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IMPROVING THE EFFICIENCY OF HIGH-SPEED MILLING OF THIN-WALLED ELEMENTS OF PARTS OF COMPLEX GEOMETRIC SHAPES

Thin-walled elements of complex geometric shapes are widely used in the aerospace and other industries. They are obtained by various methods of machining using modern numerically controlled machines. The fundamental factors for manufacturing of parts are the productivity and machining quality. The **subject** matter of the article is the vibration during high-speed milling of thin-walled elements of parts of complex geometric shapes. The **aim** of the article is to determine the possibility of increasing the efficiency of high-speed milling of thin-walled parts by finding vibration-proof processing conditions. To achieve the goal, the following **tasks** have been set and implemented: considering the features of high-speed milling of thin-walled elements of parts with complex geometric shapes, developing a technique for investigating the milling process, and identifying stable machining conditions for high-speed milling of thin-walled components. The **methods** of oscillation fixation during machining and statistical analysis of experimentally obtained results are used. The following results are obtained: the design of the experimental bench is suggested to study the process of milling thin-walled elements of parts, the technique of obtaining a quantitative characteristic of the milling conditions, which is based on determining the position of a part at the moment when a milling tooth is cutting into it is offered, and the stable machining conditions for high-speed milling of thin-walled elements of parts are determined. **Conclusions.** The decisive role of the spindle rotational velocity in achieving a low vibration level has been experimentally proven, under the conditions of high-speed milling in a vibration-resistant range of spindle velocities both the radial depth and the feed can be increased without losses in the quality of machining.

Keywords: thin-walled element, elastic system, oscillations, high-speed processing, pierce point.

Introduction

Parts that have thin-walled elements are widely used in the aerospace industry, for example, blades of axial and centrifugal disks of a gas turbine engine (GTE). Vibrations occur while machining such parts due to their moderate rigidity; they worsen the roughness of a machined surface and the dimensional accuracy.

Low indices of the surface roughness are very important for parts that are encircled by liquid or gas flows. The increase of the roughness leads to the more rapid transition of the laminar boundary layer to the turbulent one, which increases the total force of the friction resistance. Therefore, the improvement of the quality of a machined surface and blades of GTE disks boosts the engine efficiency, the endurance strength, and the resistance to the crack formation of critical parts that operate under high dynamical loads, and the increase of the dimensional accuracy of manufactured thin-walled parts promotes more balanced operation of the engine and increasing its service life and repair intervals.

Modern trends in the development of industry require manufacturing more complex geometric shapes of parts. In addition, the machine-building industry seeks to minimize a number of assembly units by switching to monolithic parts, which makes an important contribution to the complication of their structures and the increase in the number of thin-walled elements. It is also worth noting that one of the main directions of mechanical engineering today is energy efficiency, that is, the reduction of structures weight. This issue is the most important in the aviation industry, where the strength and lightness of parts are especially required.

Monolithic thin-walled parts of a complex shape are manufactured by removing up to 90% of a part allowance, which lays down high demands for the performance of this process. The issues of increasing the efficiency of machining costs are considered along with the reduction of the roughness of a machined surface and geometrical

accuracy, where the latest aspects go to the foreground only during the finishing process.

Analysis of literary sources and problem setting

Fists fundamental steps in estimating the maximum performance of the process of machining were made in the mid-1950s. Researching conducted by V. A. Kudinov [1], J. Tlusty and others [2], S. A. Tobias, W. A. Fishwick [3] enabled using the physical essence of regenerative self-oscillations excitation for creating the theory for determining stable conditions of machining.

Underlying principles of the regenerative theory of stability were worked out by S. A. Tobias [4] and J. Tlusty [5], who studied the interaction of the dynamics of the structure of a machine tool system and the dynamics of the cutting process. They determined the regeneration and the coordinate link as a main mechanism of self-oscillations during machining. H. E. Merritt [6] suggested using the regeneration and the laws of laying waves that appear due to self-oscillations on the surface of cutting in order to determine the stability of orthogonal turning. This approach was further developed by many researchers and was used as a source for estimating so-called stability lobe diagrams which are widely used today to determine the maximum possible axial depth of cut (the stability boundary) when the spindle is rotating with the greatest velocity or velocity.

This approach was initially developed for turning, although self-oscillations occur in many processes of metal finishing. When stability lobe diagrams were developed, they started to be used for other operations as well, including milling. Tlusty J. [7, 8] conducted a detailed analysis of milling stability based on the theory of regeneration self-oscillations. The fact that this type of machining has an intermittent character of the cutting force, that is linked with the entry and exit points of milling cutters, was taken into account in the later algorithm of estimating the milling stability [9–11].

