Integrated Strategies for High Performance Peripheral Milling

Law, M.[1,*], Wabner, M.[2] and Ihlenfeldt, S.[3]

Fraunhofer Institute for Machine Tools and Forming Technology IWU,
Reichenhainer Str. 88, 09126 Chemnitz, Germany
[1,*] mohit.law@iwu.fraunhofer.de; [2]markus.wabner@iwu.fraunhofer.de;
[3]steffen.ihlenfeldt@iwu.fraunhofer.de

Abstract

High performance peripheral milling is one of the most common rough machining operations in modern production environments. Productivity of these operations, characterized by material removal rates (MRR) and machining times, is a function of several parameters: spindle speed, feed, axial and radial depths of cuts, tool path type, milling mode, and feed direction. Each of these variables affects the MRRs differently; the limiting case often resulting from the dynamic interactions between the cutting tool and the work piece - characterized by chatter vibrations. This paper proposes an integrated approach incorporating all of the significant factors affecting performance to formulate a mixed mode milling strategy for the case of profile-parallel peripheral milling of a rectangular part. Numerical investigations demonstrate an improvement in machining time of up to 28% over conventional approaches. Proposed methods can be used for selection of optimal cutting conditions, tool path type, and for dynamically modifying the tool path to maximize MRRs and minimize the machining times.
Keywords: Machining strategy, Chatter vibrations, Material removal rate, Peripheral milling

1 Introduction

Peripheral milling is amongst the most common rough machining operations in the aerospace and the die and mold industries. Material is removed by sweeping a rotating tool along a predefined tool path that is parallel to the surface being generated. These tool paths are selected from those available in commercial CAD/CAM systems which do not consider the process physics during tool path generation and are mostly concerned with correctness of the tool path coordinates to ensure geometrical accuracy. However, to generate NC codes for actual milling requires the tool path to be supplemented with the proper cutting conditions of axial and radial depths of cut for geometrical definition of tool paths, and corresponding spindle speed and feed rate for cutting tool movement along the tool path.

These cutting conditions are often decided upon heuristically or based on available empirical data. This however may not ensure highest material removal rates that take the least machining time while avoiding violations of speed, power, torque and vibrations limits of the machine tool system, and may even result in selection of cutting conditions that produce severe chatter vibrations and unacceptable surface finish. Several dedicated research investigations have hence focused their attention on establishing scientific guidelines for the selection of optimal cutting conditions, and on dynamically modifying the tool path as necessary to obtain enhanced material removal rates.

Material removal rates (MRRs) are a function of several cutting parameters, including the spindle speed, feed, axial and radial depths of cuts, tool path type and milling mode, i.e. if *up/down* milling. Each of these variables affects the MRRs differently. Dominantly, the MRRs are often limited by machine tool chatter vibrations which result from the dynamic interactions between the cutting tool and the work piece. These interactions have been characterized by Weck *et. al.* (1994) and by Altintas and Budak (1995) to provide guidelines for selection of stable axial depths of cut (DOC) and spindle speed pairs. Although this provided recommendations for maximum chatter free axial DOCs, it did not guarantee maximum chatter free MRRs. To address this, Tekeli and Budak (2005) presented a method for the determination of optimal radial and axial DOC pairs. Others, namely Altintas and Merdol (2007) manipulated the federate along the tool path to increase the MRR. Heo *et. al*. (2010), and Aggarwal and Xirouchakis (2013) built on the earlier methods to present an automated selection of feed, speed, and DOCs that maximize MRRs.

Since peripheral milling typically takes the longest amount of machining times, in addition to maximizing MRRs, the machining time (MT) also needs to be simultaneously minimized. Machining times are influenced not only by the MRRs but also by the tool path strategies. MRRs are also significantly influenced by the milling mode, and, it has been well established

by Insperger *et. al.* (2003) that milling operations can be stabilized simply by changing to *down* milling from *up* milling at certain wide high-speed parameter domains. Furthermore, though it has been well established that for a given machine tool/spindle/tool/tool-holder/work piece system, the MRR and MT is governed by all of the above parameters, i.e. spindle speed, feed, axial and radial depths of cuts, tool path type and milling mode, it is less known and consequently less investigated that MRR and MT are also significantly influenced by the machining feed direction and the influence of the tool path/posture relative to the dynamically most compliant direction, as shown recently by Law *et. al.* (2013).

