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Flank face texture design to suppress chatter vibration in cutting

N. Suzuki[a,*], W. Takahashi[b], H. Igeta[a], T. Nakanomiya[a]

[a] *Department of Aerospace Engineering, Nagoya University, Chikusa-ku, Nagoya, Aichi, Japan*
[b] *Mitsubishi Material Corporation, Omiya-ku, Saitama, Japan*
Submitted by S. Shimada, Osaka Electro-Communication University, Japan

Process damping is useful in improving chatter stability in a low cutting speed range. This paper presents a texture design on tool flank faces that can effectively generate process damping. A convex structure on the flank face dampens chatter vibration even at general cutting speeds. An orthogonal cutting simulation utilizing a finite element analysis was conducted to estimate process damping force coefficients that are the functions of cutting and vibration conditions and tool geometry. Sufficient damping effect was predicted using the proposed texture via a chatter stability analysis in frequency domain. Face turning experiments verified the significant chatter suppression effect.

Cutting; Chatter; Tool

1. Introduction

Chatter vibration is a major limitation affecting the production efficiency of cutting processes. Production engineers need to set appropriate conditions that do not lead to this phenomenon of dynamic instability. To this end, various methods such as machining conditions optimization and dynamics improvement techniques are studied [1]. Among the techniques to avoid chatter vibration, process damping exhibits potential to improve chatter stability. Process damping occurs in a low cutting speed range, occasionally deteriorating productivity [1]. Therefore, it is expected to be useful for machining difficult-to-cut materials with relatively low cutting speeds. Process damping is a phenomenon in which the tool flank face establishes contact with the finished surface of the workpiece during vibration. Considering the mechanism, several models to predict chatter stability have been proposed, and the effects of machining conditions and tool geometry on process damping have been studied [2]. Altintas et al. modeled damping coefficients proportional to vibration velocity and acceleration then proposed a method for identifying parameters using fast tool servo or inverse analysis [3]. Budak et al. proposed a method to model the flank contact phenomenon as an additional damping coefficient in the system and estimate chatter stability [4]. Several extended models considering workpiece deformation in contact with the flank face have been proposed [5,6]. A few of these analysis methods are useful to predict stability considering tool wear.

If process damping can be actively developed even in the general cutting speed region, it can be potentially and effectively used as a robust chatter suppression method that enhances conventional technologies. By reducing the clearance angle of the tool or fabricating cutting edge chamfers [7], effective process damping can be realized. However, the wear progress is accelerated simultaneously; this strongly limits its availability due to shorter tool life. Baumann et al. proposed a method for providing a texture on the flank face of the minor cutting edge of milling tools and experimentally evaluated the process damping effect [8]. However, there is limited research on flank texture technology, and its effective usage in terms of process dynamics is not clarified. This paper proposes a flank texture design on the cutting tool that can effectively trigger process damping. First, the process damping phenomenon is analyzed by conducting a series of computational experiments using finite element analysis. The relationship between vibration and process damping force is modeled in frequency domain, and coefficients that are the performance indices of process damping are calculated. Using these indices, a stability limit simulation is conducted to quantitatively evaluate the effect of the texture that contributes to stability. In addition, we conducted face turning tests to experimentally verify the chatter suppression effect of the proposed flank texture.

2. Process damping simulation by finite element analysis

A tool that effectively develops process damping is proposed using flank texture; a sectional image of this tool is shown in Figure 1. A convex structure provided on the flank face establishes contact with the finished surface when a chatter vibration with a large amplitude occurs. The textured part is fabricated outside the typical flank wear area that disappears by the end of the tool life. Furthermore, the height of the texture bottom h is set to be slightly higher than the maximum recession height of the worn cutting edge. Considering an allowable maximum flank wear width l_{VB} and a nominal clearance angle γ_n, the texture height h is designed to satisfy $h > l_{VB} \tan \gamma_n$. This ensures that the texture can contact the machined surface solely during vibration. Hence, the proposed method does not adversely affect stable machining conditions. Even during vibration, excessive edge force generation can be avoided by ensuring a short texture length. The vibration-suppressing performance depends on the dynamic characteristics of the vibration and force. In particular, texture geometry and its position affect the dynamic characteristics. Hence, the flank texture design is important.

