Journal of Machine Engineering, 2022, Vol. 22, No. 2, 5–17
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *26 April 2022* / Accepted: *28 May 2022* / Published online: *30 May 2022*

turn-milling, tool life,
surface errors, chip geometry

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IMPROVED MACHINING PERFORMANCE THROUGH TURN-MILLING

As a multi-axis metal cutting operation, turn-milling has the combined characteristics of conventional turning and milling operations involving rotating workpiece and milling tool with linear feed motion in the workpiece axis direction. Although turn-milling offers many advantages in machining complex and hard-to-cut materials due to its flexible kinematics, the process presents specific challenges. The main objective of this paper is to present an overview of turn-milling operations from different perspectives. In this regard, first, the advantages of turn-milling in terms of tool life are presented. An analytical approach is given based on process kinematics to achieve better surface quality and productivity simultaneously. Additionally, the uncut chip geometry and the cutting force models are presented with experimental verification.

1. INTRODUCTION

Turn-milling is a multi-axis machining operation that can be described as a combination of milling and turning. In turn-milling, milling tool and workpiece rotate simultaneously to perform the material removal leading to intermittent cutting of parts with symmetrical or eccentric cross-sections. These characteristics of the process offer several advantages in terms of tool performance, low cutting temperature due to short contact time at the tool-chip interface, decreased tool wear, smaller chips, and easy chip evacuation. Furthermore, due to the low rotational speed of the workpiece during turn-milling, centrifugal forces are reduced in machining of large-scale parts, leading to better accuracy. Turn-milling operations can be categorized into three configurations based on the arrangement of tool-workpiece axes, including orthogonal, tangential, and co-axial configurations [1]. In this study, the most commonly used configuration, orthogonal turn-milling, where the tool axis is perpendicular to the workpiece axis, is considered. Orthogonal turn-milling provides superior solutions in machining large-scale, eccentric or symmetric parts such as large camshafts, crankshafts, or thin-walled structures in the aerospace industry. Additionally, screw-type parts such as those

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https://doi.org/10.36897/jme/150495

in air compressors can also be produced by orthogonal turn-milling using commercial and commonly used endmills instead of profiling disc tools [2]. Further, for slender screw shafts or others with helical surfaces that do not fit into 5-axis machine tools, turn-milling would be a good solution [3]. However, due to the complex kinematics of turn-milling, cutting parameters show different effects on the process compared to conventional machining operations and thus must be selected properly to achieve improved performance.

The preliminary research on turn-milling was started in 1990 by Schulz et al. [4], who introduced different process configurations. In this study, the effect of tool axis offset, chip geometry, and surface quality was studied. Later, Choudhury et al. [5] investigated the impact of different parameters on surface quality, and Kopac et al. [6] showed that eccentricity has a positive effect on surface roughness. Savas and Ozay [7] investigated the effect of feed rate and rotational speeds on surface roughness in tangential turn-milling in AISI 1040 steel. In an analytical approach, Zhu et al. [8] predicted the surface roughness and surface topography in orthogonal turn-milling through simulations, and the effect of rotational speeds and eccentricity were investigated. A detailed overview of surface quality and profile in turn-milling is presented in [9]. In addition to experimental works on surface quality, Filho [10] developed a CAD-based algorithm to predict the cutting forces in non-centric orthogonal turn-milling. Later, Karagüzel et al. [1] developed an uncut chip thickness model for orthogonal, tangential, and co-axial turn-milling based on cutting geometry and kinematics. Comak et al. [11] predicted the cutting forces by discretizing the cutter-workpiece engagement in the axial direction using MACHPRO® software package [12]. Later, an analytical model was proposed by Ortega et al. [13] in which the uncut chip geometry was modeled based on cutting geometry and process kinematics for centric orthogonal turn-milling operation.

This work aims to give a perspective on the potential and advantages of orthogonal turn-milling through analytical and experimental investigations. In Section 2, a brief introduction is given for different turn-milling configurations. Then, tool wear results are presented for different cooling conditions and materials in Section 3. The results demonstrate the high performance of turn-milling compared to conventional turning. In Section 4, the kinematics and cutting geometry of the process are discussed briefly and also used in Section 5 to develop a model to improve surface finish by preventing cusp formation, which is one of the quality problems in orthogonal turn-milling. Based on process kinematics, the uncut chip model simulation is presented and discussed in Section 6. Its significance in process mechanics, parameter selection, and process planning are elaborated, and the cutting force prediction with experimental verification is presented. Finally, the conclusions drawn from this study are summarized in Section 7, and the future outlook is given in Section 8.