This paper is hence an exercise in holistically incorporating all the significant factors that affect MRR and MT; namely, also considering the milling mode and feed directions to determine an effective machining strategy. For a given machine tool/spindle/tool/tool-holder/work piece system, at first, the machining strategies to be investigated are discussed. This is followed by detailed investigations about the different factors effecting MRR in Section 3; starting with investigating the influence of milling mode on MRR for fixed radial DOC and feed direction. Following which, the influence of variable radial DOCs for a fixed axial DOC, feed direction, and milling mode is discussed. Also discussed is the influence of variable radial DOCs, milling mode and feed direction on MRR. Based on these discussions, a systematic method for selection of cutting parameters is established in Section 4, which is then used to evaluate a peripheral milling application in Section 5; followed by the conclusions in Section 6.

2 Peripheral milling considerations

Peripheral milling requires determination of cutting conditions and the tool path to be used by the CAD/CAM system. Although work piece profile will dictate the strategy to be employed, for investigations in this study, a rectangular part and a simple profile-parallel tool path is considered as shown in Figure 1 for the two different milling modes. The MRRs in either case is represented as:

$$\text{MRR} = f(\text{depth of cut, width of cut, feed, feed direction, milling mode, i.e. } up/down) \quad (1)$$

Width of cut is assumed constant for every pass and only the axial depths of cut are changed to achieve the step final step height, D_p. For the tool path considered, the machining time is expressed as:

$$T_{mac} = nop\left[\frac{f}{A} + \frac{W_{ext}\text{-}W_{int}\text{-}2D}{f} + \frac{L_{ext}\text{-}L_{int}\text{-}2D}{f}\right] \times 60 \quad (2)$$

wherein, f is the feed in [m/min], D is the tool diameter, and A is the acceleration/deceleration of the machine feed axes. Geometric parameters in Eq. (2) are as shown in Figure 1. Number of passes (*nop*) within Eq. (2) is expressed as:

$$nop = \begin{pmatrix} ceil\left(\frac{W_{ext}\text{-}W_{int}\text{-}2D}{b}\right) + \\ ceil\left(\frac{L_{ext}\text{-}L_{int}\text{-}2D}{b}\right) \end{pmatrix} ceil\left(\frac{D_p}{a}\right). \quad (3)$$

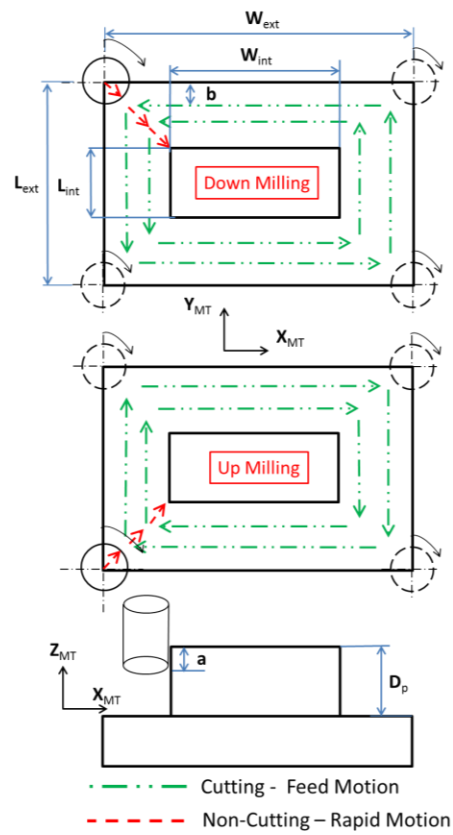

Figure 1 Schematic of peripheral milling tool paths for two different milling modes

3 Factors effecting material removal rates

Each of the factors that affect MRRs is discussed separately below to establish suitable cutting parameter selection guidelines. All investigations in this paper are carried out for a fixed machine tool/spindle/tool/tool-holder/workpiece system based on a system considered by Weck *et. al.* (1994), and by Tekeli and Budak (2005) – parameters of which are listed in Table 1.