To estimate the effect of the flank face texture, a force–vibration model is investigated considering process damping. It is difficult to explore the force–vibration relationship precisely through cutting experiments due to the limitation in measurement of dynamics. Even if the measurement is attained, it is not easy to extract the process damping force component from the total measured force separately from chip generation force component. Therefore, a series of simulation experiments is conducted using the finite element analysis to quantitatively analyze the process damping force and chatter vibration [6]. The commercial software of AdvantEdge™ is employed in this study.

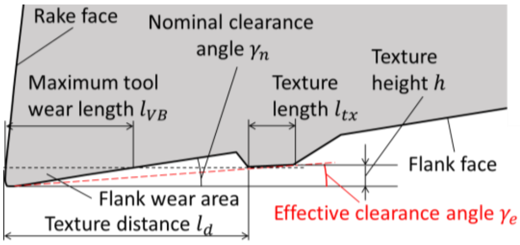
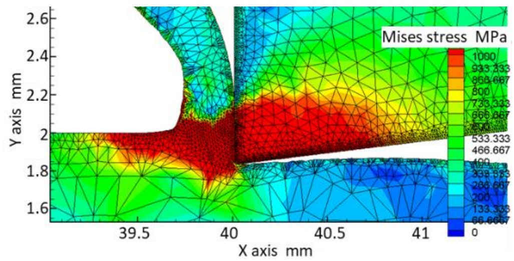
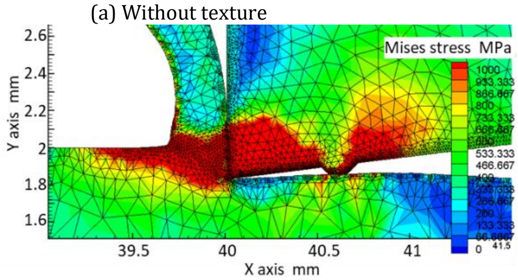


Figure 1. Proposed tool with texture on flank face.



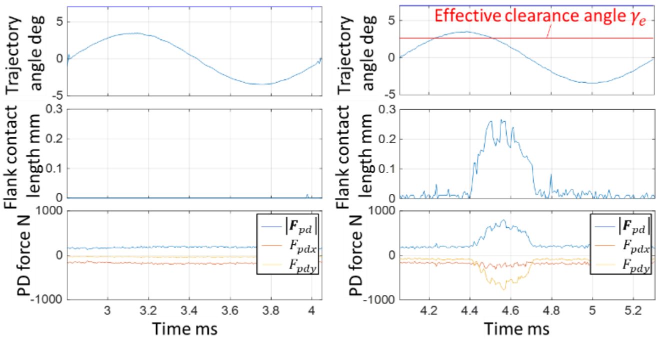
(a) Without texture



(b) With texture (l_d: 0.55 mm, l_{tx}: 0.1 mm, h: 25 µm)

Figure 2. Demonstrations of cutting process simulation with chatter vibration. (γ_n: 7°, γ_e: 2.2°, v_c: 100 m/min, ω_c: 800 Hz, u: 20 µm.)

Figure 2 shows examples of the orthogonal cutting simulations with a chatter vibration at cutting speed v_c of 100 m/min. All simulations are conducted assuming carbon steel workpiece (JIS: S45C) and tungsten carbide tool in this study. When the angle of the relative motion trajectory of the tool with respect to the nominal cutting direction, i.e., trajectory angle, exceeds the nominal clearance angle of the tool γ_n, the tool flank face establishes contact and develop process damping. Hence, the clearance angle γ_n plays a key role in process damping. The chatter frequency ω_c and amplitude u were assumed as 800 Hz and 20 µm, respectively. The maximum trajectory angle (3.5°) does not exceed the nominal clearance angle γ_n, and thus, process damping does not occur with the tool without texture. Meanwhile, the flank texture establishes contact with the work material even with the same small vibrations. This flank contact causes different stress distributions on the tool surface. From the analytical results, the normal stress $\boldsymbol{\sigma}_n$ and shear stress $\boldsymbol{\tau}_{tn}$ generated on the flank face are extracted, and the process damping force $\boldsymbol{F}_{pd} = \int(\boldsymbol{\sigma}_n + \boldsymbol{\tau}_{tn})ds$ is obtained. Figure 3 shows input trajectory angle, calculated flank contact length, and process damping forces. The trajectory angle exceeds the effective clearance angle of the textured tool γ_e, so that the flank texture establishes contact with the machined surface. Interestingly, the process damping force is generated with a time delay due to a gap between the cutting edge and the texture.