2. TURN-MILLING CONFIGURATION

In order to perform turn-milling can ideally be performed mill turn machine tools with three linear feed drives for translational motions and two rotary drives for rotations of tool and workpiece, as shown in Fig. 1a. In this figure, n_t and n_w represent the rotational speed of the tool and workpiece, respectively. The linear feed rate and the tool axis eccentricity are defined as F and e, respectively. Based on the relative alignments of the tool and workpiece axes, turn-milling operations can be performed in three different configurations as: orthogonal, tangential, and co-axial [1]. In orthogonal turn-milling, the rotation axes of the tool and workpiece are perpendicular to each other, as shown in Fig. 1. In tangential turn-milling, the axes are perpendicular likewise; however, the tool is tangent to the workpiece periphery performing cutting only with its side. In co-axial turn-milling, the rotation axes of the tool and workpiece are parallel [1]. In this study, orthogonal turn-milling as the mostly used configuration for machining parts with circular or elliptical cross-sections is considered.

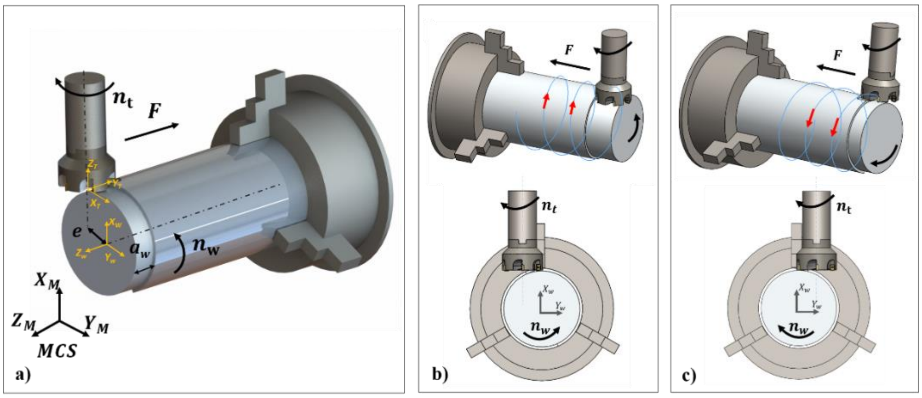

Fig. 1. Basic parameters and motions orthogonal turn-milling operations

Orthogonal turn-milling can be performed in two different modes, namely up-milling and down-milling, based on the location of the tool in Y axis with respect to the workpiece center and rotation direction of the workpiece. The up-milling and down modes are illustrated in Fig. 1b and Fig. 1c, respectively. As it can be seen, in up-milling while the tool rotates in the clockwise direction, the workpiece must rotate in the counter-clockwise direction, provided that the tool center has the eccentricity in $-Y_w$ direction in stationary workpiece coordinate system $X_w Y_w Z_w$. On the contrary, for down-milling mode, the workpiece rotation direction and the tool center eccentricity must be changed, as illustrated in Fig. 1c.

3. TOOL LIFE IN TURN-MILLING

The simultaneous rotation of the milling tool and workpiece introduces several advantages compared to conventional turning. The intermittent cutting nature of turn-milling due to the rotating milling tool decreases the contact time between the tool and workpiece. This also allows a more extended cooling period for the cutting edges until the next engagement with the material. Therefore, a significant increase in tool life is achieved, affecting the overall machining cost. In this regard, Berenji et al. [14] compared the tool life in turn-milling and conventional milling for finishing and roughing strategies.

The experiments were carried out on a Mori Seiki NTX2000 machine tool. Turn-milling processes were conducted under two different configurations on two hard-to-cut materials (see Fig. 2). For comparison of orthogonal turn-milling with turning, the workpiece material was selected AISI 316 stainless steel. Further, in order to confirm the advantages of turn-milling, tool life was also investigated in co-axial turn-milling and compared with face turning operations in cutting of Waspaloy. Note that the cutting speed and MRR for both operations were kept similar during roughing and finishing. The corresponding cutting speeds and MRRs are given in Table 1.

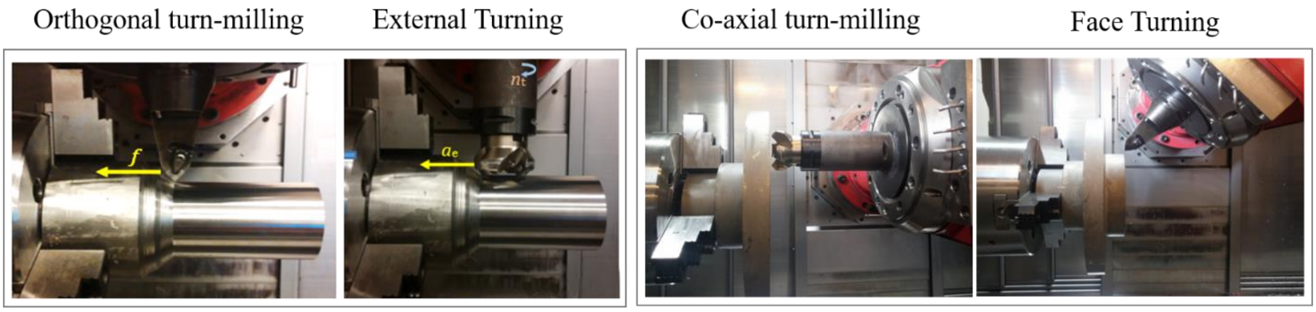

Fig. 2. Experimental setup for comparison of different configurations for turn-milling and turning operations [14]