Table 1 Parameters for milling system

Natural frequencies	ω_{nx}	600 Hz
	ω_{ny}	660 Hz
Dynamic stiffness	k_x=k_y	5600 kN/m
Damping ratios	ζ_x=ζ_y	0.035
No. of teeth	N_t	3
Cutting coeff. (tangential)	K_t	600 MPa
Radial cutting constant	K_r	0.07

3.1 Chatter free speeds and axial depths of cut for fixed feed direction, milling mode and width of cut

At first, chatter free stable spindle speeds and axial depths of cuts are determined to evaluate the maximum possible MRRs for a defined width of cut, feed direction and milling mode. The classical analytical stability model of Altintas and Budak (1995) is employed to find the stability of the system. Stability is determined using the following characteristic equation:

$$det([\boldsymbol{I}]+\Lambda[\boldsymbol{\Phi}_{OR}(i\omega_c)])=0 \tag{4}$$

where $\Lambda = \Lambda_R + i\Lambda_I = -\frac{1}{4\pi}N_t K_t a(1-e^{-i\omega_c T})$ (5)

is the complex eigenvalue of the characteristic equation; Λ_R and Λ_I are its real and imaginary parts; N_t is the number of teeth on the cutter; K_t is the cutting force coefficient of the material being cut; a is the axial depth of cut; ω_c is the chatter frequency; and, T is the tooth passing period. $\boldsymbol{\Phi}_{OR}$ within Eq. (4) known as the oriented transfer function matrix, is a function of the directional factors, $\boldsymbol{\alpha}_0$, and the tool point transfer function matrix in the machine tool principal directions, $\boldsymbol{\Phi}_{xy}$ $\left([\boldsymbol{\Phi}_{OR}]=[\boldsymbol{\alpha}_0][\boldsymbol{\Phi}_{xy}]\right)$. The limiting stable depth of cut, described by the parameters in Eq. (4-5) is analytically determined as:

$$a_{lim}=-\frac{2\pi\Lambda_R}{N_t K_t}\left[1+\left(\frac{\Lambda_I}{\Lambda_R}\right)^2\right] \tag{6}$$

Stability charts generated using the above Eq. (4-6) and the modal parameters of Table 1 are shown in Figure 2 for a radial immersion of 67% of the cutter diameter. Results for both milling modes are shown in Figure 2, and the feed direction is assumed to be in the +X direction. The region above the stability lobes in Figure 2 is unstable and that below is stable.

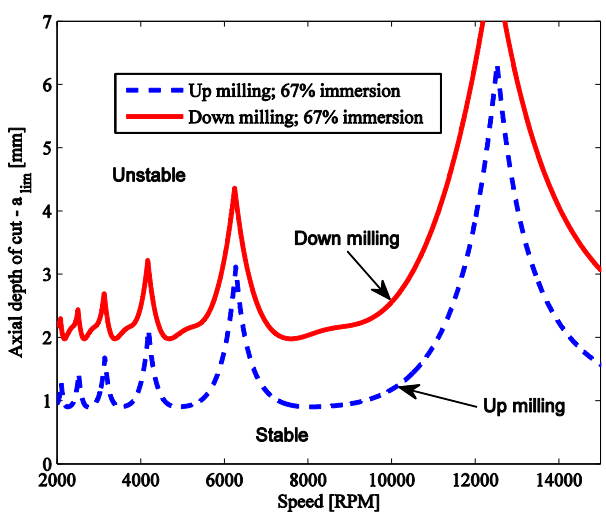

Figure 2 Stable limit of axial depth of cut as a function of spindle speed for two different milling modes. Feed direction assumed to be in +X

From Figure 2 it is evident that the stability is a strong function of milling mode, and in order to design an optimal machining strategy, this clearly must be considered. These charts offer a convenient way to select stable pairs of axial depth of cut and spindle speed to obtain high MRRs. However, the maximum possible MRR can only be achieved when the influence of the radial depths of cut and feed-direction is also taken into account, as discussed in the next Section(s).

