EFFECT OF CUTTING CONDITIONS AND TOOL GEOMETRY ON PROCESS DAMPING IN MACHINING

L.T. Tunç and E. Budak
Manufacturing Research Lab., Sabanci University, Istanbul Turkey

ABSTRACT
Process damping can be a significant source of enhanced stability in metal cutting operations especially at low cutting speeds. However, it is usually ignored in stability analysis since models and methods on prediction and identification of process damping are very limited. In this study, the effects of cutting conditions and tool geometry on process stability in turning and milling are investigated. The previously developed models by the authors are used in simulations to demonstrate conditions for increased process damping, and thus chatter stability. Some representative cases are presented and verified by experimental data and conclusions are derived.

KEYWORDS: Process damping, Stability, Tool Geometry, Cutting Conditions

1. INTRODUCTION

It is a well known that process damping caused by the interaction between the cutting tool and the workpiece may lead to increased stability especially at low cutting speeds /1/-/6/. Tlusty and Ismail /3/ showed that stability limit increases with decreasing cutting speed due to process damping. However, Altintas and Weck /6/ stated that identification and modeling of process damping is one of the unsolved problems in metal cutting. Process damping is ignored in most of the studies /7/-/9/, leading to significant errors in estimation of the stability limit at low cutting speeds. There have been several attempts for modeling of process damping. In one of the mostly tried approaches it was tried to be modeled through dynamic cutting force coefficients (DCFC) /2/. Lin et al. /4/ proposed a dynamic data system (DDS), where the amount of process damping is tried to be identified from tool vibration measurements under working conditions. Sisson and Kegg /1/, Wu /10/, Elbestawi et al. /11/, Shawky et al. /12/, and Lee et al. /13/ showed that the indentation forces due to flank-wave contact against tool vibration contribute to the process dynamics by increasing the overall damping of the system. Sisson et al. /1/ concluded that the edge hone on the tool, cutting speed and clearance angle are the most important factors for process damping. In these studies, the indentation forces are involved in the time domain simulations as a function of the tool flank - workpiece indentation volume and a material constant /10/. In one of the recent studies, dynamic cutting force coefficients are identified from series of dynamic cutting tests by Altintas et al. /14/, where the cutting tool is oscillated by a fast tool servo at the desired frequency and amplitude. The effects of cutting conditions and tool geometry on process damping are still needed to be investigated for better understanding or enhanced stability conditions.

In this paper, the effects of hone radius, clearance angle, type of the flank, i.e. tool geometry, and cutting speed, radial cutting depth, vibration frequency and vibration amplitude, i.e. cutting conditions, on process damping are investigated using the previously developed models for process damping in orthogonal cutting /15/ and end milling /16/ by the authors. The generated data for various cases are presented and used in stability analysis. The paper is organized as follows; in the next section the approach for identification and modeling of process damping is briefly explained. Then, the effects of cutting conditions and tool geometry on process damping and stability limits are shown in Section 3 and Section 4, respectively. Finally, conclusive remarks and discussions are given.

2. IDENTIFICATION AND MODELING OF PROCESS DAMPING

In dynamic cutting, a waveform is imprinted on the machined workpiece surface due to tool vibrations as shown in Figure 1. For cutting depths above the stability limit the vibration amplitude increases causing the slope of the wavy surface to increase, as well. The flank face starts to indent into the workpiece as the surface slope becomes equal or higher than the clearance angle of the cutting edge. Contact forces arise opposite to the tool vibration and proportional to the indentation volume, resulting in damping which stabilizes the process.

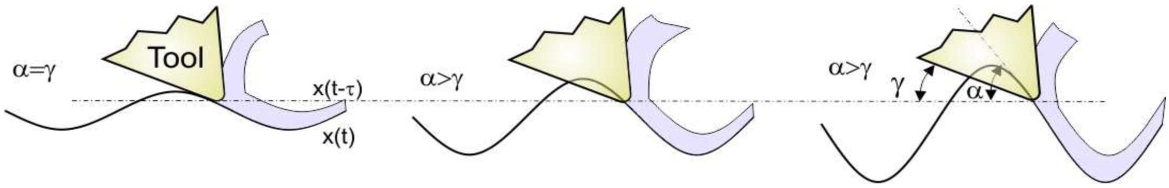


Figure 1: Indentation between the flank face and the wave form.

In this section, identification and modeling of process damping methods developed earlier /15/, /16/ is summarized. Inverse solution of the stability formulation is used for identification. Then, energy analysis is used together with the indentation volume calculations for modeling purposes.

2.1. Inverse Stability Solution for Identification of Process Damping

In this study, process damping is identified from experimental data as proposed by Budak and Tunc /15/, /16/. Where the damping effect due to the instantaneous damping forces is lumped to an average process damping coefficient, c^p, and treated in the formulation, accordingly.

