Influence of the Cut Axial Depth on Surface Roughness at High-Speed Milling of Thin-Walled Workpieces

A. I. Germashev1), V. A. Logominov1), S. I. Dyadya1), Y. B. Kozlova1), V. A. Krishtal2)

1) National University “Zaporizhzhya Polytechnic” (Zaporozhye, Ukraine),
2) SE “Ivchenko-Progress” (Zaporozhye, Ukraine)

Abstract. The paper presents the results of research on the dynamics of end milling of thin-walled work-pieces having complex geometric shapes. Since the milling process with shallow depths of cut is characterized by high intermittent cutting, the proportion of regenerative vibrations decreases, and the effect of forced vibrations on the dynamics of the process, on the contrary, increases. The influence of axial depth of cut on the vibrations arising during processing, and roughness of the processed surface have been studied in paper. The experiments have been carried out in a wide range of changes in the spindle speed at different axial cutting depths. Vibrations of a thin-walled work-piece have been recorded with an inductive sensor and recorded in digital form. Then an oscillogram has been used to estimate the amplitude and frequency of oscillations. The profilograms of the machined surface have been analysed. Roughness has been evaluated by the parameter Ra. The results have shown similar relationships for each of the investigated axial cutting depths. The worst cutting conditions have been observed when the natural vibration frequency coincided with the tooth frequency or its harmonics. It is shown that the main cause of vibrations in high-speed milling is forced rather than regenerative vibrations. Increasing the axial depth of cut at the same spindle speed increases the vibration amplitude. However, this does not significantly affect the roughness of the processed surface in cases when it comes to vibration-resistant processing.

Keywords: milling, thin-walled work-piece, high-speed milling, forced vibrations, vibrations, self-excited oscillations, spindle speed

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Влияние осевой глубины резания на шероховатость поверхности при высокоскоростном фрезеровании тонкостенных деталей

Канд. техн. наук А. И. Германшев1),
кандидаты техн. наук, доценты В. А. Логоминов1), С. И. Дядя1), Е. Б. Козлова1),
В. А. Кришталь2)

1) Национальный университет «Запорожская политехника» (Запорожье, Украина),
2) ГП «Ивченко-Прогресс» (Запорожье, Украина)

Реферат. В статье представлены результаты исследований динамики концевого фрезерования тонкостенных деталей сложной геометрической формы. Поскольку процесс фрезерования с малыми глубинами резания характеризуется высокой прерывистостью резания, доля реверсивных колебаний уменьшается, а влияние вынужденных колебаний на динамику процесса, напротив, увеличивается. Изучено влияние осевой глубины резания на колебания, возникающие...
Introduction

The key factor in thin wall machining is the dynamic behaviour of the work-piece. Thin-walled milling case covers many parts of the aerospace sector, including structural and engine parts. Thus, operating conducted under 5 axes milling which is widely used in manufacturing blisk or impellers [1]. Biermann et al. [2] presented a general approach to simulate work-piece vibrations during 5 axes milling of turbine blades. Budak et al. [3] included the effect of work-piece dynamics on chatter stability in milling of turbine blades, taking into account constant changes of the part characteristic. Thin-walled parts behavior is highly dependent from tool position due to continuously changeable structural dynamics. Path dependent 3D stability diagrams was developed to determine dynamic of the part along tool path and reaching free of chatter machining of thin-walled work-pieces [4], [5]. Munoa at al. [6] concluded that the main tendency in chatter avoidance during thin-walled machining is the use FEM models to predict the modal parameters and vibration modes, considering the variations due to material removal. One of the first study of thin-walled milling with FEM model was carried out by Kline et al. [7]. Further improving of this model was made by Budak and Altintas [8] considering the plate surface finish.

One of the important specifics of thin-walled milling of engine parts is highly interrupted nature and high spindle speed, where influence of chatter becomes lower due to low fraction of the wave [9]. In such case the surface location error regularities take place, that was noticed by Kline et al. [10], [11], Thusty [12], Montgomery and Altintas [13, 14], Smith et al. [15], Tarng et al. [16], Schmitz et al. [17–21], and others. Therefore, even under seemingly stable cutting conditions, the thin-walled structures experience forced vibrations, which depend on the work-piece / tool natural frequency and excitation frequency (or tooth passing frequency), causing big fluctuations of the flexible workpiece.

As at highly interrupted machining chatter has low influence on the state of milling process while poliresonance cause high oscillation at certain spindle speed ranges, primary goal of the paper showing that generally accepted parameter of axial depth of cut has low influence on the state of machining if good spindle speed range is reached. For validation of proposed assumption experimental study is proposed.

