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INFLUENCE OF HELICAL CUTTING-EDGE ANGLE ON END-MILLING STABILITY

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Abstract. *Increasing productivity, machining accuracy and efficient use of resources are important priorities for companies that manufacture competitive products. One of the main problems that hinders these processes is the vibration that occurs during cutting. Various methods are used to suppress vibration, one of which is the use of tools with a variable helical cutting-edge angle. However, when choosing the cutting-edge angle, it is important to consider the types of vibrations that occur during cutting, as they directly affect the efficiency of the milling process. In addition, the use of tools with different cutting-edge geometries, such as wavy, gives positive results in roughing, but becomes ineffective in finishing. The purpose of this paper is to study the effect of the helical cutting-edge angle on the stability of the end-milling at different cutting speeds. Both theoretical aspects and experimental data are considered, which make it possible to evaluate the effectiveness of using tools with different angles of inclination to ensure the stability of the machining process and increase productivity while minimizing vibrations in the most unfavorable third speed zone of oscillations for cutting. To conduct the experiments, a special stand was used to adjust the stiffness of the workpiece, record the vibrations that occur during cutting, and the time of contact between the workpiece and the tool. The milling was performed in the third high-speed oscillation zone using a tool whose design provides for the possibility of adjusting the angle of inclination of the helical cutting edge. Studies confirm that changing the angle of inclination can significantly affect the stability of the milling process, reducing the intensity of oscillations and improving machining accuracy. However, this effect depends on the initial cutting conditions, such as the cutting speed. With its increase, the amplitude of the accompanying free oscillations increases, regardless of the value of the angle of inclination. Ensuring the stability of the end-milling in the third speed zone by changing the angle of inclination is possible only at the speeds that determine the beginning of this zone. However, within the entire speed range covered by the third speed zone, it is impossible to ensure a stable milling process only due to the angle of inclination. The study emphasizes the importance of an integrated approach to selecting cutting parameters to achieve process stability.*

Keywords: *milling; milling cutter; thin-walled components; feed rate; oscillogram; accompanying free oscillations.*

1. Introduction

Increasing productivity, machining accuracy, and being economical with all types of resources are the top priorities for companies when manufacturing competitive products. One of the reasons why this is difficult is the vibrations that occur during cutting. Small values of vibrations help to ease chip formation and have a minor impact on surface quality. But such conditions occur at low cutting speeds. With its increase, the intensity of vibrations increases and the cutting process may not be possible. Various measures are used to suppress vibrations. Paper [1] proposes to consider various cutting strategies that increase the rate of material removal without vibrations using the method of structural modification. The authors of [2, 3] propose to use the geometry of the cutting edge with a radius to dampen vibrations during cutting. They found out its effectiveness at low cutting speeds. When milling in the high-speed zone, it is proposed to use a tool with a variable helical cutting-edge angle [4, 5]. For machining the side surfaces of gas turbine impellers, which is accompanied by high cutting forces and vibrations, it is proposed to use variable pitch cutters [6]. At the same time, adaptive control of the cutting force by changing the tool orientation and depth of cut on a 5-axis machine allows it to be maintained at a constant level, which significantly reduces the machining cycle. The use of end mills with wavy grooves [7, 8] increases the stability of the cutting process, but due to their specific profile, they cannot be used for finishing machining.

Researchers S. Tobias and W. Fishwick [11] suggested using lobe diagrams of stability when assigning cutting modes, which would prevent the excitation of regenerative oscillations. The widespread use of carbide cutters in high-speed machining with the use of stability diagrams makes the cutting process highly productive [10]. When determining an unstable milling process, modal analysis is used to calculate the ratio between the frequency of free oscillations of a part and the frequency of forced oscillations [9].