(a) Without texture (b) With texture

Figure 3. Predicted process damping force, flank contact length and input trajectory angle.

3. Analytical evaluation of texture effect on chatter stability

3.1. Calculation of process damping coefficients

In this section, the process damping coefficients that represent process damping effect are modeled and influence of flank texture geometry is analytically evaluated. For simplicity, vibration is assumed to occur at a constant frequency ω_c only at a depth of cut direction. Using the process damping coefficient K_{pdk} and K_{pdc}, the relationship between the process damping force F_{pd} and the vibration amplitude U in a depth of cut direction is formulated as follows in frequency domain.

$$F_{pd}(i\omega_c) = -a\left(K_{pdk} + iK_{pdc}\right)U(i\omega_c) \quad (1)$$

a is a cutting width. K_{pdk} is proportional to the vibration displacement, and thus, quantitatively represents the spring stiffness added to the system by process damping. In contrast, K_{pdc} is synchronized with velocity resulting in representing damping characteristic. Each coefficient can be calculated from the input amplitude U and the dynamic process damping force F_{pd} simulated by the finite element analysis as follows:

$$K_{pdc} = -\frac{1}{a} imag\left(\frac{F_{pd}}{U}\right),\ K_{pdk} = -\frac{1}{a} real\left(\frac{F_{pd}}{U}\right) \quad (2)$$

Figure 4 shows the influence of the vibration wavelength $\lambda = 2\pi v_c/60\omega_c$ and the vibration amplitude u on the process damping coefficients of a tool without texture. ω_c and u were scanned in the range 600–4800 Hz and 0–70 µm, respectively. The coefficients tend to be small with a long wavelength and small amplitude. The boundary condition where the coefficient increases can be roughly estimated from the relationship between the trajectory angle and the clearance angle. When the maximum trajectory angle agrees with the tool clearance angle, the amplitude and wavelength are represented as follows:

$$u = \frac{v_c \tan\gamma_n}{\omega_c} = \frac{\lambda \tan\gamma_n}{2\pi} \quad (3)$$

The condition of Eq. (3) is denoted by a red dashed line in Fig. 4. The process damping coefficients are almost zero in the area below the dashed line and increase in certain areas above it.

Figure 5 shows the estimated process damping coefficients of the textured tool. The distance from the cutting edge to the texture, i.e., texture distance l_d, was set to 0.55 mm, the texture length l_{tx} and height h were set to 0.1 mm and 40 µm, respectively. The region where the process damping coefficient is large expands compared with that of the tool without texture. The expanded region is produced by the texture contact. Another red broken line, i.e., the boundary amplitude line calculated by the effective clearance angle γ_e, roughly agrees with the boundary of the expanded region. Furthermore, there is the minimum amplitude boundary of approximately 25 μm that is slightly smaller than the texture height h.

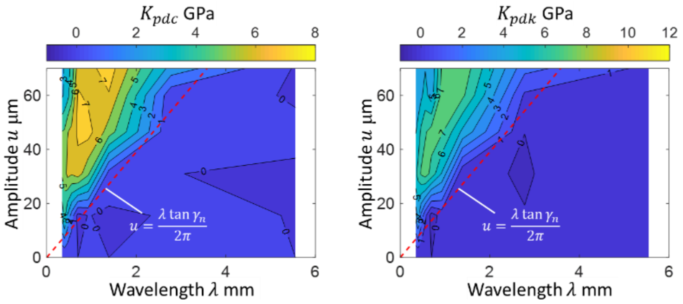


Figure 4. Calculated process damping coefficients (without texture). (γ_n: 7°, v_c: 100 m/min, ω_c: 600–4800 Hz, u: 0–70 μm.)