Table 1: Cutting parameters for tool life investigations

External turning & orthogonal turn-milling		Cutting Speed (m/min)	MRR (m^3/min)	Face turning & co-axial turn-milling		Cutting Speed (m/min)	MRR (m^3/min)
	Roughing	150	12000		Roughing	52	4300
	Finishing	240	1200		Finishing	100	850

QuattroMill® tool with inserts with MS2050 grades was used for turn-milling operations. For conventional turning, CoroTurn® RC clamp was employed with inserts 1105 grades [14]. The approximate insert cost for the turning and face milling tools are 7€ and 12€, respectively. The flank wear on the inserts was measured at specific time intervals, and the results are given in Fig. 3. Note that the life of each individual insert on the milling tool must be taken into account due to the existence of multiple cutting edges. For this purpose, the normalized tool life value for each insert on the milling tool was calculated by dividing the elapsed cutting time in Fig. 3 by the number of cutting teeth. According to Fig, 3, elapsed cutting time for allowable tool wear for orthogonal turn-milling of stainless-steel parts is 13 and 10 times higher in roughing and finishing, respectively, compared to turning. Likewise, the co-axial turn-milling achieves approximately 8 times and 7 times higher tool life in roughing and finishing, respectively, on Waspaloy compared to conventional face turning. Obviously, in addition to significant savings in tools cost, the substantially improved tool life also results in reduced tool change set up time as well as machine idle time. Despite a higher number of milling inserts with approximately 40% higher cost, turn-milling offers lower tool costs compared to turning. In this study, it is assumed that both operations were carried out on the same multi-tasking machining center where the cost difference between a mill-turn and a standard CNC lathe is not taken into account.

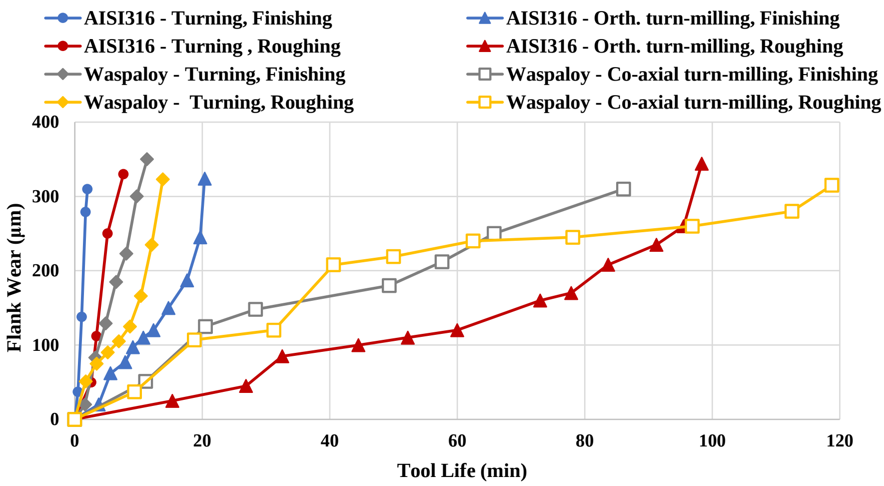

Fig. 3. Tool life comparisons at different configurations and cutting strategies [14]

Nevertheless, despite the need for more inserts in turn-milling with higher cost, orthogonal turn-milling provides 45% and 26% lower cost in roughing finishing of AISI 316 stainless steel, respectively, compared to turning. Similarly, in co-axial turn-milling of Waspaloy, savings in the order of 21% and 10% in roughing and finishing are obtained, respectively, compared to face turning [14]. It is shown that turn-milling in both orthogonal and co-axial configurations shows superior tool life compared to conventional turning for the same MRR.

