The influence of flank lands of end mills on machined surface in milling in the context of chatter

S I Dyadya¹, Ye B Kozlova¹, V I Tretiak¹, E V Kondratyuk²

¹ National University “Zaporizhzhya Polytechnic”, 64, Zhukovsky str., Zaporizhzhia, 69064, Ukraine
² Zaporizhzhia Machine-Building Design Bureau “Ivchenko-Progress”, 2, Ivanov str., Zaporizhzhia, 69061, Ukraine

E-mail: kozlova@zntu.edu.ua

Abstract. Reliability and cost-effectiveness are the main requirements for aircraft materials and structure components used in manufacturing of aviation engines. This defines the requirements for them. The majority of components are thin-walled and made of hard-to-machine materials: nickel and titanium alloys, heat-resistant steels. The use of such materials places restrictions on the use of certain cutting modes. During rough milling and semi-finish milling with end-mill cutters chatter occur. The vibrations deteriorate the machined surface of engine parts, tool life decreases and machine units are worn out. Different process technologies and constructive features of tools are used to decrease the intensity of chatter. The use of end mills having lands has yielded mixed results. The influence of land usage on surface condition and decrease of chatter in up-milling and down milling has been studied. The mechanism of influence on machined surface and chatter in up-milling and down milling has been determined. At the experimental stand studies were carried out on its effect on changes in the laws of motion of detail during the cutting process. It has been shown that in up-milling and down milling, a land \( f_l = 0.05 \) mm wide on the rear surface along the cutting tooth reduces the intensity of chatter has been shown. The results can be used to select the feed direction to reduce the intensity of chatter when milling thin-walled parts with end mills with a land on the rear surface along the cutting edges.

1. Introduction
Light weight and durability are the main requirements to machine parts and components in aviation industry. Therefore, the parts are made of hard-to-process materials and contain thin-walled elements. During end milling operations tooth entry is accompanied with shock causing vibrations. Their intensity \( (A) \) depends on stiffness of a work piece \( (k) \) and kinetic energy \( (E) \) at tooth entry [1]. Eq. 1.

\[
A = \sqrt{\frac{2E}{k}}
\] (1)

While cutting speed grows the intensity of vibration increases. It should be mentioned, there are different modes of vibration at different cutting speeds [2]. Therefore, all cutting speeds are divided into five zones. Each zone has its own values of constituent equation \( (CE) \) between cutting time – \( t_{cut} \).
and period of chatter – $T_{chatter}$ of a work piece ($CE = \frac{t_{cut}}{T_{chatter}}$) [2]. Methodology of calculations of cutting time for different types of end mills can be seen there [2]. Free vibration period is determined depending on stiffness of a work piece [1].

Division into speed zones gives the possibility to reveal unfavorable modes with chatter intensity more than 0.02 mm. Unfavorable modes should be detected at pre-production stage. These modes are common for rough end milling and semi-finish end milling of hard-processed materials in the third speed zone of vibrations ($1 < CE < 7$). Different process technologies and constructive features of tools are used to decrease the intensity of chatter in that zone.

The primary goal is to eliminate wave regeneration on cutting surface and change the conditions of rubbing between flank face and machined surface.

In the first case use cutters with variable step [3 – 8], different angles of flute helix, use modulation of cutting speeds.

Having analyzed the results of milling with alternating pitch cutters [9 – 13] it was determined tooth-to-tooth variation (pitch variation) is to be equal to a half wavelength of chatter. Under this condition the suppression of chatter takes place.

In cutter designs regulated by GOST 17025–71, 17024–71, 18372–73, 15086-69 alternating pitch is considered to be standard, therefore, the cutters made in that way are able to suppress chatter of a certain period. The period limitedness terminates the use of such cutters. Alternate gash mill cutters are able to provide necessary cutting speed in a broad vibration-free range [16 – 19].

Modulated cutting speed results in continuous phase shift between vibration trace and in-process vibrations of the system [14]. At CNC machine tools spindle speed is a programmed parameter. Spindle movement options influence speed modulation. However, the applicability of this approach of suppression of chatter is limited. It is caused by time lag of spindle and the necessity of choosing modulation depth and modulation rate for every type of processed material.

The method of suppression of chatter due to rubbing between flank and machined surface does work properly [2]. There is a flat (relieved) land (GOST 18372–73) or a cylindrical land (GOST 17025–71, 17026–71) with a width no more than $f_l = 0.05$ mm in end mills designs. Possible geometry of flank sharpening is shown in fig. 1.

