UDC 621.914.22 **doi: 10.20998/2078-7405.2022.97.03**

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CAUSES OF DIFFERENT WAVES OF MACHINED SURFACES AFTER UP AND DOWN END-MILLING

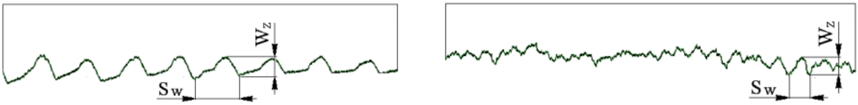
Abstract. *In modern industry, among the methods of surface treatment is widely used end-milling. Under certain conditions of its use there are self-oscillations, which significantly affect the quality of the treated surface. Various techniques are used to study this influence, in particular, the comparison of the basic fragments of the oscillogram obtained by cutting with the treated surface. It is established that it is formed by the first and last wave of self-oscillations during up and down milling, respectively. But depending on the direction of feed step and the height of the waviness on it have different meanings. Therefore, it is important to determine the reasons that lead to this result. This paper considers the features of each direction of supply that affect the formation of the treated surface. When superimposing fragments of the oscillogram obtained by up milling, it is seen that the deviation of the first wave of self-oscillations from the position of elastic equilibrium starts from the point of incision of the cutter in the part. Therefore, the pitch of the wave on the treated surface depends on the feed and the number of cuts required to cut the first protrusion on the cutting surface. The paper presents a formula for determining the length of the base of this speech. When using it, the discrepancy between the calculated wave step on the treated surface and the measured one does not exceed 4%. In the case of down milling, the last section with waviness on the cutting surface, which is cut and affects the shape of the treated surface, has a shorter base length than the opposite. This is the first reason why the pitch of the wave in the down milling is smaller than in the up. Also at formation of wave on the processed surface at down milling the feature in the form of shift on a phase of waves of self-oscillations on each following cut is observed. This increases the cutting time and the length of the cutting surface. Each subsequent forming depression is shifted towards the treated surface with a decrease in its deviation from the position of elastic equilibrium. However, the phase shift direction is opposite to the feed direction. This is the second reason why the pitch of the wave on the machined surface after the down milling is less than after the up. The calculation of the step of the wave of the treated surface after the down milling according to the results of the study of fragments of oscillograms shows that the error does not exceed 12% compared to the measured one.*
Keywords: *milling; self-oscillation; waviness; pitch; height; cutting surface.*

1. INTRODUCTION

To control the accuracy of machining on metal-cutting machines, it is necessary to know the mechanism for the formation of a machined surface. The results of research in this direction are reflected in publications [1-6, etc.]. For cylindrical end-milling, it is known that the machined surface is formed by sections of the cutting surface that are not sheared after the feed motion.

2. EXPERIMENTS AND DISCUSSION OF RESULTS

Depending on the speed zone of oscillations [7] and the feed direction, the machined surfaces have distinctive features. The presence of waviness on it is typical for milling in the third high-speed zone. However, in it, with the same milling modes, the step Sw and the height Wz of the waviness with counter feed are greater than with the associated one (Fig. 1).



a b

Figure 1 – Profile of machined surfaces after up (a) and down (b) milling

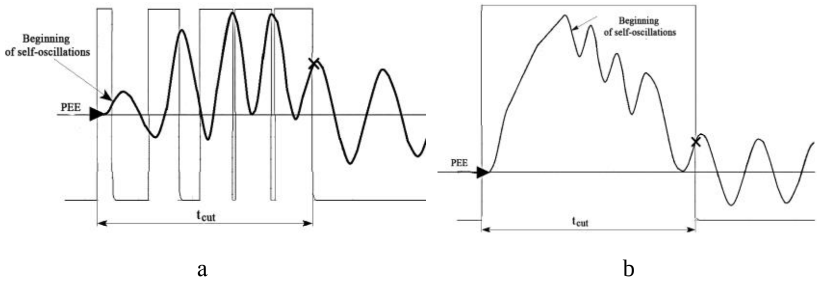
This is confirmed by their values given in table 1. They were obtained after milling samples of Steel 3 on a special stand [8] at a spindle speed n = 280 rpm, a radial depth a_e = 0.5 mm, an axial cutting depth a_p = 3 mm, feed per tooth S_z = 0.1 mm with a single-tooth carbide cutter ∅50 mm.