Karagüzel et al. [15] investigated the tool life in orthogonal turn-milling operation under different cooling conditions for different hard-to-cut materials and compared it with the conventional turning process, as shown in Fig. 4. The experiments were performed at identical cutting conditions (as given in Fig. 4). It is evident that orthogonal turn-milling under MQL

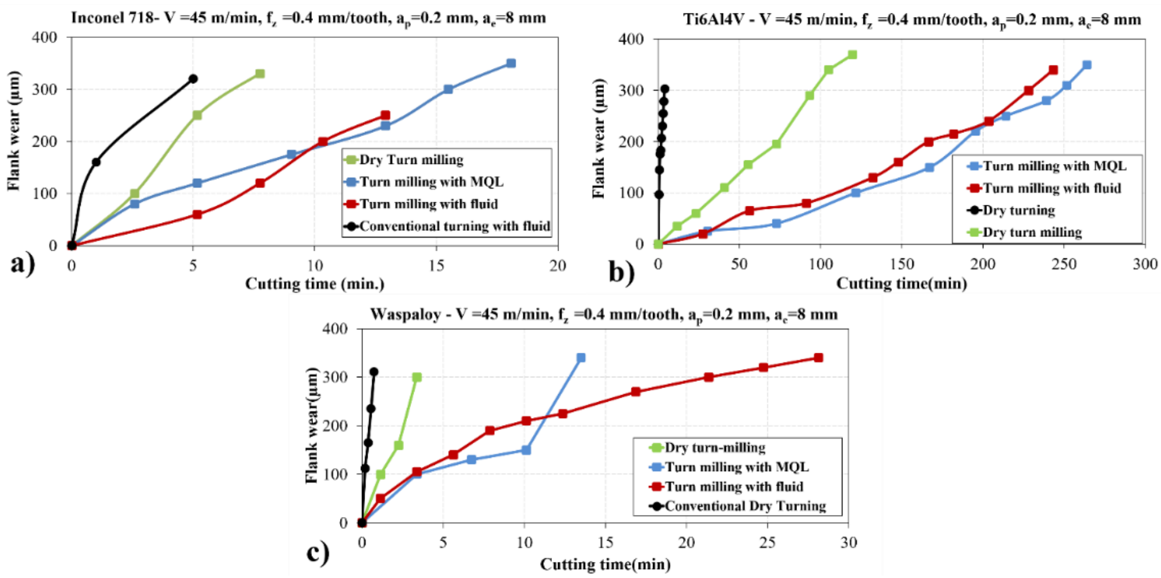

Fig. 4. Tool wear results for turn-milling of; a) Inconel 718, b) Ti6Al4V, c) Waspaloy. [15]

cooling shows a relatively longer tool life for Inconel 718 and Ti6Al4V, while flood cooling performs approximately two times better in turn-milling Waspaloy. Moreover, Fig. 4b shows that, in the worst-case scenario, even dry turn-milling results in approximately 40 times higher tool life compared to conventional dry turning. In general, turn-milling provides higher tool life than conventional turning, even in dry-cut conditions.

In addition to the cutting speed and cooling condition, Karagüzel et al. [16] showed that eccentricity significantly affects tool wear. It is deduced that the optimal eccentricity for the highest tool life depends on the contact length between tool and workpiece, which is a function of tool radius and minor edge length of the tool. The contact length between tool and workpiece as a function of eccentricity affects the tool wear and influences the uncut chip geometry, surface form errors, and, hence, cutting mechanics. The definition of contact length requires a comprehensive understanding of the process kinematics and cutting geometry.

4. KINEMATICS OF TURN-MILLING

Due to simultaneous rotations of tool and workpiece, turn-milling processes have a more complex cutting geometry and kinematics in comparison to conventional milling or turning. In turn-milling, minor and side edges engage with the material (Fig. 9), resulting in different uncut chip geometry, cutting mechanics, and dynamics compared to milling. Therefore, it is crucial to understand the effect of different geometrical and kinematic parameters on the cutter-workpiece engagement boundaries. For better visualization, the cutting geometry of orthogonal turn-milling operation is illustrated in Fig. 5.

Due to simultaneous rotational workpiece and feed motions of the tool in orthogonal turn-milling, the tool follows a helical trajectory with respect to the stationary workpiece coordinate system $X_w Y_w Z_w$ (see Fig. 5). Since the coordinate system of the tool is considered at the tooltip, all the geometrical definitions are based on the tooltip position. Hence, the circumferential feed direction of the tool on this helical path forms the angle θ_x [17]:

$$\theta_x = \tan^{-1}\left(\frac{a_w}{2\pi(R_w - a_p)}\right) \tag{1}$$

where a_p is the axial depth of cut, R_w is the workpiece radius, and a_w is the feed per workpiece revolution. θ_x defines the tool-workpiece engagement boundaries on side cutting edge of the tool. Another important parameter that defines the minor edge engagement thickness is β as shown in Fig. 5. The side edge and minor edges of the tool are shown in Fig. 5.