3.2 Chatter free speeds and widths of cut for fixed feed direction, axial depth of cut, and milling mode

Optimal combinations of radial and axial depths of cut pairs to guarantee maximum chatter free MRRs are obtained by implementing the iterative algorithm proposed by Tekili and Budak (2013). As opposed to expressing the stability charts in terms of axial DOC vs. spindle speed, the iterative algorithm represents stability charts in terms of radial depth of cut vs. spindle speed. The radial depth of cut, B is represented as:

$$B/R=1-\cos(\varnothing_{ex}) \text{ -up milling}$$
$$B/R=1+\cos(\varnothing_{st}) \text{ -down milling} \tag{7}$$

wherein R is the radius of the tool, and $\varnothing_{st}$ and $\varnothing_{ex}$ are the tooth entry and exit angles respectively. The normalized form of the radial DOC, b represented as:

$$b = B/2R \tag{8}$$

is used in the rest of the discussions for simplicity and generalization. Thus, b is unitless, and it may only have values in the range of [0, 1]. The results obtained for a fixed axial depth of cut of 1.5 mm are shown in Figure 3 for both milling modes. Feed direction is again assumed to be in the +X direction.

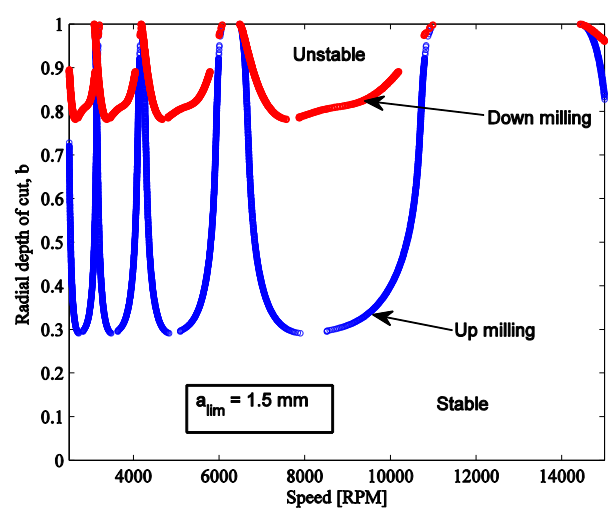

Figure 3 Stable limit of radial depth of cut as a function of spindle speed for two different milling modes. Feed direction assumed to be in +X.

From results in Figure 3 interpreted together with results in Figure 4, which relate the limiting radial DOC for different axial DOCs at a representative spindle speed of ~12500 RPM, we see that no decrease in *b* is necessary for some increase in *a*; however, after a certain point, a negatively sloped relation exists between the stable limits of axial and radial DOCs (b_{lim}); suggesting that maximum MRR can be achieved for select combinations of the axial and radial DOC pairs.

Further investigations about which combinations of the axial and radial DOCs result in the highest MRR at the ~12500 RPM speed are made in Figure 4; in which a normalized representation of MRR (normalized to the feed/tooth) at the limiting case is represented as:

$$\mathrm{MRR}^{*}=a_{lim}\times b_{lim}\times N_t\times N \qquad (9)$$

wherein *N* is the spindle speed.

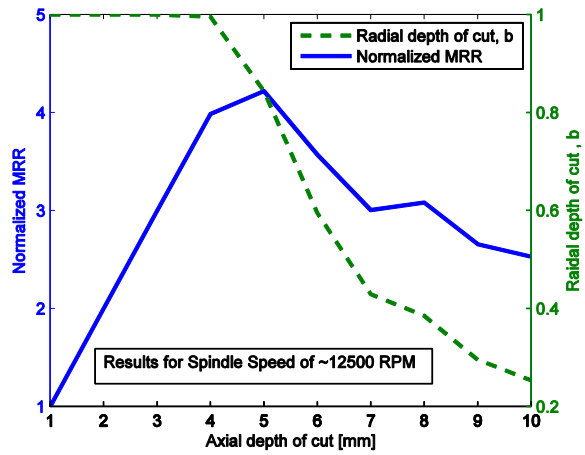

Figure 4 Maximum MRR and stable limit of radial depth of cut as a function of axial depth of cut.

