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INFLUENCE OF RADIAL DEPTH OF CUT ON INITIAL CONDITIONS OF OSCILLATIONS DURING END-MILLING OF THIN-WALLED PARTS

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Abstract. *Milling is widely used in mechanical engineering and other industries. Optimization of this process can lead to improved quality of machined parts, increased productivity and reduced wear of equipment. The paper investigates an important aspect of the milling process, namely the influence of radial depth of cut on the properties of the tool-part technological system (TS) and the amplitude of vibrations during machining. Vibrations can be a direct cause of reduction of quality and accuracy of machined parts. When the amplitude of vibrations increases, their impact on accuracy becomes critical. The analysis of studies of up and down end-milling with different radial depths of cut in the third speed zone of oscillations shows that with increasing radial depth of cut the cutting time and maximum thickness of the cut layer increases. This affects the length of the cutting surface and the character of the workpiece oscillations during up and down-milling. The length of the cutting surface determines how many waves of accompanying free oscillations of the TS and with what intensity will leave their trace on the cutting surface. In up-milling, the thickness of the cut layer increases with increasing radial depth of cut, while the amplitude of the accompanying free oscillations TS and their period decrease. At down milling the thickness of the cut layer decreases, and the amplitude of accompanying free oscillations of the TS and their period increase. A common characteristic feature of up and down-milling is the shaping of the machined surface in the cutting zone with a small thickness of the cut layer. In up-milling, this area is at the beginning of cutting, when the oscillation conditions are the same for all radial cutting depths. Therefore, the machined surfaces after up-milling with different radial cutting depths have close values of pitch and undulation height. At down-milling with increasing radial depth of cut, the amplitude of accompanying free oscillations of the TS in the profiling zone increases. This leads to an increase in the pitch and height of undulations on the machined surface. When milling in the third speed oscillation zone, it is necessary to select the radial depth of cut so that the cutting time is less than the period of the accompanying free oscillations of the TS. This will avoid undesirable oscillations and improve the quality of machining. The paper provides important results and recommendations for optimizing the milling process, considering the influence of radial depth of cut on TS properties and vibration amplitude. These findings may be useful for professionals working in the field of cutting materials processing to improve the efficiency and quality of production processes.*

Keywords: *milling; up and down-feed; radial depth of cut; accompanying free oscillations of the technological system; cutting time; thickness of the cut layer.*

1. INTRODUCTION

Ensuring accuracy and productivity in the production of workpieces are the main tasks of machine-building companies. At the same time, the main focus is on preventing the causes that adversely affect them.

One of these causes is cutting vibrations. At small vibration amplitudes they are not taken into account when selecting cutting modes and tool geometry. At large vibration amplitudes their influence on accuracy becomes decisive. Various methods are used to control vibration intensity. In heavy milling, the machine's own drives are used to suppress vibrations. They are controlled based on signals received from an external accelerometer located near the centre point of the tool. The measured acceleration is fed back to an additional control loop to regulate cutting speed and feed rate [1]. In multiaxial milling of hollow fan blades, the vibration stability of the tool depends on its motion. The use of optimization of cutting parameters on the basis of a single-line motion makes it possible to analyses the dynamic responses to different positions of the tool cutting edge and to select stable milling areas [2, 3]. Machining on the previous tool track leads to regenerative chatter. To break them, cutters with different geometries are used. Milling cutters with variable pitch create a phase shift of the current oscillation trajectory of the workpiece during cutting relative to the trace on the cutting surface from the previous cut [4 – 6]. But depending on the milling process, they can perform worse than milling cutters with a uniform pitch. Improved performance of variable-pitch milling cutters can be guaranteed by taking into account the reflected dynamic behaviour of the machine-tool-workpiece system. Cutter behaviour is tuned along stability margins at selected spindle speed ranges [7].

2. EXPERIMENTS AND DISCUSSION OF RESULTS

The studies focus on the effects of free oscillations, forced oscillations and self-oscillations [8]. The latter have the greatest impact on machining accuracy and tool life. But in [9] it is shown that at small cutting time in the process of end milling self-oscillations do not occur. In this case, the accompanying free oscillations of the TS "tool - workpiece". As free oscillations, they depend on the properties of the TS and, unlike self-oscillations, on the initial conditions. In milling, the properties of the TS and the initial conditions of oscillations depend on cutting modes and tool geometry.