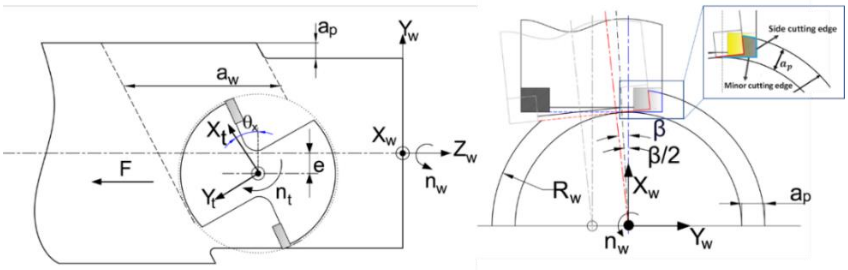

Fig. 5. Process geometry and kinematic in orthogonal turn-milling

β depends on the workpiece rotational motion during one tooth passing period and can be calculated as;

$$\beta = \frac{2\pi n_w}{n_t N} \tag{2}$$

β plays a drastic role in the definition of uncut chip thickness formed by the minor edge, circularity error, and cusp formation during orthogonal turn-milling [1, 8]. Karagüzel et al. [1] showed that as the ratio of spindle speeds $\left(\frac{n_w}{n_t}\right)$ decreases, β decreases as well, decreasing the circularity error. The translational feed rate of the tool along the workpiece axis $\left(F\ \left[\frac{mm}{min}\right]\right)$ can be formulated as a function of feed per workpiece revolution and workpiece rotational speed as follows;

$$F = n_w \times a_w \tag{3}$$

This means that for constant tool rotational speed and feed rate, the radial engagement will decrease as the workpiece rotational speed increases. Therefore, according to equations (2) and (3), the workpiece rotational speed affects the engagement thickness and boundaries of both side and minor cutting edges. The fundamentals of the process geometry and kinematics of the process introduced in this section and [17] will be used to define a procedure to prevent surface form errors in orthogonal turn-milling.

4.1. SURFACE ERRORS IN TURN-MILLING BASED ON PROCESS KINEMATICS

Different than conventional turning, orthogonal turn-milling may lead to surface errors such as circularity and cusp formation [1]. The circularity error is the difference between the desired workpiece cross-section (perfect circle) and the workpiece's polygon-shaped cross-section, caused by the simultaneous rotations of the workpiece and tool as described by Karagüzel et al. [1]. Circularity error in turn-milling cannot be eliminated due to the intermittent nature of the process, but it can be reduced by increasing the ratio of tool to workpiece spindle speeds. One of the alternatives is to increase the tool spindle speed, which leads to higher tool wear, and the other alternative is to reduce the workpiece rotational speed, which results in lower MRR. The tradeoff between the surface quality, MRR, and machining cost must be considered in the process planning stage.

Another important surface error in orthogonal turn-milling operation is the cusp formation. Previously, Karagüzel et al. [1] proposed a geometrical model for calculating cusp height and used it to determine the eccentricity value to avoid cusp formation [16]. However, the effect of the minor edge was neglected. The engagement and contact of minor edge with the machined surface are critical for tool wear, surface quality, chip formation, and cutting forces. Note that if the minor edges on the tool have an approach angle, cusp formation in orthogonal turn-milling is inevitable. A tool with zero approach angle on the minor edge can prevent cusp formation in some cases. However, because of the complex kinematics of the process, based on the eccentricity and radial depth of cut, a cusp can still be formed due to the uncut material left between two consequent stepovers even if the approach angle of the minor edge is zero. If the engagement length of the minor edge is not sufficient to wipe out the material left from the previous pass, the cusp will be formed. In order to prevent cusp formation, the feed per workpiece revolution (a_w) must be smaller than the sweeping length of the minor edge, which is shown as a_{wmax} in Fig. 6. The maximum allowable feed per workpiece revolution (a_{wmax}) depends on the eccentricity (e), and minor edge length (l_t).

By considering all the mentioned parameters, the allowable feed per workpiece revolution a_{wmax} is modeled in equation (4) using the illustration in Fig. 6. According to equation (4) it is deduced that, unlike the conventional milling process, the stepover in the orthogonal turn-milling process depends on the tool geometry, eccentricity, and axial depth of cut. It can be seen that the minor edge length defines the eccentricity ranges and hence, allowable radial depth of cut and MRR. For better understanding, equation (4) is illustrated in Fig. 7 for a tool with 31.5 mm diameter, adopted from Berenji et al. [17].

$$a_{wmax} = \begin{cases} l_t + m & e = 0 \\ \sqrt{R_t^2 - (e-m)^2} - \sqrt{(R_t - l_t)^2 - (e-m)^2} & 0 < e < R_t - l_t - m \\ 2\sqrt{2R_t l_t - l_t^2} & e = R_t - l_t - m \\ 2\sqrt{R_t^2 - (e-m)^2} & R_t - l_t - m < e \leq R_t \end{cases} \tag{4}$$

where $m = \frac{(R_w - a_p)\beta}{2}$ and l_t is the minor edge length, and β is defined in equation (2).

