equals to optimum value ($e=21\text{mm}$). For this case, for relatively small feed [mm/rev] values, the wiper insert has no worthwhile effect on surface roughness.

Fig. 17. Variation of surface roughness improvement with eccentricity.

4.4. Tool Wear

Stephenson et al. [12] point out that for the same cutting conditions intermittent cutting produces less cutting temperature than in continuous cutting operations. Because it contains cutting and non-cutting periods in each cycle which provides time to cool down. By this way, thermal based tool wear on cut was reduced. Thus, one of the most significant advantages of turn-milling is increased tool life [8]. In order to understand the eccentricity effects on tool life, experiments were conducted on AISI 1050 steel and Seco Duratomic 50 mm diameter milling tool with four teeth was used.

Fig. 18. Eccentricity effect on tool wear in AISI 1050 Steel.

Fig. 18 illustrates tool wear results with respect to cutting length, which is calculated for individual tool, for different eccentricity values. When the eccentricity is equal to optimum value ($e=21\text{mm}$) the engagement length between workpiece and tool reaches its maximum level which contributes more uniform distribution of the pressure on cutting tool. As a consequence of this, the tool life reaches its maximum for $e=21\text{mm}$. In this experiment cutting tool, which have 25 mm radius and 4 mm minor cutting edge length, is used. The difference between these values determines the optimum eccentricity value which provides the maximum engagement length between tool and workpiece. Selection of eccentricity as almost nearly the cutting tool radius ($e=21\text{mm}$) will result in the highest tool life. However, there is a limit for this improvement. When eccentricity becomes equal to the cutting tool radius, the engagement length between the tool and workpiece decreases dramatically. At this position, only the side edges of the cutting tool participate in the cutting zone. As a result, excessive cutting loads are exerted on a small part of cutting tool which causes decreased tool life.

5. Conclusion

The present paper describes effects of eccentricity in orthogonal turn-milling starting with the chip formation. From geometrical analysis, relationships between tool, workpiece and eccentricity are developed. A surface roughness model in circumferential direction is also introduced, and simulated for different conditions to demonstrate the effects of process parameters on surface quality. It is shown that by using this model, process parameters can be determined to increase the MRR without sacrificing surface quality. Extensive cutting tests are conducted to investigate the eccentricity effects on both tool life and axial surface roughness, and the results are discussed.

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