As evident above, the normalized MRR does not necessarily increase monotonically, and in this particular case it reaches a maximum after which it starts to decrease. This behavior along with dependence of MRR on the feed direction and milling mode is discussed in the next Section(s).

3.3 Influence of feed direction, variable radial depths of cut and milling mode on chatter free MRR

Dependence of MRR on the feed direction is accounted for by projecting the vibrations $(\boldsymbol{\Phi}_{xy})$ of the tool in machine tool principal directions (xy) into the feed (uv) directions when the tool is travelling at an angular orientation of ϕ with respect to the *x* axis. The feed-plane transfer function matrix at the tool point, $\boldsymbol{\Phi}_{uv}$, as per Law *et. al.* (2013) is:

$$[\boldsymbol{\Phi}_{uv}]=[\boldsymbol{R}][\boldsymbol{\Phi}_{xy}][\boldsymbol{R}]^{-1} \qquad (10)$$

wherein $\boldsymbol{R} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix}$ is a rotational operator.

Solution to Eq. (4-6) updated to account for different feed directions (0-360˚) by use of Eq. (10) results in absolute minimum stable DOC which vary across feed directions in proportion to the magnitude of projections of the modes in that direction.

Speed independent feed direction-dependent absolute axial stable DOCs for different radial DOCs for the *up* milling mode are shown in Figure 5; with speed dependent behavior being treated in the next Section(s). The regions inside the stability envelopes are stable. The absolute limiting depth of cut is plotted radially, while the machining (feed) directions are plotted circumferentially.

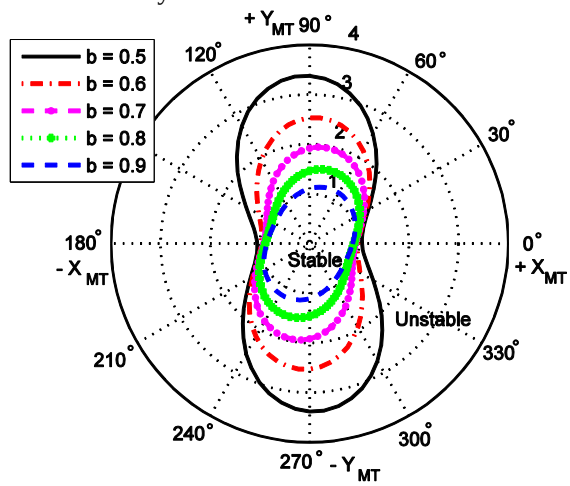

Figure 5 Speed-independent feed direction-dependent stability diagrams with different radial depth of cut conditions for *up* milling mode only

As evident, an increase in the radial DOCs, i.e. radial engagement, results in a smaller stability envelope. The shape and envelope of the stability boundaries are a strong function of the engagement conditions and the milling mode. Though Figure 5 shows results only for the *up* milling mode, in the case of *down* milling, these envelopes orient themselves with respect to the *up* milling case by an amount equal to the engagement; as discussed in the next Section.

Having demonstrated the dependence of MRR on the spindle speed, feed, axial and radial depths of cuts, milling mode, and feed direction; an integrated machining strategy is now formulated in Section 4.

4 Proposed integrated strategy

The steps of the proposed method are shown in Figure 6. For a defined tool, machine and workpiece, at first, parameters as listed in Table 1 need be obtained, following which, chatter free speed and feed direction-dependent stability envelopes are generated. These include information about stable pairs of axial and radial depths of cuts and milling modes. The proposed strategy

forms the basis of dynamically modifying tool paths to maximize MRRs. Selected parameters should not violate machine power and torque limits – constraints that are assumed to be inactive in present investigations.