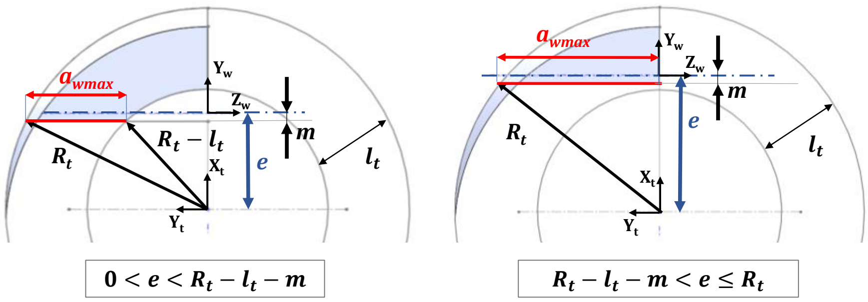

Fig. 6. Cutting geometry model to define a_{wmax} at two different eccentricity conditions

It is evident that as the minor edge length increases the allowable feed per workpiece revolution (a_{wmax}) also increases. However, the maximum value of a_w which defines the radial depth of cut in a specific eccentricity that depends on minor edge length.

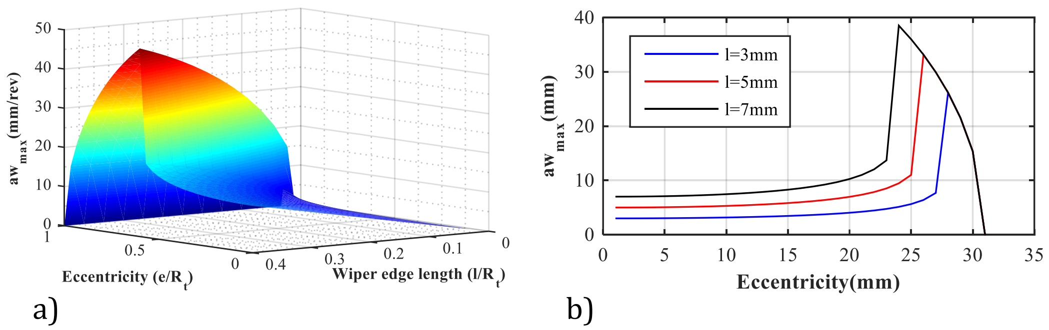

Fig. 7. Effects of eccentricity and minor edge length on maximum allowable feed per workpiece revolution [17]

As a result, if the tool has longer minor (wiper) edge length, higher feed per workpiece values will be achieved, increasing the MRR without sacrificing the surface quality. In this regard, employing the proposed model leads to higher productivity with an error-free surface by selecting the proper eccentricity and feed per tooth value based on the tool diameter and minor edge length.

The orthogonal turn-milling experiments were performed on the Mori Seiki NTX 2000 multi-tasking machine tool to verify the proposed model. The workpiece is stainless steel with 116 mm diameter, where a 63 mm diameter face-milling cutting tool with four inserts having minor edge length (l_t) of 12.7 mm and zero minor edge approach angle was used. During the experiments, the cutting speed and feed per tooth were kept constant as 200 m/min and 0.1 mm/rev/tooth, respectively. Two different experiments were conducted to show the effect of eccentricity on both productivity and surface quality. The parameters used in the experiments are given in Table 2.

Table 2. Parameters used in experiments [17]

Exp. No:	n_t (rpm)	n_w (rpm)	a_w (mm/rev)	a_p (mm)	e (mm)
1	1000	1	20	0.5	15
2	1000	1	40	0.5	22

The resulting workpiece surfaces are shown in Fig. 8. While the maximum feed per workpiece revolution in experiment 1 is $a_{wmax} = 16.2\,\frac{\text{mm}}{\text{rev}}$ for $e = 15$ mm, setting a_w as 20 mm/rev which is higher than the allowable value, results in very poor surface quality with uncut material left on the surface (see Fig. 8 (1)). On the other hand, for experiment 2 with an eccentricity of $e = 22$ mm the allowable feed per workpiece is $a_{wmax} = 45\,\frac{\text{mm}}{\text{rev}}$. In this case, better surface quality without uncut material was achieved at an even higher a_w value, as seen in Fig. 8 (2). It is evident that since the eccentricity and radial depth of cut in experiment 2 are selected based on the proposed model, the cusp formation is prevented while the MRR is doubled. Using the proposed procedure, one can choose all turn-milling parameters considering surface quality and productivity.