2.1.1. Turning

For a single degree of freedom (SDOF) orthogonal cutting system the absolute stability limit can be written in terms of the total transfer function and the cutting force coefficient as follows /6/:

$$a_{\lim} = -\frac{1}{2K_f \, Re\left[G^t\right]_{\min}} \tag{1}$$

In above equation Re $[G^t]_{min}$ represents the minimum of the real part of the transfer function with total damping, i.e. including structural and process damping. Equation (1) can be re-arranged /15/ and written in terms of the feed cutting force coefficient, K_f, the modal stiffness, k, and damping ratio, ζ /15/ as follows:

$$a_{\lim} = \frac{2k\zeta}{K_f} \tag{2}$$

After some mathematical manipulations the process damping coefficient is expressed in terms of the experimental, $a_{\lim}$ which includes the effect of process damping, and theoretical, $a_{\lim}^{hs}$ which excludes the effect of process damping, stability limits:

$$c_p = c\left(\frac{a_{\lim}}{a_{\lim}^{hs}} - 1\right) \tag{3}$$

Equation (3) provides a very practical way for identification of the process damping coefficient by knowing the stability limit at any cutting speed. Moreover, the specific process damping coefficient per unit cutting depth can also be defined, which is further used in estimation of stability limit through modeling.

$$\overline{c_p} = c\left(\frac{1}{a_{lim}^{hs}} - \frac{1}{a_{lim}}\right) \tag{4}$$

2.1.2. Milling

In end milling, the expression for analytical stability limit proposed by Altintas and Budak / 8/ is used for identification of process damping. The stability limit is related to the total transfer functions of the system through the eigenvalue, Λ, which provides an opportunity to identify the process damping from the experimental data /16/:

$$a_{lim} = -\frac{2\pi\Lambda_R}{NK_t}\left(1+\kappa^2\right)$$

$$\text{where } \Lambda = -\frac{1}{2a_0}\left(a_1 \pm \sqrt{a_1^2 - 4a_0}\right) \tag{5}$$

The eigenvalue of the system with total damping, Λ_{exp}, is calculated by substituting the experimental stability limit, a_{lim}, and chatter frequency, ω_c, /16/:

$$\Lambda_{exp} = -\frac{a_{lim} NK_t\left(1-\cos\omega_c T\right)}{4\pi} - \frac{a_{lim} NK_t \sin\omega_c T}{4\pi} i \tag{6}$$

Then, the expression for the eigenvalue of the system, Λ, is equated to Λ_{exp} and this equality is solved iteratively /16/ in order to identify the total damping ratios in -x and -y directions, ζ_x^t and ζ_y^t, which includes structural and process damping.

2.2. Modeling of Process Damping

Process damping coefficients are specific to tool geometry and cutting conditions, which require them to be identified for each case under interest. However, if the process damping coefficients are related to the indentation volume and an indentation coefficient such a requirement can be eliminated. In this section, energy balance analysis used for modeling of process damping is briefly discussed. The details of the approach can be found in references / 15/ and / 16/.

2.2.1. Calculation of specific process damping coefficients

The indentation force due to flank-workpiece contact is modeled as a function of the indentation volume and the indentation constant, K^d. The energy analysis is used to determine the indentation coefficient from the experimentally identified process damping coefficient by equating the energy dissipated by them to each other / 15/. The average specific process damping coefficient is written in terms of the indentation volume and indentation constant as follows / 15/:

$$\bar{c}_p = \frac{K^d}{A\pi}\int_0^T U(t)\cos\left(\omega_x t\right)dt \tag{7}$$

In equation (7) A is the vibration amplitude at the border of stability, ω_x is the vibration frequency, and T is the period of a single vibration wave. The same approach is used for calculation of the average specific process damping coefficients for milling, as well. However, the averaging is done for one revolution of the cutter as the damping force in chip thickness direction is oriented in two orthogonal directions as the tool rotates /16/.

2.2.2. Estimation of stability limit

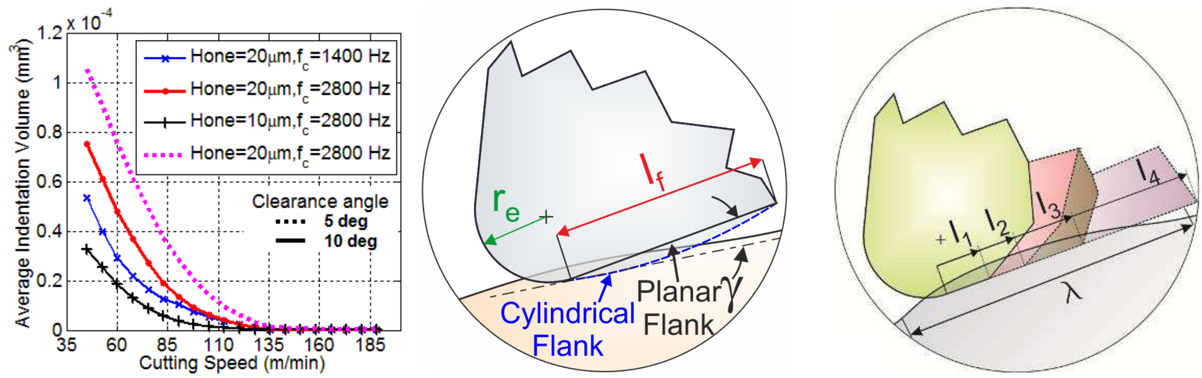
The calculated specific process damping coefficients are multiplied with the average contact length and used in estimation of the stability limit under given conditions. In orthogonal cutting, where the contact length is equal to the cutting depth, the average specific process damping is substituted back into equation (4) and the stability limit is expressed as follows:

$$a_{lim} = \frac{c a_{lim}^{hs}}{c - \bar{c}_p a_{lim}^{hs}} \qquad (8)$$

However, in milling there is not any explicit relation between the stability limit and the average specific process damping coefficients as two orthogonal degrees of freedom are involved in process dynamics. The contact length is defined as the length of the flute in cut with the material and it is averaged over one revolution of the tool. Therefore, calculation of the average contact length requires the cutting depth to be known, which can be calculated only if the process damping coefficients are known. This creates a recursive relation between the stability limit and the process damping coefficients. Therefore, an iterative procedure is followed to estimate the stability limit in milling /16/.