![Figure 1. Geometry of flank sharpening: 1. Flat relieved tooth. 2. A tooth with a land $f_l$: AB – a cylindrical land, CB – a flat (relieved) land](image-url)
The characteristics of the mill tooth are the following: the tooth is plain with double-angle point $\alpha_1 = 11 - 16^\circ$ and $\alpha_2 = 24 - 30^\circ$. Tooth 1 is conventional, flat relieved, while tooth 2 has a land $f_l$. Depending on the method of sharpening a land can be either cylindrical – $AB$ or flat (relieved) – $CB$. The shape of the land determines conditions of tooth surface rubbing with the machined surface.

When the tip of tooth $A$ travels on the circumference – $d_{cutter}$ a cylindrical land touches the tip of tooth, so relief angle in every point is $\alpha = 0^\circ$. When the tip of tooth $C$ travels on the circumference – $d_{cutter}$ relief angle of flat land $CB$ becomes negative. At point $B$ flank can have plastic contact with the machined surface.

Both decrease of vibrations intensity and good level surface are equally important in milling processes. It is evidently that level surface after up-milling using a tool with a land has practically the same waviness as after milling using a conventional flat-relieved tool.

Consequently, the research of mechanism of using end mills tools with lands to decrease vibrations intensity and refine level surface of machined parts is of primary importance. Equally important is to determine the parameters of such influence in both up-milling and down milling.

2. Materials and methods
A special testing device was used for cutting a thin-walled work piece with an end mill during the experiments [2]. The design of the testing device gave the opportunity to separately investigate three factors influencing vibration processes. These factors are: characteristics of elastic system, properties of the machined material and the choice of cutting modes. The testing device with a specimen on it was firmly clamped to the table of vertical milling machine. A milling cutter of a special structure was fixed in the spindle [2].

Cutters were mounted sequentially in the cutter holder. A conventional flat relieved tool ($f_l = 0$) was mounted first, while a tool with a land on flank face ($f_l = 0.05$ mm) was mounted after that. The machining was being done in the third speed zone both in up-milling and down milling.

Vibrations of elastic system of workpieces in milling with the use of conventional tools and tools with lands of 0.05mm wide were being recorded in oscillograms.

Profilograms of machined workpieces were recorded after milling. The values of waviness height and waviness step were measured. Oscillograms were divided into basic fragments. They helped to determine range of chatter – $R_2$ and period of chatter – $T_{chatter}$, deviation of first wave from position of elastic equilibrium in up-milling and deviation of last wave – $\Delta_{d_{prof}}$ in down milling.

These parameters of vibratory motion influenced by the availability of the land are linked with formation of machined surface profile. Amplitude of chatter is a measure of their intensity. The period of chatter is linked with waviness step of the machined surface. Deviations of first wave from elastic equilibrium in up-milling and deviations of last wave in down milling determine the position of profile forming cavity on machined surface after each cut of the tooth [20].

The experiments were done under the following conditions.
- Cutting modes: spindle rotation rate – $n = 280$ rev/min; radial depth of cut $a_r = 0.5$ mm; axial depth of cut $a_p = 3.4$ mm; feed per tooth $S_z = 0.1$ mm; feed path – up-milling and down milling; free cutting.
- Cutter tool: cutter diameter $d_{cutter} = 50$ mm; teeth number $z = 1$; cutting edge inclination $\omega = 0^\circ$; material of cutting edges – BK8; free vibration frequency $f_{fz} = 833$ Hz.
- Elastic system of the work piece: free vibration frequency $- f_{fz} = 439$ Hz.
- Specimen material in St. 3 GOST 380-2005.

An electrical contact device was used for making oscillograph charts [2]. Tooth-in-cut time – $t_{cut}$, i.e. the time span from the tooth entry into a work piece till the tooth exit was clocked and recorded.

3. Presentation of the main material and analysis of the results
Figure 2 shows profilograms of machined surfaces after both up-milling and down milling with a conventional tool and a tool with a land $f_l = 0.05$ mm.
Up milling

Down milling

\( f_l = 0 \)

\( f_l = 0.05 \text{ mm} \)

Figure 2. Profilograms of machined surfaces after both up-milling and down milling with a conventional tool and a tool with a land \( f_l \)

Profilograms show waviness height – \( W_z \) and waviness step – \( S_w \). Analysis of values got after up-milling and down-milling shows that characteristics are steadier after up-milling. Average numerical values are done in table 1. The obtained data prove the tool having the flank land influences surface forming, first of all decreasing waviness step. As for waviness height, it considerably decreases in down milling while practically does not change in up milling.