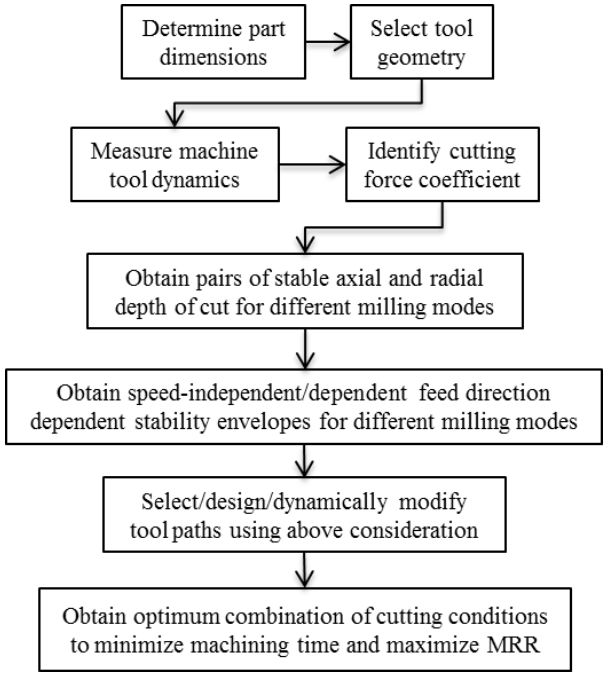

Figure 6 Overview of the proposed strategy

The above strategy is deployed to obtain the speed and feed-direction dependent stability envelopes for two different radial depths of cut at a spindle speed of ~12500 RPM as shown in Figure 7. As evident, results for b = 0.67 have the largest possible stable envelope, allowing for axial DOCs up to ~8 mm at certain feed orientations, and an approximate ~6 mm axial depth of cut for almost all feed directions.

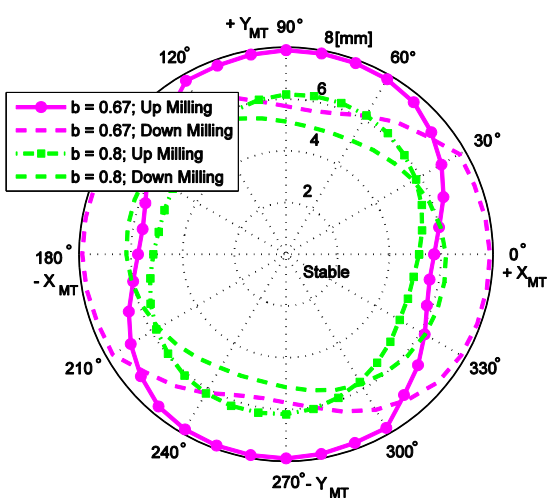

Figure 7 Speed (@12500 RPM) and feed-direction dependent stability envelopes for different radial depths of cuts and milling modes

These speed dependent feed-direction dependent stability envelopes follow a similar trend as that of the speed independent results in Figure 5, i.e. the envelope shrinks as radial depths of cut increase. These results are tabulated in Table 2 for establishing pairs of stable limits of axial and radial depths of cut for different speeds and milling modes for feed directions in the +X and +Y directions only. A feed/tooth of 0.2 at a speed of ~12500 RPM is assumed for a tool diameter of 20 mm in computing the MRR in Table 2.

Table 2 Pairs of stable limits of axial and radial DOC for different milling modes and feed directions

		a_{lim} [mm]		MRR [cm^3/min]	
Milling Mode	b_{lim} [mm]	Feed in +X	Feed in +Y	Feed in +X	Feed in +Y
up	0.67 D	5.7	7.9	573	794
	0.8 D	5.2	6.3	625	756
down	0.67 D	7.9	5.7	794	573
	0.8 D	6.3	5.2	756	625

As evident both from Figure 7 and Table 2, the limiting axial DOC for feed in the +X direction in the case of *up* milling is equivalent to the limiting axial DOC for feed in the +Y direction in the case of *down* milling. This property is of great significance, and will help translate the above results into an optimal machining strategy as is discussed in the next Section.

5 Application: Mixed mode milling

As is plain in Table 2, the stable limiting axial DOC for all radial DOCs is lower along the +X feed direction than the +Y feed direction for the case of *up* milling, and vice-a-versa for the case of *down* milling. Since cutting takes place along both principal directions for the profile parallel tool path being investigated, if cutting was done in only one of the milling modes, it would result in sub-optimal performance. To avoid this, a new mixed mode milling strategy as shown schematically in Figure 8 is proposed to be followed.