This paper presents the results of research into the influence of radial depth of cut on the accompanying free oscillations of the TS during up and down end-milling of a thin-walled part. Cutting at these feed directions is performed according to two fundamentally different schemes. But in both cases the thickness of the cut layer is variable (Fig. 1). In up-milling, it increases from the tool plunge until it leaves the workpiece (Fig. 1, a). In down milling, it decreases from the tool plunge until it leaves the workpiece (Fig. 1, b) [10].

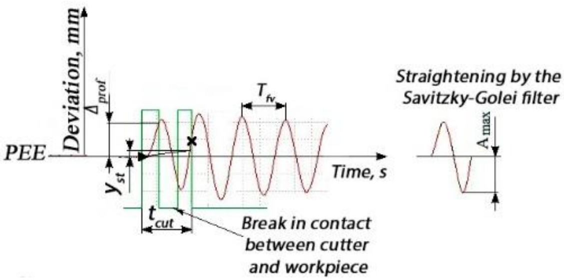
Figure 1 - Cutting patterns for up (a) and down (b) end-milling [10]
a_e – radial cutting depth; $a_{\max}$ – maximum thickness of the layer to be cut; S_z - feed per tooth

The studies were carried out on an experimental bench [11] when milling a St. 3 sample with a single-tooth carbide milling cutter ∅54 мм. Axial depth of cut – a_p = 4 mm, feed per tooth – S_z = 0,1 mm/tooth, spindle speed – n = 280 rpm, radial cutting depth – a_e = 0.1; 0.3; 0.5 mm. Stiffness of thin-walled plate – j_{pl} = $2{,}98 \cdot 10^6$ N/m, free oscillation frequency – f_{fo} = 512 Hz. Free oscillation frequency of the cutter – f_{fr} = 1315 Hz, cutter stiffness – $j_{fr} = 34 \cdot 10^6$ N/m.

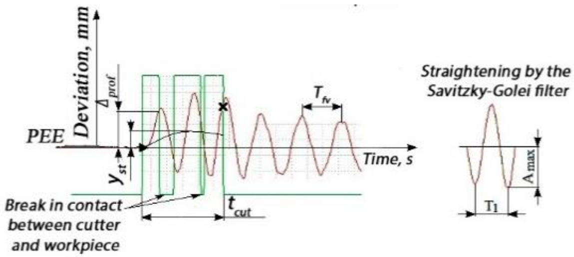
Cutting speed v = 47 m/min (n = 280 rpm) is recommended when machining difficult-to-machine materials. These materials are used to produce aircraft engine parts. This speed falls into the third speed zone of oscillations [11], in which the intensity of oscillations is high. Milling in this zone was chosen to better illustrate the effect of radial depth of cut on the vibration amplitude and properties of the TS.

During the experiments, oscillograms of oscillations of the thin-walled part and profilograms of the machined surfaces were recorded. They are shown in Fig. 2 – 5. The oscillogram fragments and profilograms were used to determine the parameters of oscillations of the workpiece during cutting, pitch and height of undulations on the machined surface. When determining the period and amplitude of the accompanying free oscillations, the Savitsky-Goley filter was used to straighten the oscillogram fragment.

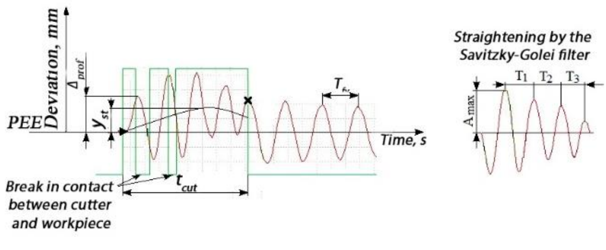
The oscillograms of the oscillations of the workpiece using the electro-contact device showed areas of contact breakage during cutting and the absence of friction between the cutter and the specimen.