3. EFFECT OF CUTTING CONDITIONS AND TOOL GEOMETRY ON PROCESS DAMPING

At low cutting speeds the stability limit directly depends on the average process damping coefficient, which is a function of the indentation volume. The nonlinear relation between the indentation volume and several parameters is illustrated in Figure 2a. In this section, the effects of tool geometry and cutting conditions on average specific process damping coefficients in turning and milling are discussed through representative simulations. Cutting speed, vibration frequency and radial depth of cut are considered as the most important parameters affecting process damping. In addition, hone radius, flank geometry, and clearance angle, i.e. tool geometry parameters, (see Figure 2b) also have significant effect on process damping.



(a) Variation of indentation volume. (b) Cutting edge geometry. (c) Flank length in milling.

Figure 2: Indentation volume and cutting edge geometry.

In general, milling tools are manufactured with either planar or cylindrical flank faces. The former type is divided into two segments with clearance angles γ_1, γ_2 and lengths l_1 and l_2 as shown in Figure 3a. Therefore, the length of the clearance face (see Figure 2c) is also an important parameter for planar flank geometries as it affects the indentation volume. The cylindrical flank geometry is defined by an amount of drop, d_1, at angle, Φ_1, measured from the radial axis of the cutting edge (see Figure 3b). The clearance between the cutting edge and the workpiece is governed by the drop distance, whose effect is also discussed.

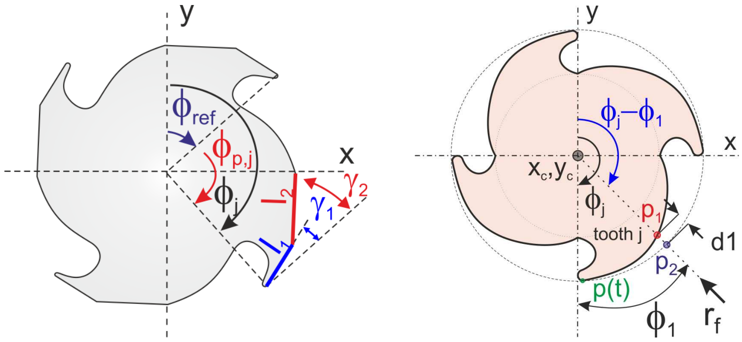


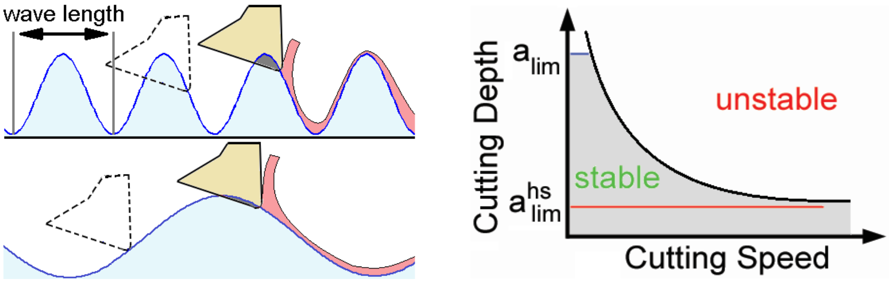
Figure 3: Types and definitions of flank geometries.

Representative simulations and experimental data related to the effect of edge geometry on process damping in orthogonal cutting are presented for the cases given in Table 1, where indentation force coefficients of 10,000 and 70,000 N/mm^3 / 15/ are used for AL7075 and AISI105, respectively. Milling analysis is also performed for half immersion down milling of Ti6Al4V for the cases given in Table 1, where the indentation force coefficient of 30,000 N/mm^3 / 16/ is used.

Table 1: Analysis cases for process damping.

Orthogonal Cutting						
Case	Material	Hone Radius (µm)	Clearance Angle(°)	Modal Parameters: Stiffnes s (N/µm)	Frequency (Hz)	Damping Ratio (%)
1	AISI1050	60	3,5,7 (°)	15.9	1267	2.62
2	AISI1050	10,30,60	3 (°)	16.7	1181	2.34
End Milling						
			Clearance Angle(°) / Drop Distance(µm)	Frequency (Hz) x	Frequency (Hz) y	Amplitude x, y
3	Ti6Al4V	10	[6,8,..,20](°)	2500	2500	10,10
4		10	[50,75, …,250](µm)	3000	3000	10,10
5		[10, 15,.,50]	20(°)	3000	3000	10,10
6		10	6(°)	3000	3000	10,10
7		10	10(°) / 110(µm)	2000	2000	15,15