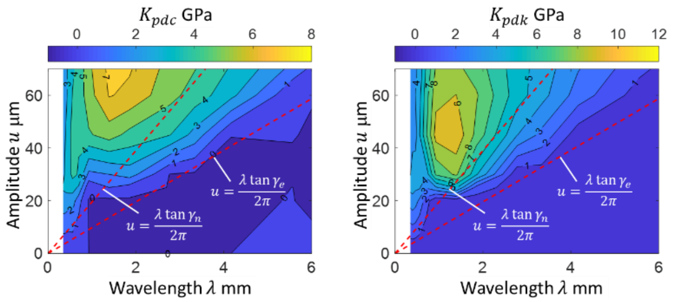


Figure 5. Calculated results in process damping coefficients (with texture). (γ_n: 7°, γ_e: 3.5°, v_c: 100 m/min, ω_c: 100–4800 Hz, u: 0–75 μm, l_d: 0.55 mm, l_{tx}: 0.1 mm, h: 40 μm.)

Figure 6 compares the estimated results of the process damping coefficient for the different texture heights. The boundary amplitude for process damping decreases with the texture height. Figure 7 shows the influence of texture length. Each coefficient tends to increase with the texture length. The effective wavelength to increase process damping slightly shifts with the texture length. Both results indicate that small h and large l_{tx} are better to increase process damping effectively. However, these designs trigger larger edge forces generation due to the flank texture contact. Hence, there should be limits in practical use in terms of tool wear and process forces.

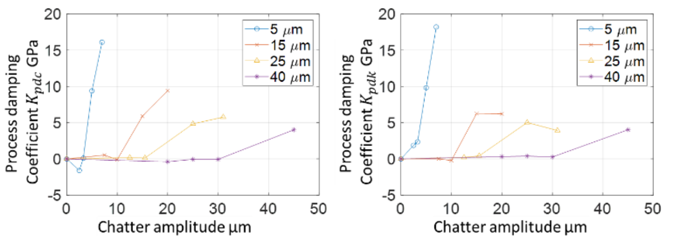


Figure 6. Influence of texture height h. (γ_n: 7°, v_c: 100 m/min, ω_c: 600 Hz, l_d: 0.55 mm, l_{tx}: 0.1 mm.)

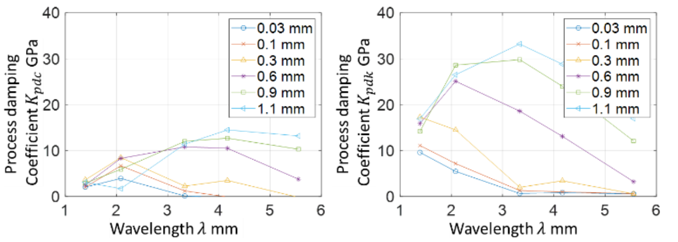


Figure 7. Influence of texture length l_{tx}. (γ_n: 7°, v_c: 100 m/min, ω_c: 300–1200 Hz, u: 20 μm, l_d: 0.55 mm, h: 25 μm.)

Figure 8 shows the influence of the texture distance l_d. The wavelength region where the process damping coefficients K_{pdk} or K_{pdc} increase shifts with l_d. K_{pdk} increases effectively in the region where the half wavelength corresponds to the texture position, whereas K_{pdc} increases in the region where one forth to one third of the wavelength agrees with the texture position, indicating that the phase of the process damping force is associated with the tool motion trajectory and relative position of the texture. The motion trajectory depends on the cutting speed and vibration frequency. In other words, there are specific cutting speeds and frequency combinations in which each process damping coefficient effectively increases. Therefore, the position of the texture needs to be designed appropriately considering the interaction of cutting speed and vibration frequency.