Chatter during cutting process influence machined surfaces. The changes on the surfaces are caused by changes in vibration motion and peculiarities of up-milling and down milling. Up-milling implies minimum chip thickness at the very beginning, so chatter manifests themselves immediately after the tooth entry. Down milling starts with maximum chip thickness, so chatter appear when chip thickness decreases reaching definite values.

Table 1. Average values of waviness step and waviness height of machined surfaces

| Feed path | Up-milling | | Down milling | |
|-----------|------------|---------|---------------|---------|
|            | Conventional tool \((f_l = 0)\) | With land \((f_l = 0.05 \text{ mm})\) | Conventional tool \((f_l = 0)\) | With land \((f_l = 0.05 \text{ mm})\) |
| Waviness step, \(S_w\), (mm) | 2.65 | 2.33 | 1.09 | 0.87 |
| Waviness height, \(W_z\), (mm) | 0.086 | 0.099 | 0.111 | 0.051 |

Fragments of oscillograms of vibrations of work pieces in up-milling and down milling with the use of a conventional tool and a tool with a land of \( f_l = 0.05 \text{ mm} \) wide are shown in fig. 3. Tool cutting time – \( t_{cut} \), range of chatter – \( R_2 \) and period of chatter – \( T_{chatter} \), deviations from the position of elastic equilibrium – \( PEE \) in the zone of surface formation – \( \Delta_{up\ prof} \) and \( \Delta_{d\ prof} \) are shown in fig. 3.

Table 2 shows values of amplitude and period of chatter in up-milling and down milling using a flat-relieved tool and a tool having a land of \( f_l = 0.05 \text{ mm} \) wide.

The presence of land \( f_l = 0.05 \text{ mm} \) on flank reduces intensity of chatter caused by rubbing on machined surface in down milling by a factor of 1.86. The same process under the same conditions in up-milling results in decrease of vibration by a factor of 1.34. The period of vibration proportionally decreases. Waviness step on the machined surface depends on the period of vibration [20]. This statement is confirmed with measurements shown in table 1.

It should be emphasized that the use of land \( f_l = 0.05 \text{ mm} \) has no influence on the results of up-milling in the zone of machined surface profiling. Fig. 3 clearly proves this provision.

Deviations of first wave from elastic equilibrium have close numerical values both in up-milling and in down milling. The choice of a flat-relieved tool or a tool having a land of \( f_l = 0.05 \text{ mm} \) wide practically does not influence the resulting values. The influence of land is manifested in profiling
zone, in particular, it results in decreasing both chatter and their period. All these considerations explain why waviness step decreases while waviness height does not change.

Maximum chip thickness at the beginning of down milling process dampens chatter. When a flat relieved tooth travels deeper the chip thickness minimizes, so the intensity of vibration increases. With the use of a tool having land of \( f_l = 0.05 \) mm wide the intensity of vibration increases only marginally due to the land contact with machined surface. In down milling process the surface is formed at the tooth exit. Therefore, decrease in intensity of chatter due to the use of land of \( f_l = 0.05 \) mm wide contracts the period of vibrations and reduces the value of \( \Delta d_{\text{prof}} \) (fig. 3). Moreover, waviness step and waviness height on machined surface become less (fig. 2)

**Figure 3.** Fragments of oscillograms of work piece vibration in up-milling and down milling with the use of a conventional tool and a tool with a land of \( f_l = 0.05 \) mm wide
Table 2. Values of amplitude and period of chatter in up-milling and down milling using a flat-relied tooth and a tooth having a land

| Feed path | Up-milling | Down milling |
|-----------|------------|--------------|
| Cutting edge | Conventional tool ($f_l = 0$) | With land, ($f_l = 0.05$ mm) | Conventional tool ($f_l = 0$) | With land, ($f_l = 0.05$ mm) |
| Range of chatter, $R_2$, (mm) | 0.130 | 0.097 | 0.126 | 0.069 |
| Period of chatter, $T_{chatter}$, (sec) | 0.00205 | 0.00191 | 0.00153 | 0.0013 |

4. Conclusion
On the basis of the conducted research, the influence of flank lands on the rear surface of the end mills on the formation of the machined surface have been established.

1. The presence of lands of $f_l = 0.05$ mm wide on flanks of end mills positively influences on suppression of chatter due to changes in rubbing of tool flank and machined surface both in up-milling and down milling.

2. Both in up-milling and down milling the use of lands of $f_l = 0.05$ mm wide decreases the period of chatter and therefore causes reducing of waviness step on machined surface.