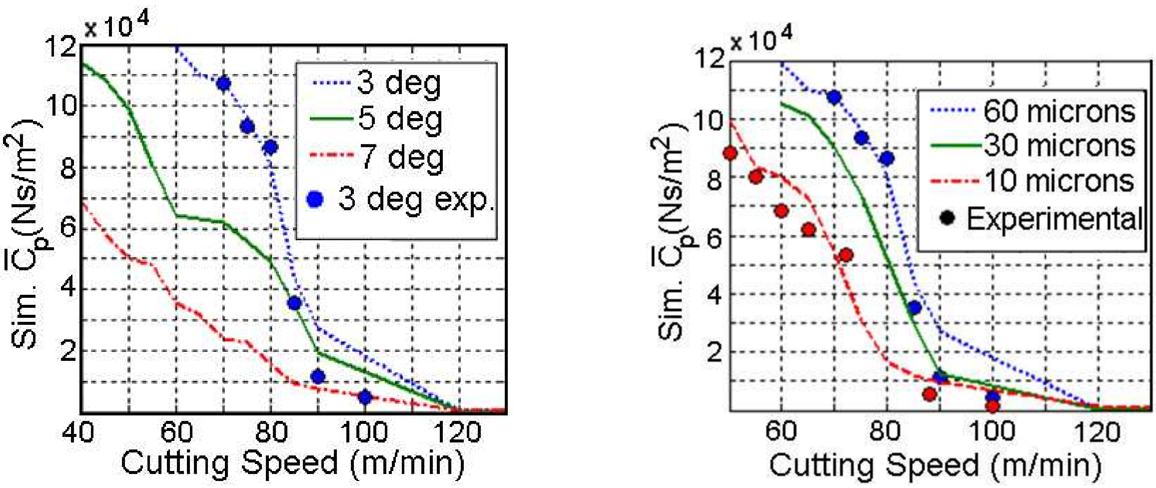
In cases 1 and 2 orthogonal cutting is analyzed where the rest of the cases deal with end milling. The effect of clearance angle on process damping in orthogonal cutting is investigated in case 1, where hone radius is set to 60 microns. In case 2, clearance angle is fixed at 3 degrees and comparison is performed for hone radii of 10, 30 and 60 microns. In case 3, the effect of clearance angle on process damping in end milling is investigated, where the hone radius is 10 microns. The effect of the drop distance for end mills with cylindrical flank geometry is analyzed in case 4, where the hone radius is set at 10 microns and the drop is measured at 10 degrees. In case 5, the effect of hone radius is considered, the cutting edge has clearance angle of 20 and 70 degrees at the first and second segments, respectively. In case 6, different values for length of the flank face are used in the simulations at several cutting speeds. The clearance angle at the first and second segments is 6 and 50 degrees, respectively, and the hone radius is 10 microns. In case 7, comparison between cutting edges with linear and cylindrical flank face is performed, where the details are given in Table 1.



(a) Indentation area (b) Absolute stability

Figure 4: Variation of absolute stability limit and indentation area with speed.

The wavelength decreases with decreasing cutting speed, causing surface slope to increase which in turn increases the indentation volume. As a result the average process damping coefficient increases with decreasing cutting speed. The absolute stability limit decreases to a^{hs}_{lim} at higher speeds where the effect of process damping diminishes. However, the stability limit tends to increase towards a_{lim} at low cutting speeds due to increased process damping (see Figure 4). In Figure 5 it is seen that the process damping drastically decreases with increasing cutting speed, where the results of cases 1 and 2 are plotted. A similar trend for end milling is also observed as shown in Figure 6, where the results of cases 3, 4 and 5 are presented. In the rest of this section effects of other parameters are investigated.



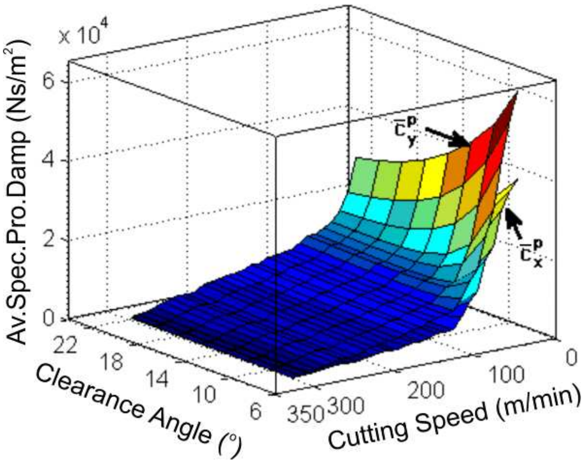
(a) Case 1, effect of clearance angle. (b) Case 2, effect of hone radius.

Figure 5: Effect cutting speed on process damping in orthogonal cutting.