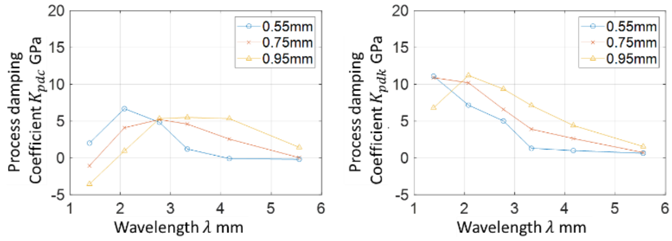


Figure 8. Influence of texture distance l_d. (γ_n: 7°, v_c: 100 m/min, ω_c: 300–1200 Hz, u: 20 μm, l_{tx}: 0.1 mm, h: 25 μm.)

3.2. Influence of process damping coefficients on chatter stability

To investigate influence of the process damping coefficients on chatter stability, a chatter stability analysis of the plunge cutting in frequency domain was conducted. Figure 9 shows a block diagram of the analytical model. In this system, the following equation holds at the stability limit. The critical cutting width $a_{\lim}$ can be obtained by solving its characteristic equation. The process damping coefficients depending on U and λ are given using finite element analysis in advance.

$$F(i\omega_c) = F_c + F_{pd} = -a_{\lim}\{K_f(1 - e^{-i\omega_c T}) + (K_{pdk} + iK_{pdc})\}G(i\omega_c)F(i\omega_c) \quad (4)$$

K_f is a specific cutting resistance, T is a teeth passage period, and $G(i\omega_c)$ is the frequency response function of the structural system.

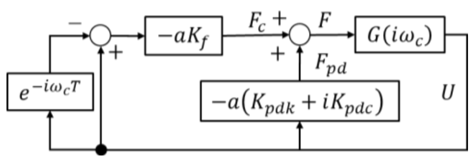


Figure 9. Block diagram of cutting process with process damping.

Figure 10 shows the results of analyzing the relationship between the asymptotic stability limit and the process damping coefficients. For simplicity, the frequency response function was defined with a natural frequency of 1 kHz, a damping ratio of 0.03, and an equivalent spring constant of 10^7 N/m. The specific cutting resistance K_f is set to 1 GPa. Without process damping, the asymptotic stability limit is 0.62 mm. This is a minimum, and the chatter stability increases with positive process damping coefficients. The asymptotic stability limit increases to 1 mm under the condition that roughly satisfies $K_{pdc} = 0.37 - 0.023K_{pdk}$. When $K_{pdc} \geq 0.93$ GPa, the system stabilized irrespective of K_{pdk}. Figure 5 shows that K_{pdc} can exceed 0.93 GPa easily. In the region of $\lambda < 3$ mm, i.e., $v_c < 180$ m/min, K_{pdc} is sufficiently larger than 1 GPa when the amplitude is approximately 30 μm or more than that. Thus, the proposed texture is effective even at the normal cutting speed range. K_{pdk}

increases in the same region; however, the value is not sufficiently large to suppress chatter vibration by itself. Therefore, in order to utilize process damping efficiently, it is effective to design the texture so that K_{pdc} increases.

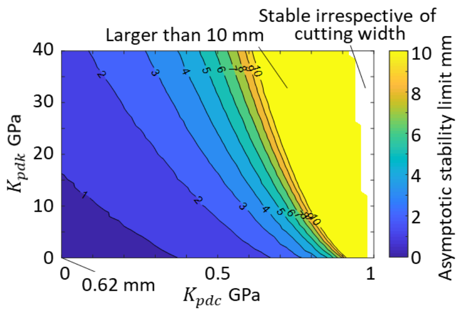


Figure 10. Influence of K_{pdk} and K_{pdc} on asymptotic stability limit.

4. Experimental verification

Face turning experiments of brass workpiece (JIS: C2801) were conducted using a CNC lathe, and chatter stability for a normal tool and a textured tool is compared. Figure 11 shows a schematic of the experimental setup and conditions. The tool is fed at a feed rate of 0.5 mm/rev from the outer side to the inner side with a spindle speed of 300 min^{-1}, such that the cutting speed is continuously reduced. The shank has a parallel leaf spring structure and exhibits a specific compliance in the z direction. Considering first bending mode of 520.5 Hz, λ is less than 2.42 mm. The vibration displacement of the tool in the z direction is measured using an eddy current displacement sensor. The clearance angles of the tools are 10° and 7° for the end and side cutting edges, respectively. Hence, the process damping occurs at the side cutting edge. For the textured tool, a convex texture was applied parallel to the side cutting edge, whose l_{tx}, h, and l_d are designed to be 0.05 mm, 8 µm, and 0.2 mm, respectively. Laser processing was applied to obtain the designed flank face geometry. Due to the small h, the effective clearance angle is small. Thus, a strong process damping effect is expected. From Eq. (3), the vibration amplitude is expected to be less than about 12 µm. However, the allowable flank wear width l_{VB} is small.