a_e = 0.1 mm
a



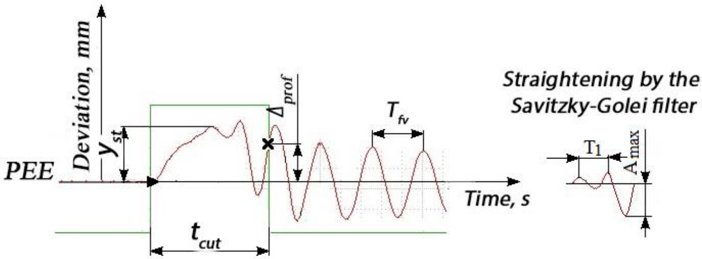
a_e = 0.3 mm
b



a_e = 0.5 mm
c

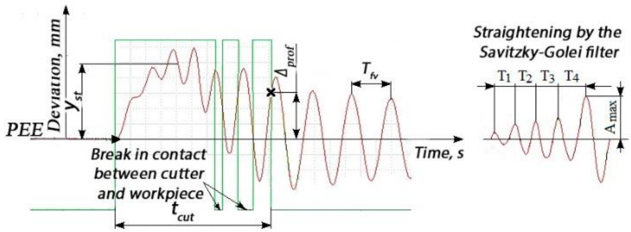
Figure 2 - Fragments of oscillograms of workpiece oscillations during up milling with different radial depth of cut.

► - tool plunging; x – tool exit from the workpiece; PEE - position elastic equilibrium of the part; A_{max} – maximum amplitude of the accompanying free vibrations of the workpiece when cutting; t_{cut} - cutting time; y_{st} – static deflection of the workpiece from the radial component of the cutting force P_y; T_{fv}- free vibration period of the part; T_1, T_2, T_3 – periods of accompanying free oscillations of the TS, Δ_{prof} – deviation from the PEE of the first wave of accompanying free oscillations during counter milling



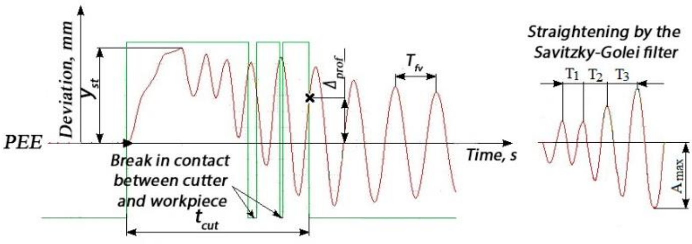
a_e = 0.1 mm

a



a_e = 0,3 mm

b

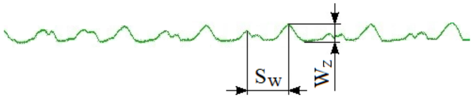


a_e = 0,5 mm

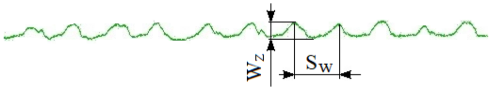
c

Figure 3 - Fragments of oscillograms of workpiece oscillations during down milling with different radial depth of cut

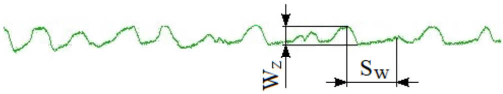
Δ_{prof} – deviation from the elastic equilibrium position of the last wave of accompanying free oscillations during down milling



a_e = 0.1 mm
a

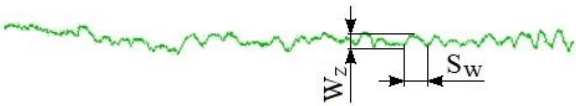


a_e = 0.3 mm
b

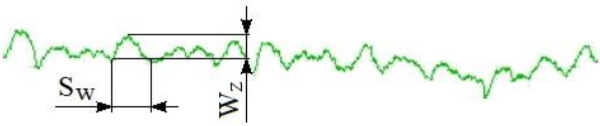


a_e = 0.5 mm
c)

Figure 4 - Profilograms of machined surfaces after up milling with different radial depth of cut
S_w – waviness pitch; W_z – waviness height



a_e = 0.1 mm
a



a_e = 0.3 mm
b

a_e = 0.5 mm
c

Figure 5 - Profilograms of machined surfaces after down milling with different radial depth of cut

Tables 1-3 show the values of parameters of workpiece oscillations during cutting, pitch and height of undulations of machined surfaces after up and down milling.