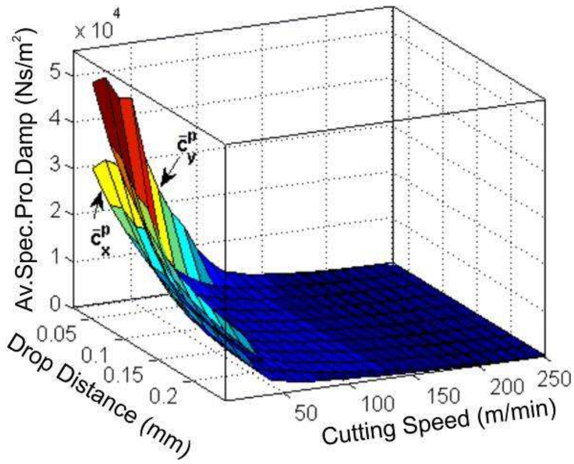
3.1. Effect of Clearance Angle, Drop Distance and Hone Radius

The clearance between the cutting edge and workpiece is governed by the clearance angle or drop distance for the cutting edges having planar flank face and cylindrical flank face, respectively. The clearance decreases with both decreasing clearance angle and drop distance, resulting in increased indentation volume. In this respect, clearance angle and drop distance affect the process damping in a way similar to the cutting speed. The variation of average specific process damping coefficient with clearance angle in orthogonal cutting, i.e. case 1, is plotted in Figure 5. Whereas, the effect of clearance angle, i.e. case 3, and drop distance, i.e. case 4, on process damping in end milling is presented in Figure 6a and Figure 6b. It can be said that average specific process damping substantially decreases with increasing clearance angle and drop distance.

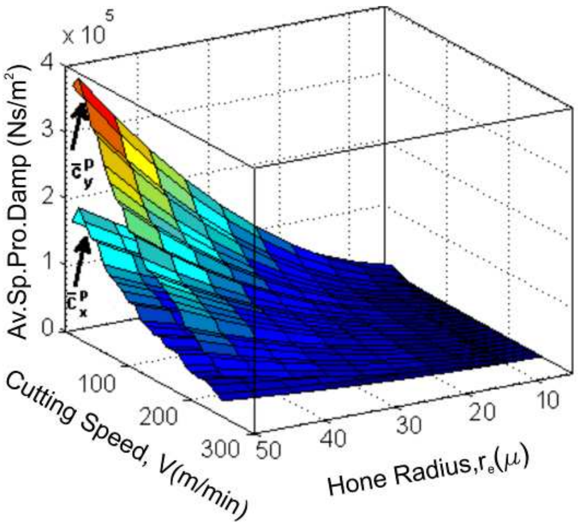
In the literature it is shown that the existence of hone radius causes the workpiece material to be extruded against the cutting tool /10/, which allows the tool penetrate into the workpiece. If the tool is sharp enough, i.e. the hone radius is very small, the extrusion effect does not occur and the tool hone does not penetrate into the workpiece. Therefore, larger hone radius causes increased indentation volume. The effect of hone radius on process damping is analyzed in case 2 and case 5, as presented Figure 5b and Figure 6c, for orthogonal cutting and end milling, respectively. It can be concluded that larger hone radius values result in increased specific process damping.