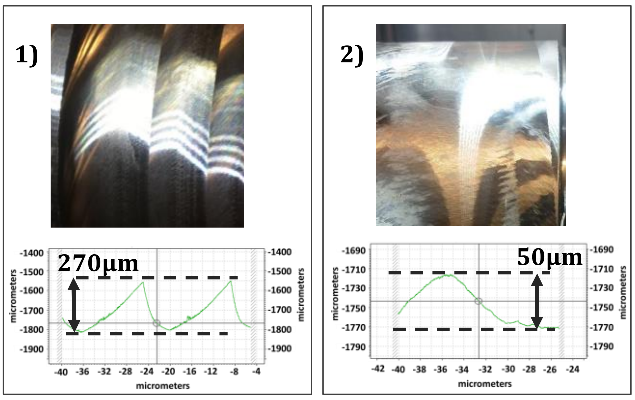

Fig.8. Surface profiles obtained in experiments given in Table 2 [17]

5. UNCUT CHIP GEOMETRY AND CUTTING MECHANICS

The previous sections provide information for selection of turn-milling conditions considering tool wear, surface quality, MRR and process geometry. Machine tool limitations such as available power and torque are other constraints to be considered in parameter selection. For this reason, prediction of the uncut chip thickness and cutting forces is vital. Due to the rotating tool and workpiece, the uncut chip geometry in orthogonal turn-milling is different than conventional milling; hence, having a precise simulation of chip geometry is significant in cutting force estimation. Berenji et al. [17] simulated the uncut chip thickness based on the cutting geometry and process kinematics described in Fig. 5. The instantaneous axial depth of cut (chip height) can be calculated using the formula given below [17];

$$Z_i(\phi_{i,j}) = \sqrt{R_w^2 - \left(R_t \sin(\theta_x + \phi_{i,j}) - |e|\right)^2} - \left(Rw - a_p\right) \tag{5}$$

where $\phi_{i,j}$ is the angular position of tooth j and angular increment i within the immersion boundaries.

Based on equation (5), the varying instantaneous axial depth of cut is illustrated in Fig. 9, [17] The simulated uncut chip geometries were compared and validated with the CAD models for varying instantaneous axial depth of cut and minor edge geometry.

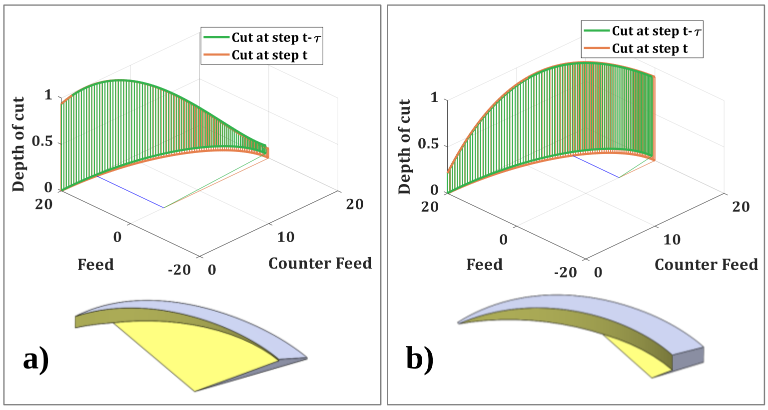

Fig. 9. Chip geometry for R_t=20 mm, R_w=125 mm, a_p=1 mm, a) e=5 mm, b) e=15 mm [17]

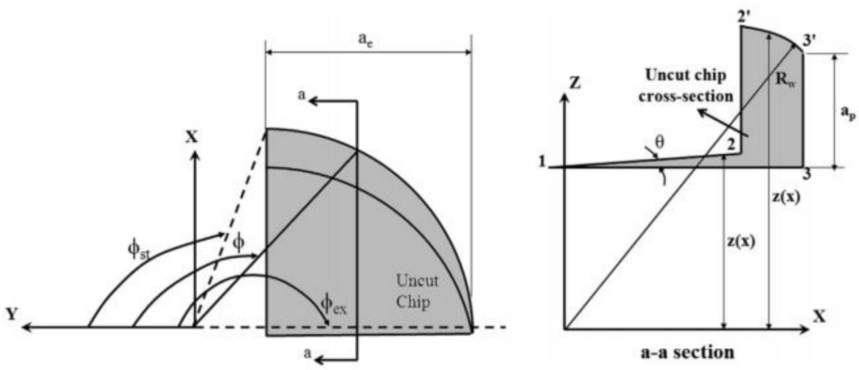

Fig.10. Cross-section of uncut chip geometry in TCS in orthogonal turn-milling [1]

It is seen that for different eccentricities, engagement of the minor edge varies, and the instantaneous axial depth of cut also alters drastically. This phenomenon influences the process mechanics and dynamics significantly. Karagüzel et al. [1] proposed a cutting force prediction model based on the CAD representation of the uncut chip geometry illustrated schematically in Fig. 10.