Table 1- Measurement results of oscillogram fragments after up milling

a_e, mm	t_{cut}, 10^{-3} s	y_{st}, mm	A_{max}, mm	Δ_{prof}, mm	T_{fv}, 10^{-3} s/ f_{fv}, Hz	T_1, 10^{-3} s/ f_{fv}, Hz	T_2, 10^{-3} s/ f_{fv}, Hz	T_3, 10^{-3} s/ f_{fv}, Hz
0,1	2,2	0,009	0,065	0,061	1,95/512	-	-	-
0,3	4,12	0,026	0,076	0,070	1,95/512	1,72/581	-	-
0,5	7,0	0,042	0,086	0,068	1,95/512	1,6/625	1,6/625	1,28/781

Table 2 - Measurement results of oscillogram fragments after down milling

a_e, mm	t_{cut}, 10^{-3} s	y_{st}, mm	A_{max}, mm	Δ_{prof}, mm	T_{fv}, 10^{-3} s/ f_{fv}, Hz	T_1, 10^{-3} s/ f_{fv}, Hz	T_2, 10^{-3} s/ f_{fv}, Hz	T_3, 10^{-3} s/ f_{fv}, Hz	T_4, 10^{-3} s/ f_{fv}, Hz
0,1	4,68	0,084	0,051	0,055	1,95/512	1,12/892	-	-	-
0,3	8,04	0,144	0,101	0,088	1,95/512	1,08/925	1,12/892	1,48/675	1,68/595
0,5	9,24	0,181	0,122	0,099	1,95/512	1,04/961	1,2/833	1,52/657	-

Table 3 - Step and height of undulations of the machined surface after up and down milling

a_e, mm	Feeding direction			
	Up milling		Down milling	
	S_w	W_z	S_w	W_z
0,1	2,05	0,065	0,61	0,036
0,3	2,13	0,061	0,94	0,075
0,5	2,13	0,066	1,27	0,102

In end milling, the thickness of the cut layer is determined by the feed rate on the tool tooth. Its maximum thickness depends on the radial depth of cut (Fig. 6).

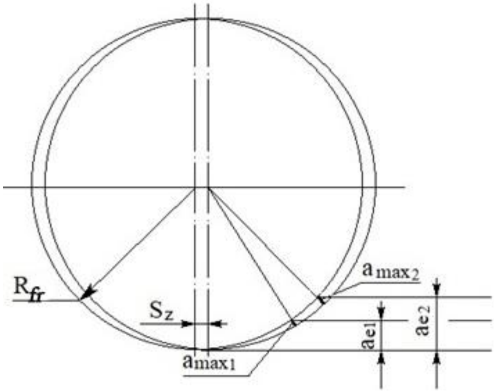


Figure 6 - Maximum thickness of the cut layer – a_{max} at different radial cutting depths – a_e

S_z - feed rate per cutter tooth; R_{fr} – cutter radius; a_{max1} – maximum thickness of the cut layer at cutting depth a_{e1}; a_{max2} – maximum thickness of the cut layer at cutting depth a_{e2}

Fragments of oscillograms shown in Fig. 2–3 show that the effect of radial depth of cut on the cutting process is related to cutting time.

When cutting with a radial depth of a_e = 0.1 mm, the oscillogram fragment for counter milling (Fig. 2, a) shows oscillations that have no period due to the short cutting time. At down milling with the same cutting depth, oscillations that have a period are recorded on the oscillogram fragment (Fig. 3, a). In this case, the amplitude of oscillations is smaller than in up milling due to the start of cutting from the greatest thickness of the cut layer.

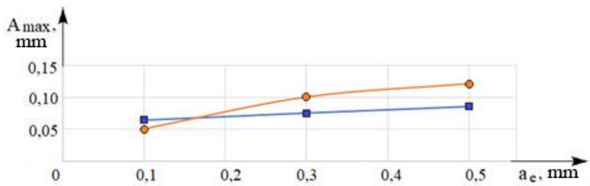
When cutting with a radial depth of a_e = 0.3 mm, the cutting time increases and on the fragment of the oscillogram during up milling (Fig. 2, b), the accompanying free oscillations of the TS have a period. At the same time, the maximum thickness of the cut layer is insufficient to damp the oscillations. Therefore, their amplitude increases. At down milling with the same cutting depth, the number of waves accompanying free oscillations and their amplitude increase in the fragment of the oscillogram (Fig. 3, b). The period of these oscillations is shorter during down milling than during up milling.