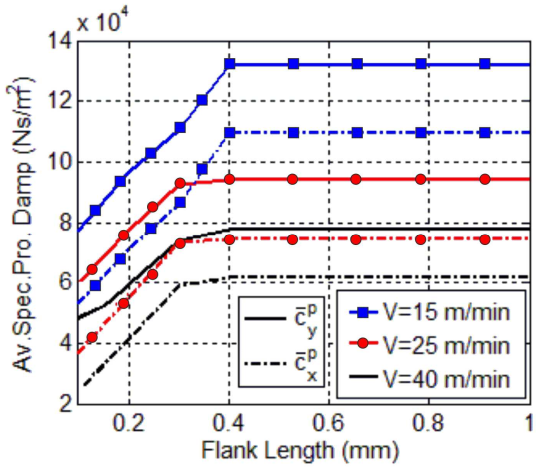
(a) Clearance angle



(b) Drop distance



(c) Hone radius



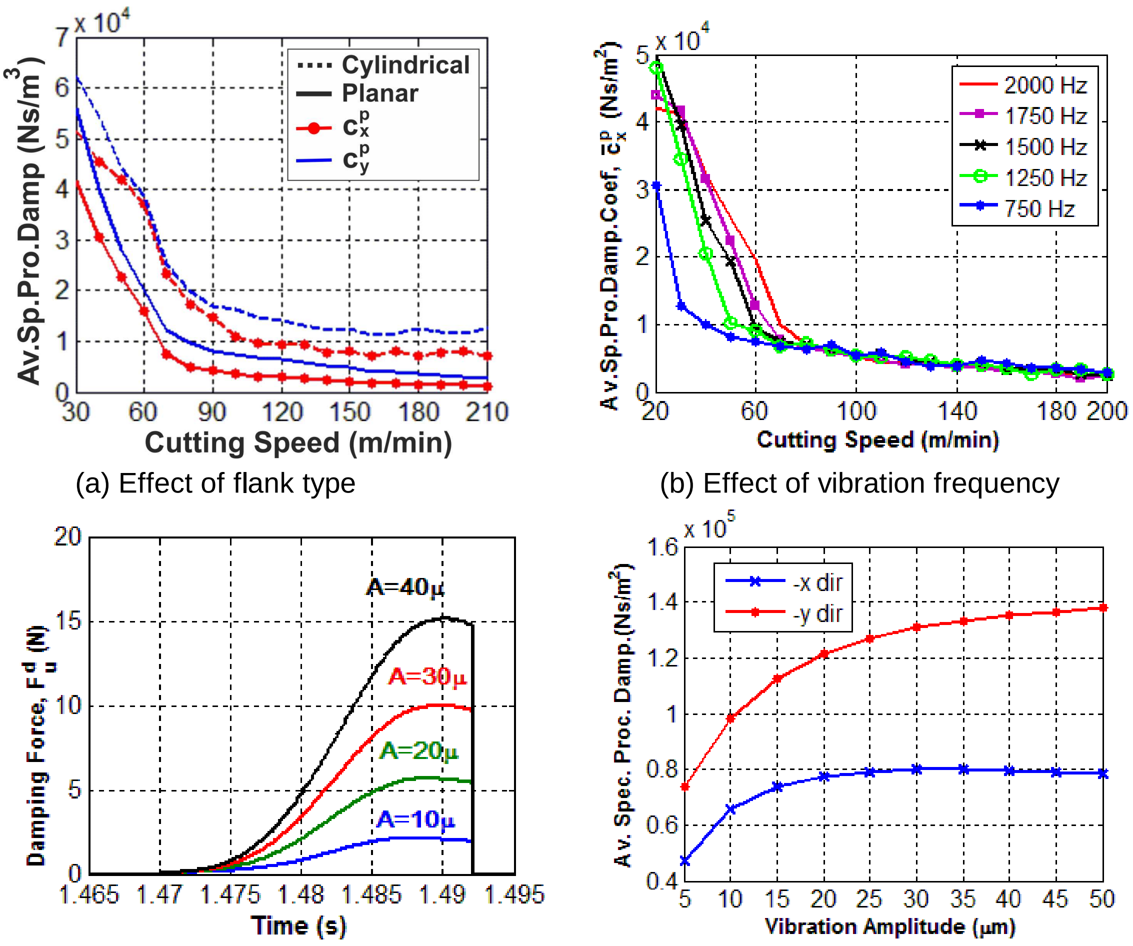
(d) Flank length

Figure 6: Effect of tool parameters on process damping in milling.

3.2. Effect of Flank Length and Type

For cutting tools having planar flank face either only the first or both of the two segments may penetrate into the workpiece under vibration according to the ratio between the segment lengths and the wavelength, as illustrated in Figure 2c. Therefore, under some circumstances process damping may be affected by the length of the segments for planar flank geometry. In Figure 6d, such a case is analyzed, where hone radius and clearance angle are 10 microns and 6 degrees, respectively. The average specific process damping coefficient increases with segment length and then it saturates, where the saturation point varies with cutting speed.

The slope of the planar flank face is constant along the edge. However, the slope starts from zero and continuously increases for cylindrical flank faces due to the circular cross section. Therefore, the variation of indentation volume and hence process damping directly depends on flank type. For instance, when the surface slope is smaller than the clearance angle the indentation volume is very small if the cutting tool has planar flank face. However, even for very small surface slopes, the indentation volume may be significant for tools with cylindrical flank face. Comparison between planar and cylindrical flank face is given in Figure 7a, where it is seen that cylindrical flank face results in higher process damping even at higher cutting speeds.



(a) Effect of flank type (b) Effect of vibration frequency

(c) Amplitude vs. damping force (d) Effect of vibration amplitude.

Figure 7: Effect of flank type, vibration frequency and amplitude.

3.3. Effect of Vibration Frequency and Amplitude

For a given cutting speed the surface slope increases with vibration frequency (see Figure 4a), resulting in more indentation volume and damping force. The increased damping force dissipates more regeneration energy resulting in higher average process damping coefficient. The effect of vibration frequency on the average specific process damping coefficient in –x direction is shown in Figure 7b. Process damping increases as the vibration frequency increases, especially at low cutting speeds.

The vibration amplitude is another important parameter for stability as the indentation volume and the damping force are nonlinearly related to the vibration amplitude. Therefore, limit cycle oscillations, which is a well known phenomena in nonlinear dynamics, can be observed under certain circumstances / 15/. In this respect, the stability limit depends on the vibration amplitude, i.e. acceptable maximum stable oscillation amplitude. In other words, at cutting depths of a_1 and a_2 the system may converge to stability at vibration amplitudes of A_1 and A_2. For a half immersion-down milling of Ti6Al4V the variation of the indentation (damping) force in –u direction and resulting average process damping coefficients in –x and –y directions for different vibration amplitudes are plotted in Figure 7c and Figure 7d, respectively, where the nonlinear effect of the vibration amplitude on the damping force and the resulting process damping are clearly seen.

4. EFFECTS OF TOOL GEOMETRY AND CUTTING CONDITIONS ON STABILITY LIMIT

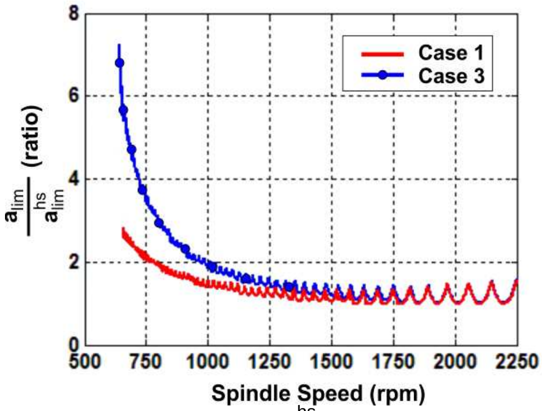
Similar to process damping, stability limit is also affected by indentation forces as they increase the overall damping in the process. In this section, the variation of stability limit with cutting edge geometry and cutting conditions is discussed through representative cases. Cases considered in simulations are listed in Table 2 where the modal parameters are given in Table 3.