Manufacturers of cutting tools such as LIHSING, DHM, SUMITOMO, NACHREINER, GUHRING, and others take into account the influence of the helical cutting-edge angle on reducing the intensity of vibrations. To ensure the stability of the cutting process when machining carbon, stainless, and hardened steels, they recommend using cutters with a helical cutting-edge angle of 30° to 60°. Cutting modes are also added to this. However, it is recommended to reduce the speed if excessive vibration occurs. According to GOSTs 17025-71 and 17026-71, domestic HSS milling cutters with a normal tooth are manufactured with helical cutting-edge angles of 30° to 35°, and with a large tooth - from 35° to 45°. According to GOST 18372-73, for carbide milling cutters, the helical cutting-edge angle for a number of 3 cutting teeth is 30-40°, and for a number of 4 and 5 teeth it is 30-35°.

In contrast to straight tooth cutter milling cutters, where cutting starts at the smallest layer thickness in counter milling and starts at the largest layer thickness in plunge milling, in helical cutting, when the helical cutting-edge angle is greater than zero, the cutting conditions are reversed and, in any feed direction, cutting starts at the smallest layer thickness to be cut and ends at the smallest layer thickness. Under these favorable conditions, the cutting force changes gradually. The research of A.

M. Rosenberg [12] found that in oblique milling, the normal component of the cutting force differs slightly in magnitude from the circumferential force and depends little on the angle of inclination. The friction force on the front surface of the cutting-edge increases with increasing tilt angle and reaches a significant value at an angle of 70°, which has a positive effect on oscillation damping [12]. However, to ensure the stability of the cutting process using helical cutting-edge angles, it is necessary to take into account the types of oscillations that occur. This issue for end milling is poorly understood. Therefore, the purpose of this work is to determine the effect of the cutting-edge angle on the stability of end milling at different cutting speeds.

2. Experiments and discussion of results

A special stand was used for the experiments, which allows adjusting the stiffness of the part, recording vibrations during cutting, and the time of contact between the part and the tool [12]. Milling was carried out in the third high-speed oscillation zone with a special cutter, the design of which provides for adjusting the angle of inclination of the helical cutting edge [12].

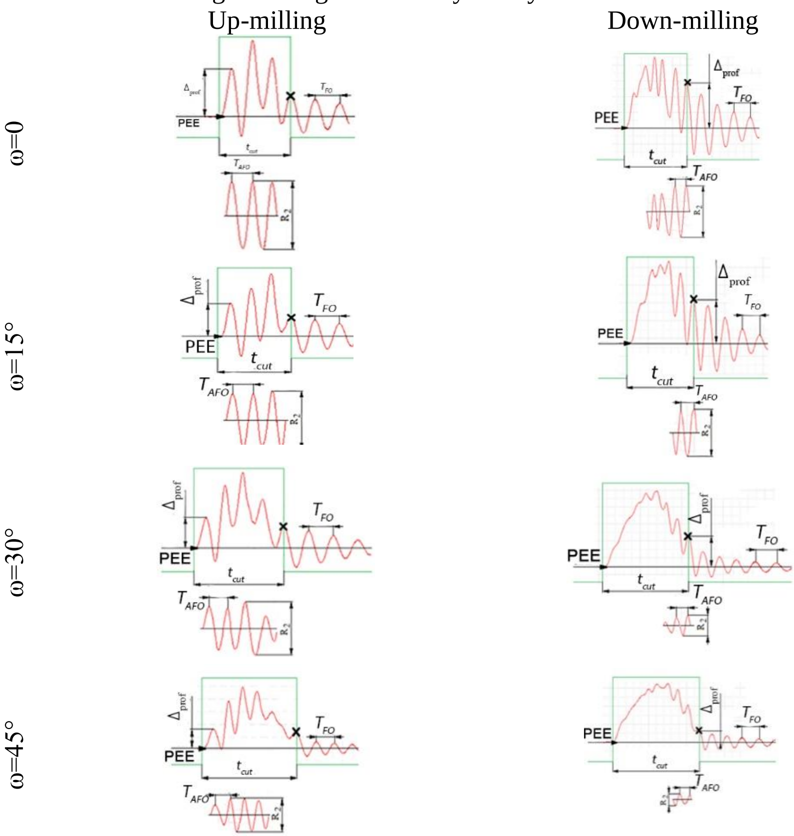
Table 1 shows the initial data for the study.