During the cutting time with radial depth of a_e = 0.5 mm at up milling there is an increase in the amplitude of accompanying free oscillations of the TS at minimum thickness of the cut layer and its subsequent decrease with increasing thickness of the cut layer (Fig. 2, c). The period of accompanying free vibrations is also variable when milling with variable thickness of the cut layer. It decreases as the thickness of the layer to be cut increases. At down milling with a radial cutting depth of a_e = 0.5 mm, the maximum thickness of the cut layer increases and in the fragment of the oscillogram (Fig. 3, c) the accompanying oscillations of the TS start later than at cutting with a depth of a_e = 0.3 mm. When the thickness of the sheared layer decreases, the amplitude of the accompanying free oscillations increases and negative damping is observed, when the amplitude A of the accompanying free oscillations of the TS increases according to the exponential law [12]:

$$A = A_0 e^{\beta t} \cos(\omega t + \varphi_0), \quad (1)$$

where A_0 – initial amplitude;
β – attenuation factor;
ω - cyclic frequency;
φ_0 - initial phase of oscillation.

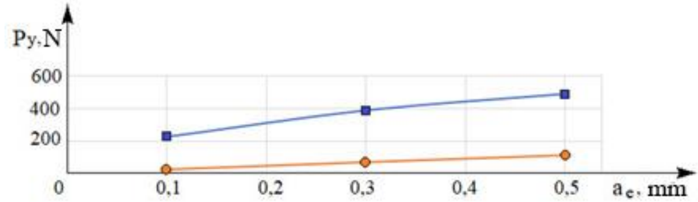
Fig. 7 shows the graphs of dependence of the maximum amplitude of accompanying free oscillations of the TS during up and down milling on the radial depth of cut.



● – maximum amplitude of accompanying free oscillations of the TS during down milling;
■ – maximum amplitude of accompanying free oscillations of the TS during up milling;

Figure 7 - Effect of radial depth of cut – a_e on the maximum amplitude of the accompanying free vibrations TS A_{max}

In addition to the influence on the character of accompanying free oscillations of the TS during up and down milling, the radial depth of cut affects the elastic pushback of the workpiece associated with the action of the radial component of the cutting force P_y (Fig. 8). It is greater in down milling, when cutting starts from the greatest thickness of the layer to be cut.



● - radial component of cutting force during up milling;
■ - radial component of cutting force during cross milling.

Figure 8 - Effect of radial depth of cut – a_e on the radial component of the cutting force P_y

Different cutting schemes for up milling and down milling affect the properties of the tool-piece technological system. The stiffness of the tool-piece system is higher in down milling than in counter-cut milling. Therefore, the oscillation periods of the workpiece during down milling are shorter than during up milling. The number of waves on the cutting surface is greater in down milling than in up milling.

Despite the above mentioned differences in the cutting process during up milling and down milling, there is one common feature between them. In both cases, the shaping zone of the machined surface is located in the cutting area with the minimum thickness of the cut layer.

In up milling, the depth of the forming depression is determined by the deviation from the elastic equilibrium position (PEE) of the first wave of the accompanying free oscillations TS – Δ_{prof}. It has close values when milling with different radial depths of cut. Therefore, machined surfaces after up milling with different radial depths of cut have similar values of S_w pitch and W_z waviness height.

At down milling, the depth of the forming depression is determined by the deviation from the PEE last wave of the accompanying free oscillations of the TS – Δ_{prof}. Increasing the amplitude of accompanying free oscillations at the section with minimum thickness of the cut layer with increasing radial depth of cut increases the value of Δ_{prof}. Therefore as the radial depth of cut increases the pitch S_w and the waviness height W_z of the machined surface increase during down milling.

3. CONCLUSIONS

The performed studies show that the influence of radial cutting depth on the properties of the technological system "tool-piece" and the amplitude of accompanying free oscillations of the TS is related to the cutting time and the maximum thickness of the cut layer, which increase with increasing radial depth. At down milling it affects the time of occurrence of accompanying free oscillations of the TS and their amplitude, which increases according to the exponential law. At up milling, the amplitude of accompanying free oscillations of the TS at the beginning of cutting with a small thickness of the cut layer increases, but with increasing thickness of the cut layer it decreases.