3. In up-milling chatter occur at the beginning of cutting process and impact the profiling zone until the land contacts the surface being cut.

4. In up-milling the use of land of $f_l = 0.05$ mm wide does not influence waviness height of machined surface. The influence of the land on suppression of chatter is manifested only after profiling zone is machined.

5. In down milling the land of $f_l = 0.05$ mm wide has stronger effect on suppression of chatter because forming occurs at the exit of the tool, therefore the land has contact with the surface being cut.

6. The best results of using the land $f_l = 0.05$ mm wide on the flank of end mills in the third speed zone are achieved in down milling.

References
[1] Kuzmichev V 1987 Laws and formulas of physics Kiev: Scientific opinion 864
[2] Vnukov Yu, Dyadya S, Kozlova Ye, Logominov V and Chernovol N 2017 Chatter in milling thin-walled elements of parts Zaporozhye: ZNTU 208
[3] Svinin V M and Savilov A V 2017 Application of variable teeth pitch face mill as chatter suppression method for non-rigid technological system Conf. Series: Materials Science and Engineering 327
[4] Budak E 2017 An Analytical Design Method for Milling Cutters with Nonconstant Pitch to Increase Stability, Part 1: Theory; Part 2: Application, ASME J. Manuf. Sci. Eng. 125 29–38
[5] Slavicek J 1965 The Effect of Irregular Tooth Pitch on Stability of Milling Proc. 6th MTDR Conference (London: Pergamon Press) 15–22
[6] Opitz H, Dregger E U and Roese H 1966 Improvement of the Dynamic Stability of the Milling Process by Irregular Tooth Pitch Proc. 7th International MTDR Conference (New York: Pergamon Press) 213–227
[7] Suzukia N, Kojimaa T, Hinoa R and Shamotoa A 2012 A Novel Design Method of Irregular Pitch Cutters to Attain Simultaneous Suppression of Multi-Mode Regenerations 3rd CIRP Conference on Process Machine Interactions 98–102
[8] Vanherck P 1965 Increasing Milling Machine Productivity by Use of Cutters with Non-Constant Cutting Edge Pitch *8th MTDR Conference* (Manchester) 947–960

[9] Tlusty J, Ismail F and Zaton W 1983 Use of Special Milling Cutters Against Chatter *Proc. NAMRC* **11** 408–415

[10] Shalamov V 1991 Choice of tooth divergence of cutters, *Progressive technology of finishing and finishing processing coll. of articles* (Chelyabinsk) 14–22

[11] Altintas Y, Engin S and Budak E 1991 Analytical Stability Prediction and Design of Variable Pitch Cutters, *ASME J. Manuf. Sci. Eng.* **121**, 173–178

[12] Shamoto E and Saito A 2016 A novel deep groove machining method utilizing variable-pitch end mill with feed-directional thin support *Precision Engineering* **43** 277–284

[13] Sellmeier V and Denkena B 2011 Stable islands in the stability chart of milling processes due to unequal tooth pitch *International Journal of Machine Tools and Manufacture* **51** (2) 152–164

[14] Svinin V M, Savilov A V, Zarak T V 2018 Self-oscillation regeneration control by irregular tooth pitches. *Advances in Engineering Research: International Conference on Aviamechanical Engineering and Transport (AviaENT 2018)* **158** 399–405

[15] Sims N D, Mann B and Huyanan S 2008 Analytical prediction of chatter stability for variable pitch and variable helix milling tools, *Journal of Sound and Vibration* **317** (3–5) 664–686

[16] Wan M, Zhang W H, Dang J W and Yang Y 2010 A unified stability prediction method for milling process with multiple delays, *International Journal of Machine Tools and Manufacture* **50** (1) 29–41

[17] Yusoff A R and Sims N D 2011 Optimisation of variable helix tool geometry for regenerative chatter mitigation, *International Journal of Machine Tools and Manufacture* **51** (2) 133–141

[18] Dombovari Z and Stepan G 2012 The effect of helix angle variation on milling stability *Journal of Manufacturing Science and Engineering* **134** (5) 661–683

[19] Sims N D 2016 Fast chatter stability prediction for variable helix milling tools *Proceedings of the institution of mechanical engineers, part C. Journal of mechanical engineering science* **230** (1) 133–144 doi: 10.1177/0954406215585367

[20] Dyadya S 2017 Investigation of the formation of the machined surface of a thin-walled part element in end cylindrical milling with chatter *Modern Engineering Technologies* **12** 5–18