Table 1. Initial data for the research

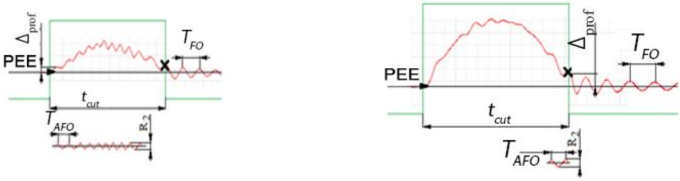
Radial depth of cut a_e, mm	Axial depth of cut a_p, mm	Feed rate S_z, mm/tooth	Angle of inclination of the cutting edge ω, deg	Spindle speed n, rpm (speed, v, m/min)	Cutter diameter D, mm/ number of teeth z	Frequency of free oscillations of the part f_{fo}, Hz	The period of free oscillation of the part, T_{FO},10^{-3} s
0,5	4	0,1	0, 15, 30, 45, 60	280 (44)	50/1	455	2,19

First of all, it should be noted that during end-milling, due to the short cutting time, no self-oscillations occur [13]. Therefore, the main sources affecting tool life and machined surface quality are the accompanying free and forced oscillations. According to the ratio of the cutting time to the period of free oscillations, parts [12] divide the effect of possible oscillations into five speed zones [12]. Since different materials are processed at different cutting speeds, this distribution can be used to determine which types of vibrations need to be counteracted. It should be noted that the effect of these oscillations is a physical manifestation of the system's excitation from the impact when the cutter plunges. While forced vibrations are always present during cutting, the accompanying free oscillations (AFO) are present only for a certain time, until the cutting time is less than the AFO period. It is the third speed zone of oscillations that is the most unfavorable for the accuracy of the machined surface shape, because it is the zone where the waviness from the cutting surface is transferred as a heredity and where the intensity of the AFO is the highest.

Fig. 1 shows fragments of the waveforms obtained during milling according to the initial data given in Table 1. To determine the period and magnitude of the AFO, the waveform was aligned using the Savitsky-Golay filter.



ω=60°



► - cutting into the workpiece, × - exit of the cutter from the workpiece, PEE – position of elastic equilibrium, Δ_{prof} – deviation of the AFO forming wave from the PEE, T_{AFO} – period of accompanying free oscillations of the part, T_{FO} – period of free oscillation of the part, t_{cut} – cutting time

Figure 1 - Fragments of oscillation waveforms of a workpiece during end-milling with cutters with different helical cutting-edge angles

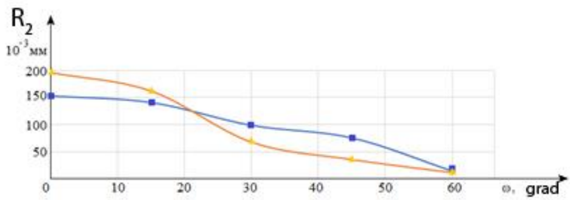
Changing the helical cutting-edge angle ω changes the thickness of the layer to be cut. This affects the properties of the workpiece. With an increase in the angle of inclination during up- and down-milling, the period of the AFO and their span R_2 decrease. Their values are shown in Table 2.

In Fig. 2 and Fig. 3 show graphs of the dependences of the span R_2 and the period of the AFO on the angle of inclination of the angle of inclination the helical cutting edge ω.