Table 2: Cases for simulation of stability limit.

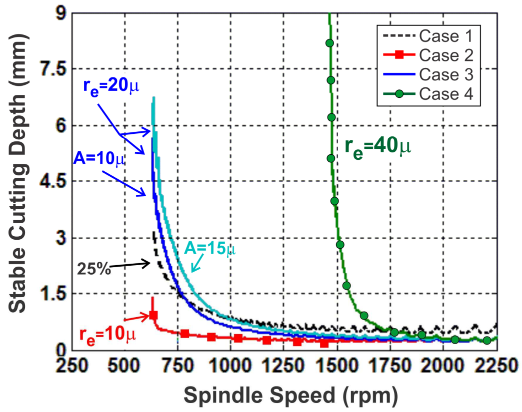
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Cutting Conditions	Radial (%)	25	50	50	50	50	50	40	
	Mode	Down	Down	Down	Down	Down	Down	Down	
Tool Geometry	Flank Type	Planar	Planar	Planar	Planar	Cylin.	Planar	Planar	Planar
	Hone (μm)	20	10	20	40	20	20	15	60
	Clearance(^{o})	10	10	10	10	NA	5	10	3
	Drop (mm)	NA	NA	NA	NA	0.1	NA	NA	NA
Material		Ti6Al4V							AL7075

Table 3: Modal parameters for simulation of stability limit.

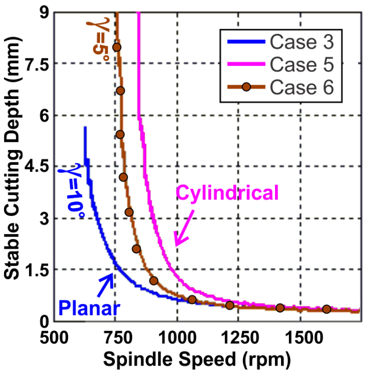
Milling			
Direction	Modal Mass (kg)	Natural Frequency (Hz)	Damping Ratio (%)
X	0.225	3154	1.74
Y	0.228	3151	2.03
Orthogonal Cutting			
X	0.284, 0.851, 3.229	1195, 681, 343	1.49, 1.25, 1.04



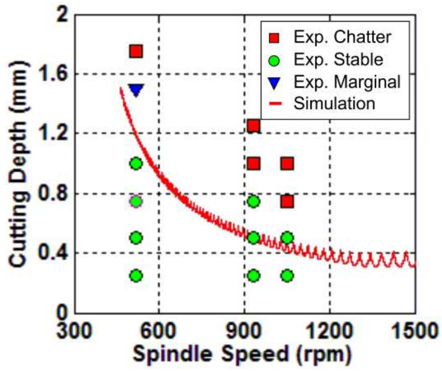
(a) a_{lim} / a^{hs}_{lim} for 25% and 50% immersion



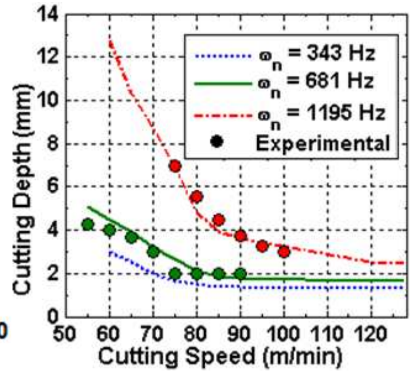
(b) Cases 1-4



(c) Cases 3- 6



(d) Case 7



(e) Case 8

Figure 8: Simulation of stability limit.

The simulated stability limits are presented in Figure 8. In classical stability analysis / 8, 9/ it is well known that the increased radial cutting depth results in decreased absolute stability. However, inclusion of the process damping effect into the stability analysis may lead to different observations. The contact time between the cutting tool and the workpiece per one tool rotation increases with radial cutting depth, resulting in more indentation volume. When cases 1 and 3 are compared the effect of radial immersion on stability limit can be observed. The normalized stability limit for quarter and half radial immersion cases is plotted in Figure 8a by dividing the stability limit to the high speed absolute stability limit. It is observed that for half immersion case, normalized stability limit is higher relative to quarter immersion case. Comparison of cases 2, 3 and 4, in Figure 8b, illustrates the effect of hone radius on stability limit. It is seen that the stability limit substantially increases with the hone radius. In addition, the critical cutting speed at which the process damping becomes effective also depends on the hone radius. For instance, process damping starts to be effective at 600 rpm (22 m/min), 900 rpm (34 m/min) and 1600 rpm (60 m/min) for hone radius of 10, 20 and 40 microns, respectively. Case 3 is simulated for stable vibration amplitude of 10 microns and 15 microns in order to see the effect of vibration amplitude on the stability limit (see Figure 8b). It is observed that if the stable vibration amplitude increases larger stability region can be obtained. Comparison of cases 3, 5 and 6 is presented in Figure 8c, where the effect of clearance angle and the type of flank geometry can be observed. Comparison of cases 3 and 5 clearly illustrates the significant effect of flank type on the stability limit at low cutting speeds. When the clearance angle and drop distance for planar and cylindrical flank geometries lead to similar clearance geometry, cylindrical flank results in higher stability border. As the results of the simulations performed for 5^o (case 6) and