The uncut chip boundaries were modeled mathematically, and the differential tangential, radial, and axial cutting forces were calculated, summed up, and then transformed into the machine coordinate system, and then validated with experiments. The cutting forces were measured by a rotary dynamometer on Mori Seiki NTX 2000 machine tool, and the validations are given in Fig. 11a It is seen that experimental results and predictions are in good agreement. Fig. 11b also shows the effect of eccentricity on the maximum resultant forces. As it can be seen, as the eccentricity increases, the resultant forces decrease. There are several other approaches to determining the uncut chip geometry and process mechanics.

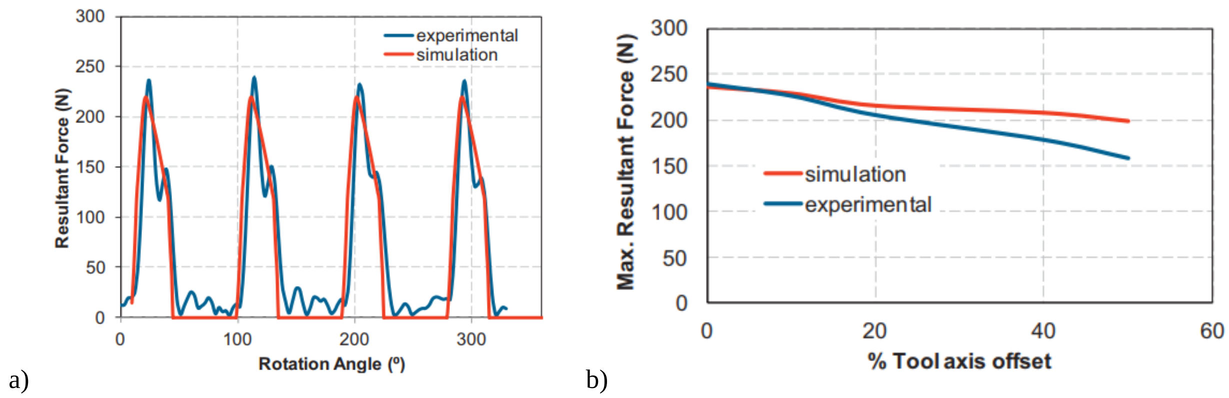

Fig. 11. a) Cutting force validation in turn-milling, b) Effect of tool axis offset (eccentricity) on maximum force [1, 16]

6. CONCLUSION

In this study, orthogonal turn-milling is elaborated through previous research in terms of tool wear, cost, surface quality, and process mechanics. The intermittent nature of turn-milling reduces the contact time of the tool and allows the tool to cool down, leading to significant tool life improvement compared to conventional turning. This tool life improvement makes turn-milling a cost-efficient process in machining hard-to-cut materials despite a higher number of required inserts with higher cost for milling tools. The tool life improvement was also verified under different cooling conditions. Based on the tool life comparisons, it is deduced that MQL is a better alternative than flood cooling in turn-milling of hard-to-cut materials. Furthermore, the cusp formation as a surface form error in orthogonal turn-milling was discussed based on the process geometry and kinematic model. It is experimentally verified that the cusp formation depends on the engagement characteristics of the minor edge, which is defined by the minor edge length, eccentricity, and stepover. The maximum allowable stepover also depends on the eccentricity, and by adjusting these values, higher MRR can be achieved without cusps on the surface. It is also shown that the allowable maximum stepover increases for tools with a longer minor edge, leading to substantial MRR increases.

Additionally, the uncut chip geometry is modeled analytically. The instantaneous axial depth of cut varies within the cutter-workpiece engagement boundaries, where the variation trend depends on eccentricity drastically. Accordingly, the cutting forces were calculated analytically and verified with experiments. It is concluded that the maximum forces also alter with eccentricity as expected. As a result, turn-milling offers several advantages in machining large-scale parts with hard-to-cut material. However, to achieve the particular advantages of the process, a profound understanding of its kinematics, mechanics, and dynamics is vital.

7. FUTURE OUTLOOK

Several researchers studied turn-milling in terms of tool life, surface quality, process mechanics, and dynamics, which resulted in valuable outcomes. Turn-milling processes have the potential to be extended and investigated further in several aspects such as the following.

- Special minor edge geometries can be investigated to reduce cutting forces, contact length, and wear rate and increase MRR in orthogonal turn-milling.
- Additionally, effects of other minor edge geometrical parameters, such as hone radius, oblique angle, clearance, etc., on surface quality, cutting temperature as well as process damping can be studied.
- The dimensional accuracy and surface integrity of thin-walled tubes or slender flexible parts machined using orthogonal turn-milling, and conventional turning can be examined and compared. The effect of eccentricity and tool geometry can be influential during process planning and optimization to achieve higher accuracy.
- Process dynamics and chatter stability models must be developed based on chip geometry and cutting mechanics. The effects of additional process parameters on stability need to be studied in detail.

ACKNOWLEDGEMENTS

The support from DMG Mori, Tubitak (110M522), and Pratt & Whitney Canada are greatly appreciated by the authors.

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