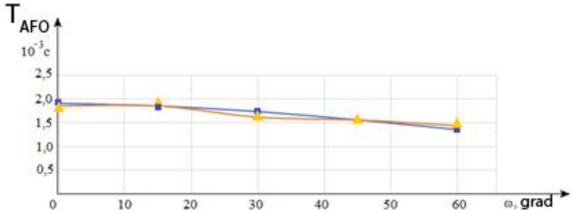
Table 2 – Period and span of the AFO when milling with different angles of inclination of the cutting edge

Feed direction	Span of the AFO R_2, 10^{-3} mm					The period of the AFO T_{AFO}, 10^{-3} s				
	0	15°	30°	45°	60°	0	15°	30°	45°	60°
Up-milling	153	141	99	76	15	1,92	1,86	1,74	1,56	1,35
Down-milling	196	162	68	36	12	1,86	1,86	1,62	1,56	1,44

In Fig. 2 and Fig. 3 show graphs of the dependences of the span R_2 and the period of the AFO on the angle of inclination of the helical cutting edge ω.



■ – up-milling; ▲ – down-milling
Figure 2 – Dependence of the AFO span R_2 on the angle of inclination of the helical cutting edge ω



■ – up-milling; ▲ – down-milling
Figure 3 – Dependence of the period of the AFO on the angle of inclination of the helical cutting edge ω

The correlation coefficient between the AFO span R_2 and of the angle of inclination helical cutting edge ω is (-0.97), which is described by the regression equation:

$$R_2 = -0{,}0023 \cdot \omega + 0{,}165, \text{ (mm)}$$

The correlation coefficient between the period of the AFO and the slope angle ω is (-0.98), which is described by the regression equation:

$$T_{\text{AFO}} = -1 \cdot 10^{-5} \cdot \omega + 0{,}002, \text{ (s)}$$

When milling with a spindle speed of n = 280 rpm (cutting speed v = 44 m/min), the period of the AFO decreases by more than 10 times, or by more than 90%, with an increase in the angle of inclination ω from 0 to 60º. At all values of ω, the period of the AFO is less than the period of free oscillations of the workpiece. In general, it decreases from 12% to 38%. However, provided that the oscillations have a favorable effect on the chip formation process, with an $R_2/2$ amplitude of up to 20 microns, stable milling will occur only when ω is greater than 60º for counter milling and greater than 45º for down milling.

When using the angle of inclination to ensure stable milling, it should be remembered that the intensity of the AFO depends on the initial cutting speed. In Fig. 4 shows fragments of the oscillation waveforms of a workpiece during end-milling with an inclination angle of ω = 60º at a spindle speed of n = 710 rpm (cutting speed of v = 111 m/min).

Up-milling Down-milling

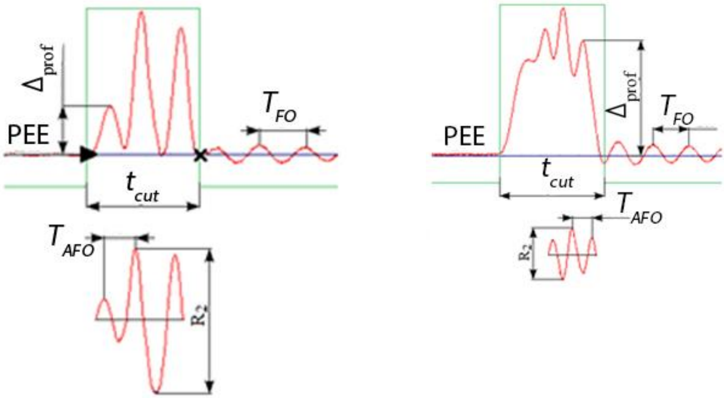


Figure 4 – Fragments of workpiece vibration waveforms during milling at a spindle speed of n = 710 rpm

Table 3 shows the values of the swing and period of the AFO when milling at a speed of v = 111 m/min with a cutter with an inclination angle of ω = 60º.

With a 2.5-fold increase in cutting speed, the AFO span during up-milling increases 11 times, and during down-milling it increases 7 times. That is, the process of milling with an end-mill with an inclination angle of ω = 60º in third speed zone of oscillations becomes unstable.