Table 1 – Step and height of waviness after up and down milling

Feed direction	Waviness step, S_w, mm	Waviness height, W_z, mm
Up milling	2,6	0,103
Down milling	1,08	0,075

The height of the waviness after down milling is 1.37 times, and the step of waviness is 2.4 times less than after the down milling. It was shown in [9-11] that during down milling, the deviations from the position of elastic equilibrium (PEE) on the last wave of self-oscillations, which form the height of waviness on the machined surface, are less than the deviations from PEE on the first wave of self-oscillations during up milling. This explains the differences in waviness heights for different feed directions. To explain the differences in the pitch of the waviness, it is necessary to consider the features of each feed direction during milling.

First of all, it should be noted that up and down milling takes place under different cutting conditions. With up milling, cutting begins with the smallest thickness of the cut layer, with associated milling - with the largest. When milling with self-oscillations, this feature is reflected in the beginning of their occurrence. In up milling, self-oscillations begin immediately after the cutter cuts in, while in down milling, after a certain time, when the thickness of the cut layer decreases (Fig. 2).



► – inserting a cutter into a workpiece; ×– exit of the cutter from the part;
$t_{рез}$ – cutting time, PEE – position of elastic equilibrium

Figure 2 – Fragments of oscillograms obtained during up (a) and down (b) milling

This feature in both feed directions affects the fact that the profiling zone of the machined surface is always subject to self-oscillations. With up milling, it is formed on the first wave of self-oscillations, with down milling, on the last wave of self-oscillations. A wavy profile on the machined surface is obtained in the form of heredity after cutting off the protrusions on the cutting surface [9-11]. In up milling during the feed movement, the sheared protrusion increases the thickness of the sheared layer and reduces the deviation from the PEE on the first wave of self-oscillations. On Figure 3 shows the overlay of successive fragments of oscillograms that form one wave on the machined surface (for better clarity, fragments of 1, 5, 10, 15, 20, 25 and 27 cuts are shown out of 27 fragments of oscillograms).

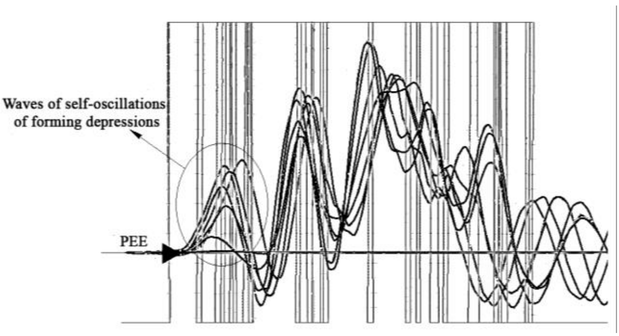


Figure 3 – Overlay of fragments of oscillograms after up and down milling

From Figure 3 shows that all deviations from the PEE of the first wave of self-oscillations start from the point of entry. This means that the step of waviness on the machined surface is formed during the feed movement and cutting off the first protrusion on the cutting surface. The length of the base of the protrusion – L can be calculated by the formula:

$$L = \frac{\pi dnt}{60}, \quad (1)$$

where d – the cutter diameter, mm;

n – spindle speed, rpm;

t – the time from the plunge of the tool into the part and to the cavity behind the first ledge, determined from the oscillogram.

In ongoing research for up milling $t = 3.6\cdot10^{-3}$s. Therefore, the sheared protrusion on the cutting surface will have a base length $L = 2.63$ mm. When applied to the tooth $S_z = 0.1$ mm, to cut it, you will need 27 cuts and the step of the waviness will be equal to $S_w = 2.7$ mm, which is close to the measured value. The error between the calculated and measured waviness pitch does not exceed 4%.