Differences in the character of cutting vibrations are related to the variable thickness of the cut layer and different cutting patterns in up and down milling.

The common characteristic feature of up and down milling is the shaping of the machined surface in the cutting area with the minimum thickness of the cut layer. In up milling, the oscillations at the beginning of cutting at different radial cutting depths occur under the same conditions. Therefore, the pitch and height of the waviness on the machined surface have close values. In down milling, the amplitude of the accompanying free oscillations of the TS at the tool exit increases with increasing radial depth of cut. Therefore, with increasing radial depth of cut, the pitch and height of waviness on the machined surface increases after down milling.

When milling in the third speed zone of oscillations, the radial depth of cut should be chosen so that the cutting time is less than the period of the accompanying free oscillations of the TS in order to eliminate the negative effect of oscillations on the machined surface.

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ВПЛИВ РАДІАЛЬНОЇ ГЛИБИНИ РІЗАННЯ НА ПОЧАТКОВІ УМОВИ ВИНИКНЕННЯ КОЛИВАНЬ ПІД ЧАС КІНЦЕВОГО ФРЕЗЕРУВАННЯ ТОНКОСТІННИХ ДЕТАЛЕЙ

Анотація. *Фрезерування широко застосовується в машинобудуванні та інших галузях промисловості. Оптимізація цього процесу може призвести до поліпшення якості оброблених деталей, підвищення продуктивності та зниження зносу обладнання. У статті досліджується важливий аспект процесу фрезерування, а саме вплив радіальної глибини різання на властивості технологічної системи «інструмент – деталь» (ТС) та амплітуду коливань у процесі обробки. Вібрації можуть бути безпосередньою причиною зниження якості та точності оброблених деталей. При зростанні амплітуди коливань їхній вплив на точність стає критичним. Виконаний аналіз досліджень зустрічного і попутного кінцевого фрезерування з різними радіальними глибинами різання в третій швидкісній зоні коливань показує, що зі збільшенням радіальної глибини різання збільшується час різання і максимальна товщина шару, що зрізається. Це впливає на довжину поверхні різання і характер коливань деталі під час зустрічного і попутного фрезерування. Від довжини поверхні різання залежить, скільки хвиль супроводжувальних вільних коливань ТС і з якою інтенсивністю залишать свій слід на поверхні різання. Під час зустрічного фрезерування зі збільшенням радіальної глибини різання товщина шару, що зрізається, збільшується, а амплітуда супроводжуючих вільних коливань ТС і їхній період зменшуються. При попутному фрезеруванні товщина шару, що зрізається, зменшується, а амплітуда супроводжуючих вільних коливань ТС і їхній період збільшуються. Загальною характерною особливістю зустрічного і попутного фрезерування є формоутворення обробленої поверхні в зоні різання з малою товщиною шару, що зрізається. При зустрічному фрезеруванні ця ділянка припадає на початок різання, коли умови коливання однакові для всіх радіальних глибин різання. Тому оброблені поверхні після зустрічного фрезерування з різними радіальними глибинами різання мають близькі значення кроку і висоти хвилястості. При попутному фрезеруванні зі збільшенням радіальної глибини різання збільшується амплітуда супроводжуючих вільних коливань ТС у зоні профілювання. Це призводить до збільшення кроку і висоти хвилястості на обробленій поверхні. Під час фрезерування в третій швидкісній зоні коливань необхідно підбирати радіальну глибину різання так, щоб час різання був меншим за період супроводжуючих вільних коливань ТС. Це дасть змогу уникнути небажаних коливань і поліпшити якість обробки. Стаття надає важливі результати та рекомендації для оптимізації процесу фрезерування, враховуючи вплив радіальної глибини різання на властивості ТС та амплітуду коливань. Ці висновки можуть бути корисними для фахівців, які працюють у галузі обробки матеріалів різання, для підвищення ефективності та якості виробничих процесів.*

Ключові слова: *фрезерування; зустрічна і попутна подача; радіальна глибина різання; супроводжуючі вільні коливання технологічної системи; час різання; товщина шару, що зрізається.*