Table 3 – Period and span of the AFO during up- and down-milling at a cutting speed of v = 111 m/min with a cutter with an inclination angle of ω = 60º

Feed direction	Span of the AFO R_2, 10^{-3} mm	The period of the AFO T_{AFO}, 10^{-3} s
Up-milling	175	1,44
Down-milling	81	1,26

3. Conclusions

The study of the influence of the inclination angle ω on the stability of end-milling shows that third speed zone of oscillations, where AFOs operate, the cutting speed plays an important role. An increase in the angle has a positive effect on reducing the intensity of the AFOs. But it depends on the initial conditions, which include the cutting speed. With its increase, the AFO amplitude increases. Ensuring the stability of end-milling in the third speed zone due to the angle of inclination ω is possible at cutting speeds that determine the beginning of this zone. But in the entire range of cutting speeds covering the third speed zone, it is impossible to ensure stable cutting due to the angle of inclination ω.

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ВПЛИВ КУТА НАХИЛУ ГВИНТОВОЇ РІЗАЛЬНОЇ КРАЙКИ НА СТАЛІСТЬ КІНЦЕВОГО ФРЕЗЕРУВАННЯ

Анотація. *Підвищення продуктивності, точності обробки та ефективне використання ресурсів є важливими пріоритетами для підприємств, що займаються виготовленням конкурентоспроможної продукції. Однією з основних проблем, що стримує ці процеси, є вібрації, які виникають під час різання. Невеликі коливання мають незначний вплив на якість поверхні деталі, однак, із збільшенням швидкості різання інтенсивність вібрацій зростає, що призводить до зниження точності обробки. Для пригнічення вібрації використовують різні методи, одним з яких є використання інструментів зі змінним кутом нахилу гвинтової різальної крайки. Ці інструменти сприяють зменшенню амплітуди коливань, особливо при високих швидкостях різання. У роботах, що присвячені даній темі, пропонуються різні стратегії, які дозволяють підвищити швидкість видалення матеріалу без виникнення вібрацій за допомогою методів структурної модифікації. Однак при виборі кута нахилу різальної крайки важливо враховувати типи коливань, що виникають під час різання, оскільки вони безпосередньо впливають на ефективність процесу фрезерування. Крім того, використання інструментів з різними* *геометріями різальної крайки, як, наприклад, з хвилеподібною формою, дає позитивні результати при чорновій обробці, але при оздоблювальній стає неефективним. Метою цієї роботи є дослідження впливу кута нахилу гвинтової різальної крайки на сталість кінцевого фрезерування при різних швидкостях різання. Розглядаються як теоретичні аспекти, так і експериментальні дані, що дають можливість оцінити ефективність застосування інструментів з різними кутами нахилу для забезпечення стабільності процесу обробки та підвищення продуктивності при мінімізації вібрацій в найбільш несприятливій для різання третій швидкісній зоні коливань. Для проведення експериментів використовувався спеціальний стенд, який дозволяє регулювати жорсткість деталі, записувати коливання, що виникають під час різання, та час контакту деталі з інструментом. Фрезерування проводилося в третій швидкісній зоні коливань за допомогою інструменту, конструкція якого передбачає можливість регулювання кута нахилу гвинтової різальної крайки. Дослідження підтверджують, що зміна кута нахилу може суттєво впливати на стабільність процесу фрезерування, знижуючи інтенсивність коливань і покращуючи точність обробки. Але цей ефект залежить від початкових умов різання, таких як швидкість різання. З її збільшенням амплітуда супроводжуючих вільних коливань зростає, незважаючи на величину кута нахилу. Забезпечення сталості кінцевого фрезерування в третій швидкісній зоні за рахунок зміни кута нахилу можливе лише при швидкостях, що визначають початок цієї зони. Однак, в межах всього діапазону швидкостей, що охоплює третя швидкісна зона, забезпечити стабільний процес фрезерування тільки за рахунок кута нахилу неможливо. Дослідження підкреслює важливість комплексного підходу до вибору параметрів різання для досягнення стабільності процесу.*

Ключові слова: *фрезерування; фреза; тонкостінний елемент; напрям подачі; осцилограма; супроводжуючі вільні коливання.*