Experimental setup

Data acquisition for thin-walled end milling process has some features related to the specifics of this process. Due to the high intermittency of thin-walled end milling process it consists of consecutive alternation of cutting and free movement of the part. Part behaviour during milling process affects quality of surface finish, dimensional accuracy, manufacturing tool wear, etc. By the time free movement of the part is not so important, because of tool-work-piece system break. Moreover, free oscillations of the part might have bigger amplitude than part deflection during milling. However, data acquisition records all machining
process. So, to evaluate thin-walled milling process accurately, it becomes significantly important to separate cutting process from the entire processing signal. Such procedure is carried out by measuring contact system of experimental setup, which allows recording a contact signal simultaneously with the displacement sensor that measures oscillation of thin plate during processing (Fig 1).

**Results**

For investigating the axial depth of cut influence on the state of machining at milling of thin-walled components, two series of experimental tests were conducted with parameter $a_e = 0.5 \text{ mm}$ and $a_e = 1.5 \text{ mm}$. Maximal amplitude of the part oscillation was measured during the tests.

In Fig. 2 it is shown part’s amplitude oscillation changes at different spindle speeds. For both series of experimental tests it was observed the same regularities and spindle speed ranges with low and high amplitudes. The biggest amplitude was observed at spindle speed $n = 2700–3000 \text{ rpm}$, $n = 3500–4500 \text{ rpm}$, $n = 7700–8500 \text{ rpm}$, while low amplitude was noticed at $n = 3100–3500 \text{ rpm}$, $n = 5300–6900 \text{ rpm}$, $n = 9500–10000 \text{ rpm}$.

As poliresonance has a dominant influence at highly interrupted machining of thin-walled components it is proposed to observe this chart in terms of tooth passing and natural frequency ratio (Fig. 3). From this chart it is easy to notice that maximum amplitude was observed at the ratio 1.0, 0.5, 0.33 and close to them regions. The lowest amplitude was seen at 0.75, 0.44 and lower then 0.3. It should be noticed that if time of cutting becomes more than period of chatter conditions are conductive to appearance of chatter. For this and other reasons, the poliresonance does not have a dominant influence on the cutting process at low passing and natural frequency ratio.

The surface quality is presented in the Fig. 4. Curves have similar trends as in the figure of the part oscillation (Fig. 2). Such regularities are described in authors’ work [9]. This chart shows sensitivity of thin-walled components to cutting conditions. Taking into account observed spindle speed range the surface roughness changes more than in 20 times for certain spindle speeds (for example at $n = 3700 \text{ rpm}$). In some cases spindle speed difference is less than 5 % (for example at $n = 3500 \text{ rpm}$).

![Fig. 1. Experiment setup](image1)

![Fig. 2. Dependence of oscillation amplitude on spindle speed chart](image2)

![Fig. 3. Dependence of oscillation amplitude on tooth passing and natural frequency ratio](image3)

![Fig. 4. Dependence of surface roughness on spindle speed chart: \( - 0.5 \); \( - 1.5 \)](image4)
In the Fig. 5 profilograms of machined surface after experimental tests is shown. For the comparison milling condition with the max and min part oscillation level is chosen. These profiles shows that in case of small oscillation increasing of axial depth of cut does not significantly influence on the cutting process. Amplitude of the work-piece oscillation and surface roughness rise less than 30%.

In the same time in case of bad state of machining bigger axial depth of cut causes much more higher oscillation level (more than in 2 times) and damage of the surface. Such results allows to notice that at highly interrupted milling poliresonance regularities usage allows to increase axial depth of cut and save good quality of the machining.

![Fig. 5. Profile of the machined surface at max and min oscillation level of the workpiece](image-url)
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CONCLUSION

Paper proposes experimental investigations of the influence axial depth of cut on the state of thin-walled milling and quality of surface finish. Based on the results it should be concluded, that thin-walled parts are extremely sensitive to spindle speed variation as their behavior during processing depends on excitation frequency. Analyses of the part oscillation and surface roughness show that spindle speed determines the influence of the axial depth of cut. If spindle speed range with good state of cut is reached, increasing of axial depth of cut does not provide significant changes in the cutting process and machining quality. In either case, if oscillation with high amplitude is observed, an axial depth of cut plays an essential role in increasing vibration level. And furthermore, a high vibration level may lead to damage surface and tool breaking.

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