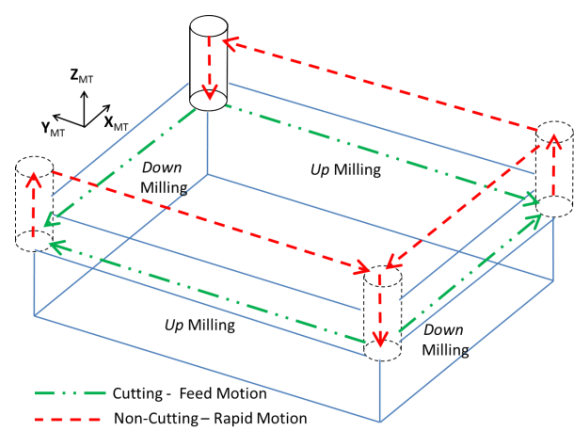

Figure 8 Proposed mixed mode milling strategy

In the proposed strategy, milling mode is selected for a given feed direction based on the highest possible MRR in that feed direction. This however results in several non-cutting motions in the rapid feed mode; and the total machining time of Eq. (2) is hence modified as:

$$T^*_{mac} = nop\left[\frac{f}{A} + \frac{W_{ext}\text{-}W_{int}\text{-}2D}{f} + \frac{L_{ext}\text{-}L_{int}\text{-}2D}{f}\right]\times 60 + nop\left[\frac{f}{A} + \frac{W_{ext}\text{-}W_{int}\text{-}2D}{2A} + \frac{L_{ext}\text{-}L_{int}\text{-}2D}{A}\right]\times 60 \quad (11)$$

wherein, the feed, f, is computed for a feed/tooth of 0.2 mm/tooth at a spindle speed of ~12500 RPM for three teeth; and, A, for the machine tool is assumed to be 1 g.

Results for machining time and number of passes required using the optimal conditions identified above are compared with conventional methods for each of the two radial DOCs discussed in Table 2. To ensure a stable cutting irrespective of the milling mode and feed direction in the conventional case, the axial DOCs are taken as the minimum of the two possible DOCs for the two different feed directions and milling modes; whereas for the proposed mixed mode strategy, they are taken as per the highest allowed as per Table 2.

Part dimensions (in [mm]) for the investigations are taken as: W_{ext}= 150; W_{int}= 100, L_{ext} = 200; L_{int} = 150; and, D_p= 30. As evident from Table 3, peripheral milling with the newly proposed mixed mode milling strategy requires between 16-33% less number of passes than those required with the conventional strategy of either *up/down* milling. Since there is an increase in the non-cutting time due to several tool retract motions in rapid feed mode, the improvement in machining times are not of the same order as the improvement in the number of passes; with the improvements in machining times ranging from 11-28%.

Table 3 Comparison of required number of passes and machining times between conventional and proposed approach for peripheral milling

		Conventi-onal *up/down* milling	Proposed mixed mode method	% Improv-ement
$b_{lim}=0.67D$	a_{lim} [mm]	5.7	7.9	-
	nop	12	8	33
	T^*_{mac} [min]	2.07	1.48	28
$b_{lim}=0.8D$	a_{lim} [mm]	5.2	6.3	-
	nop	12	10	16
	T^*_{mac} [min]	2.07	1.85	11

6 Conclusions

Detailed investigations were carried out to understand and characterize how the spindle speed, feed, axial and radial depths of cuts, milling mode, and feed direction influence the material removal rates and machining times. Based on these discussions, a systematic integrated approach was formulated that suggests a mixed mode milling strategy may outperform conventional machining strategies for profile parallel peripheral milling. Numerical investigations suggest improvements ranging from 11-33% over conventional approaches. Experimental validation is necessary and forms part of the planned future work. Methods presented can be used for selection of optimal cutting conditions and tool path type, including, if necessary dynamically modifying the tool path as necessary.

7 Acknowledgements

This research was supported by the Fraunhofer Gesellschaft's ICON Project for Strategic Research Co-Operation on Sustainable Energy Technologies.

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