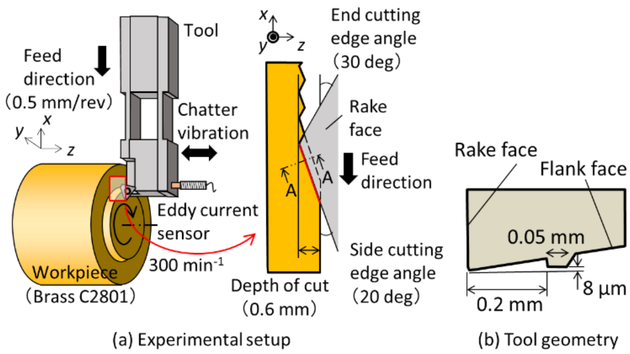


Figure 11. Schematic of face turning experiment.

Figure 12 shows the experimental results. Chatter vibration occurred in the normal tool from the start of cutting, and after the amplitude increases to approximately 45 µm, the vibration gradually decreased from 4 s and became stable. The cutting speed at 4 s is approximately 56 m/min, and the vibration wavelength is 1.79 mm. In contrast, the textured tool did not generate chatter vibration irrespective of the cutting speed, and the amplitude was less than 5 µm. The photograph of the machined surface shows that chatter marks are transferred on the machined surface using the normal tool, whereas chatter vibration does not occur when the textured tool is used. Hence, the proposed textured tool can effectively induce process damping and suppress chatter vibration. In other experiments with carbon steel workpiece, chatter vibration was suppressed by the same effect. In contrast, on the flank face of the tool after cutting, the workpiece material adhered to the textured part. If adhesion considerably develops, it may cause problems such as large edge force generation and damaging the cutting edge. This phenomenon can be avoided by designing larger texture height h and texture distance l_d. However, it is necessary to design properly considering that the effective wavelength range and the boundary amplitude change at the same time.

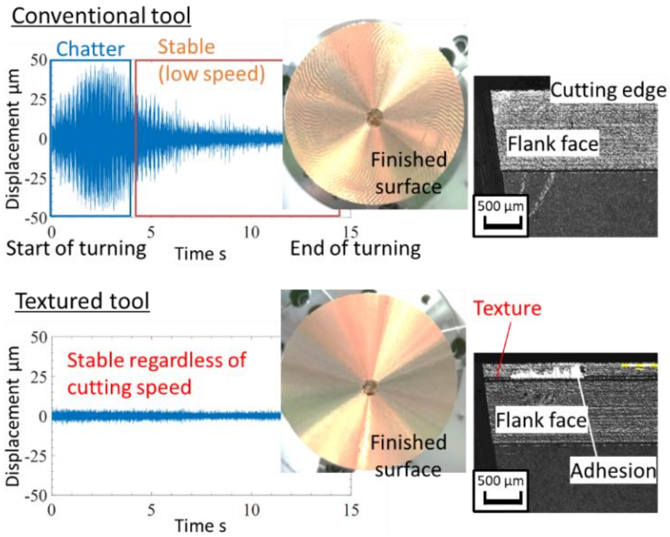


Figure 12. Experimental results of face turning tests.

5. Conclusion

A flank texture that can effectively develop process damping was proposed. The finite element analysis was conducted to evaluate the effects of vibration and cutting conditions and tool geometry on the process damping force. Analytical results indicated that the proposed method can effectively improve chatter stability in a specific frequency range. The texture distance, height, and length are the key parameters to design and optimize the functionality of the texture. Face turning experiments clarified that the proposed texture is appropriate to effectively suppress chatter vibrations. Future work will optimize texture design for adhesion suppression and robustness against chatter frequency.

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