10^o (case 3) of clearance angles it can be concluded that, clearance angle has a significant effect on stability limits at low cutting speeds. As clearance angle decreases, stability limit increases. In case 7, the simulations are compared with experiments for representative verification. In Figure 8d, it is seen that the estimated stability limits agree well with experimental results. In case 8 the relation between stability limit and natural frequency is considered in orthogonal cutting, where hone radius is 60 microns and clearance angle is 3 degrees. According to the results given in Figure 8e, it can be said that increased vibration frequency results in increased stability limit.

5. CONCLUSIONS

In this paper, effects of cutting conditions and tool geometry on process damping are investigated through simulations and experimental results. Previously developed models for identification and modeling of process damping / 15, 16/ are used in the simulations, and the following conclusive remarks are derived;

- When cutting speed decreases process damping and hence stability increases substantially. The stability increase, and the critical speed where it starts to become effective, depends on the tool geometry and chatter frequency.
- Flank face geometry, clearance angle and drop distance have also strong effects on the process damping and chatter stability at low cutting speeds. It is observed that cylindrical flank geometry results in increased process damping when compared to planar flank geometry even at higher cutting speeds. Under certain circumstances, length of the flank face for planar flank geometry may become important for process damping.
- Higher hone radius causes more process damping and stability.
- Vibration frequency is another important parameter where higher vibration frequency leads to increased indentation volume and process damping.
- Vibration amplitude is an important criterion for simulation of process damping. It is observed that process damping coefficient nonlinearly changes with vibration amplitude and behaves like a softening spring.
- In milling, increase in total contact length between the tool and the material results in higher process damping, thus higher stability. Due to this effect, increased radial depth of cut may not result significant decrease in stability limits unlike the situation for high cutting speeds where the effect of process damping diminishes. Similar effects should be expected for increased number of cutting teeth and helix angle on milling tools.

7. REFERENCES

1. Sisson, T.R., Kegg R.L., An Explanation of Low-speed Chatter Effects, ASME Journal of Engineering for Industry, 91 (1969) 558–951.
2. Tlusty, J., Analysis of the State of Research in Cutting Dynamics, Annals of the CIRP, 27/2 (1978) 583-589.
3. Tlusty, J., Ismail, F., Special Aspects of Chatter in Milling, ASME, J. Eng. Ind, 105 (1983) 24-32.
4. Lin, S.C., Devor, R.E., Kapoor, S.G., Sutherland J.W., A New Approach to Estimating the Cutting Process Damping Under Working Conditions, Transactions of NAMRI/SME, (1990) 154-160.
5. Kals H.J.J., On the Calculation of Stability Charts on the Basis of the Damping and Stiffness of the Cutting Process, Annals of the CIRP, 19 (1971) 297-303.

6. Altintas Y., Weck M., Chatter Stability in Metal Cutting and Grinding, Annals of the CIRP, 53/2 (2004) 619–642.
7. Minis, I., Yanushevsky R., Tembo A, Hocken, R., Analysis of Linear and Nonlinear Chatter in Milling, Annals of the CIRP 39 (1990) 459-462.
8. Altintas Y., Budak E., Analytical Prediction of Stability Lobes in Milling, Annals of the CIRP, 44/1 (1995) 357-362.
9. Budak E., Analytical Models for High Performance Milling. Part II: Process Dynamics and Stability, International Journal of Machine Tool & Manufacture, 46 (2006) 1489-1499.
10. Wu, D. W., A New Approach of Formulating the Transfer Function for Dynamic Cutting Process, ASME Journal of Engineering for Industry 111 (1989) 37-47.
11. Elbestawi, M.A., Ismail F., Du, R., Ullagaddi, B.C., Modeling Machining Dynamics Including Damping in the Tool-Workpiece Interface, Trans. of ASME, Journal of Engineering for Industry 116 (1994) 435-439.
12. Shawky, A.M., Elbestawi, M.A., An Enhanced Dynamic Model in Turning Including the Effect of Ploughing Forces, Trans. of ASME, Journal of Manufacturing Science and Engineering, 119 (1997) 10-20.
13. Lee, B.Y., Tarng, Y.S., MA, S.C., Modeling of the Process Damping Force in Chatter Vibration, International Journal of Machine Tool & Manufacture, 35/7 (1995) 951-962.
14. Altintas, Y., Eynian, M., Onozuka, H., Identification of dynamic cutting force coefficients and chatter stability with process damping, Annals of the CIRP, 57/1 (2008) 371-374.
15. Budak, E., Tunc, L.T., A New Method for Identification and Modeling of Process Damping in Machining, Trans. of the ASME, Journal of Manufacturing Science and Engineering, 131/051019 (2009) 1-10.
16. Budak, E., Tunc, L.T., Identification and modeling of process damping in turning and milling using a new approach, CIRP Annals-Manufacturing Technology, 59 (2010) 403-408.