In contrast to up-and-down milling, the machined surface is formed at the exit of the cutter. Here, the cut off wavy section of the cutting surface has a shorter base length than with the opposite one. Its length can be calculated by formula (1) based on the time t determined from the last wave of self-oscillations on the down milling waveform. In ongoing research $t = 1.32\cdot10^{-3}$ s. In this case, the calculated length of the cut section will be equal to $L = 0.96$ mm. Removing it will require fewer cuts. This is one of the reasons why the undulation pitch is smaller in up milling than in down milling. It should also be noted that the period of self-oscillations during up milling is longer than during down milling (in the ongoing studies, $1.75\cdot10^{-3}$ s (571 Hz) and $1.52\cdot10^{-3}$ s (657 Hz), respectively). When waviness is formed on the machined surface after down milling, a feature appears in the form of a phase shift – $\Delta\varphi_{1-2}$ self-oscillation waves on each subsequent cut (Fig. 4).

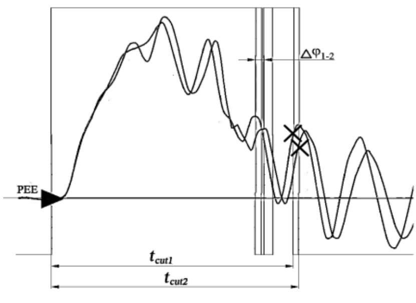
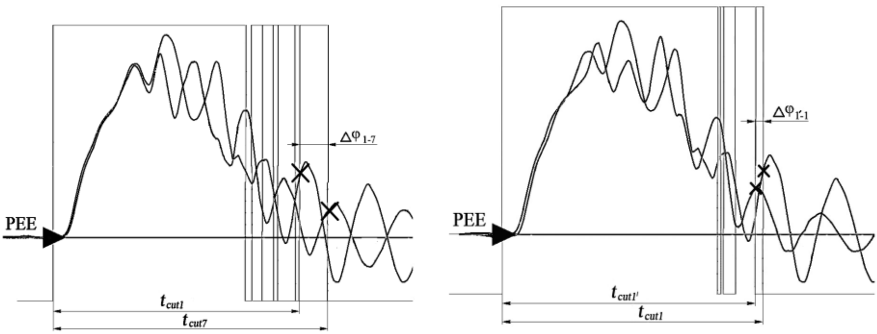


Figure 4 – Phase shift of self-oscillation waves during down milling $\Delta\varphi_{1-2}$ on the subsequent cut

This leads to an increase in cutting time and the length of the cutting surface. Each subsequent shaping cavity is displaced towards the machined surface with a decrease in its deviation from the PEE. Seventh cut with longest cutting time t_{cut7} (Fig. 5 a), cuts the valley closest to the PEE. It will be one of the peaks of the waviness on the treated surface. The phase shift between cuts had the following values: $\Delta\varphi_{1-2}$ = 0.175 mm, $\Delta\varphi_{2-3}$ = 0.117 mm, $\Delta\varphi_{3-4}$ = 0.087 mm, $\Delta\varphi_{4-5}$ = 0.204 mm, $\Delta\varphi_{5-6}$ = 0.2 mm, $\Delta\varphi_{6-7}$ = 0.2 mm. Total shift $\Delta\varphi_{1-7}$ = 0.983 mm (Fig. 5 a). In down milling, the direction of feed is opposite to the direction of the phase shift. Therefore, the actual distance between the first and seventh depressions remaining on the machined surface when feeding S_z = 0.1 mm/tooth will be equal to 0.383 mm. The presence of a phase shift in the direction opposite to the feed is the second reason why the step of waviness in down milling is smaller than in up milling. It should also be noted that the depressions from the first to the seventh cut form only half of the waviness pitch. After cutting off the last protrusion from the cutting surface, subsequent cutting begins the formation of the second half of the waviness step.



a b

Figure 5 – Overlay of fragments of oscillograms after down milling

During the previous cuts during the feed movement, the workpiece moved by 0.7 mm. The new largest cavity in the machined surface left from the cutting surface formed over time $t_{cut1'} = 8.3\cdot10^{-3}$ s, will be at a distance of 0.95 mm from the previous largest cavity left from the cutting surface formed during cutting $t_{cut1} = 8.64\cdot10^{-3}$ s (Fig. 5 b). After that, cutting with a phase shift begins and the formation of a new waviness height. With three cuts and a total shift of 0.6 mm, the calculated waviness pitch will be 0.96 mm. The error between the calculated value of the waviness step on the machined surface after down milling and the measured one does not exceed 12%.

3. CONCLUSIONS

1. The common thing in the formation of waviness on the machined surface after up and down milling is cutting off the protrusions on the cutting surface. But with up milling, they are at the beginning of the cutting surface, and with down milling, at its end.

2. In up milling, the length of the base of the protrusion cut off from the cutting surface, which affects the step of waviness on the machined surface, is greater than the length of the base of a similar protrusion during down milling. This is the first reason why the step of the waviness after down milling is smaller than after the up milling.

3. The wavy pitch in up milling depends on the amount of feed and the number of cuts made by the tool when cutting off the first protrusion on the cutting surface.

4. The undulation step in down milling depends on the amount of feed, the number of cuts of the cutter when cutting off the last protrusion on the cutting surface, and the phase shift between subsequent cuts, directed in the direction opposite to the feed direction. This is the second reason why the step of waviness after down milling is smaller than after up milling.

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ПРИЧИНИ РІЗНОЇ ХВИЛЯСТОСТІ ОБРОБЛЕНИХ ПОВЕРХНОНЬ ПІСЛЯ ЗУСТРІЧНОГО І ПОПУТНОГО КІНЦЕВОГО ФРЕЗУВАННЯ

Анотація. *У сучасній промисловості серед методів обробки поверхонь широко застосовується кінцеве фрезерування. За певних умов його використання виникають автоколивання, які істотно впливають на якість обробленої поверхні. Для дослідження цього впливу використовуються різні методики, зокрема, зіставлення отриманих при різанні базових фрагментів осцилограми з обробленою поверхнею. Встановлено, що вона формується першою та останньою хвилею автоколивань при зустрічному та попутному фрезеруванні відповідно. Але в залежності від напрямку подачі крок та висота хвилястості на ній мають різні значення. Тому актуальним є визначення причин, що призводять до такого результату. У цій роботі розглядаються особливості кожного напряму подачі, що впливають на формування обробленої поверхні. При накладанні фрагментів осцилограми, отриманих при зустрічному фрезеруванні, видно, що відхилення першої хвилі автоколивань від положення пружної рівноваги починається від точки врізання фрези в деталь. Тому крок хвилястості на обробленій поверхні залежить від подачі та кількості різів, необхідних для зрізання першого виступу на поверхні різання. У роботі наведено формулу для визначення довжини основи цього виступу. При її використанні розбіжність між розрахованим кроком хвилястості на обробленій поверхні та виміряним не перевищує 4%. При попутному фрезеруванні остання ділянка з хвилястістю на поверхні різання, що зрізається та впливає на форму обробленої поверхні, має меншу довжину основи, ніж при зустрічному. Це перша причина, чому крок хвилястості при попутному фрезеруванні менший, ніж при зустрічному. Також при формуванні хвилястості на обробленій поверхні при попутному фрезеруванні спостерігається особливість у вигляді зсуву по фазі хвиль автоколивань на кожному наступному різі. Це призводить до збільшення часу різання та довжини поверхні різання. Кожна наступна формоутворююча западина зміщується у бік обробленої поверхні із зменшенням її відхилення від положення пружної рівноваги. Однак напрямок зсуву по фазі протилежний напрямку подачі. Це друга причина, через яку крок хвилястості на обробленій поверхні після попутного фрезерування менший, ніж після зустрічного. Розрахунок кроку хвилястості обробленої поверхні після попутного фрезерування за результатами дослідження фрагментів осцилограм показує, що похибка не перевищує 12% порівняно з виміряним.*

Ключові слова: *фрезерування; автоколивання; хвилястість; крок; висота;, поверхня різання.*