Considering high-speed milling of parts of complex geometric shapes requires clear understanding the peculiarities of this process which lie in the fact the process of machining is intermittent when cutting with a single milling cutter is replaced with free motion of the instrument and the part. This phenomenon is caused by a small arc of a milling cutter contact and a part that is being machined due to low radial and axial depths of cut. It should be noted that the value of the axial depth is limited by the complex shape of a part that can be obtained because of the line small size. The axial depth can be increased; however, this parameter is artificially decreased since a part is machined with a small-diameter instrument or thin-walled elements are machined. The probability of vibrations is very high under such conditions, and to minimize it radial depths are decreased.

Self-oscillations attenuate at relatively low cutting velocities under the conditions of the intermittent cutting. Nevertheless, high-speed machining of thin-walled parts is one of the most difficult cases in the sphere of metal finishing. The authors concluded that the vibration stability of milling thin-walled parts is based on forced oscillations but not on self-oscillations. Depending on the combination of dynamic characteristics of a machined part and excitation frequencies of the system, it is possible to

predict the state of milling, the level of vibrations and the quality of a machined surface.

The goal of the research

The goal of this work is to determine probabilities of enhancing the efficiency of machining by increasing the radial velocity and feed as well as the impact of these parameters on the vibration stability of milling.

Research materials and methods

To study the process of milling thin-walled parts, the bench is suggested, which is shown in fig. 1. The detailed information about this bench is given in works [12, 13]. The gripping device is a heavy base that is placed on the table of a milling machine through the electric insulation and is designed to fix a springing element (of a thin-walled plate) securely. A machined sample is rigidly fixed on the plate. The sample is moved while milling due to the thrust force of the milling cutter; the displacement transducer measures the length of the motion according to the change of the gap clearance - Δ .

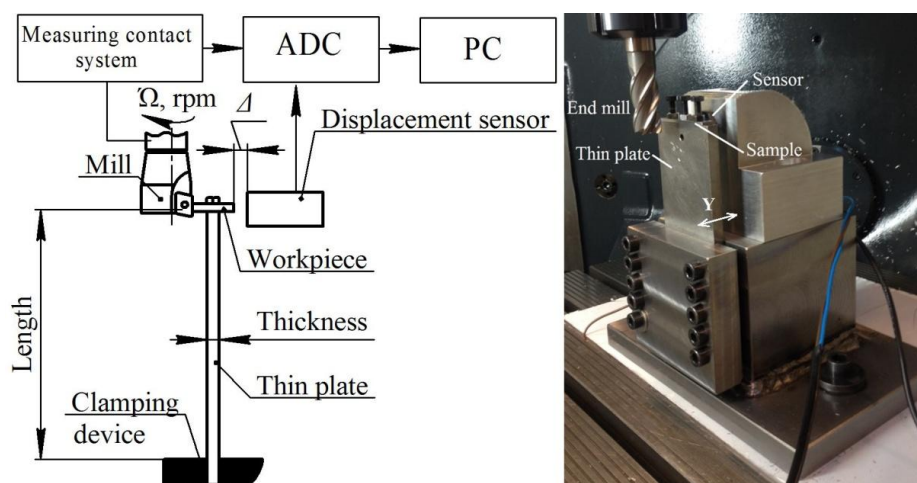


Fig. 1. The experimental bench for studying the high-speed milling of thin-walled parts

The system of measuring the contact conditions of an instrument with a part was added to the bench [14, 15]. When a milling cutter contacts a machined sample, an electric signal is fed through the mobile current collector to the ADC (analogue-to-digital converter). The signal from the current collector and the signal of the sample motion are recorded simultaneously, which enables their highly accurate overlapping (fig. 2). The system of measuring the contact between the milling machine and the instrument is a key element of the experimental bench for studying the process of intermittent cutting as it enables dividing the oscilloscope record of a part oscillation into the process of cutting and the idling.

Fig. 2 shows the fragment of the process of a part machining by the measuring equipment of the experimental bench. The overlap of two signals enables determining the moment when a tooth of the milling cutter starts contacting a sample being machined (the pierce

point), the sites of a probable exit of a milling cutter from the tooth engagement with the allowance within the arc of their contact, and the end of cutting (the exit point).

Fig. 2 (a) shows the ideal case when a part remains in one and the same position at the beginning of cutting, that is when its disalignment from the equilibrium along the Y axis does not change at the pierce point. In this case, the elimination of the allowance by each tooth of a milling cutter occurs under the same conditions.

In fig. 2 (b) the pierce point changes its position along the axis of the part deviation, while the length of the allowance also differs each time when the tooth of the milling cutter is cutting. Multiple repetitions of this process lead to a significant deterioration in the quality of machining, which is characterized by the high waviness, as well as by the increase in the amplitude of oscillation of a part.

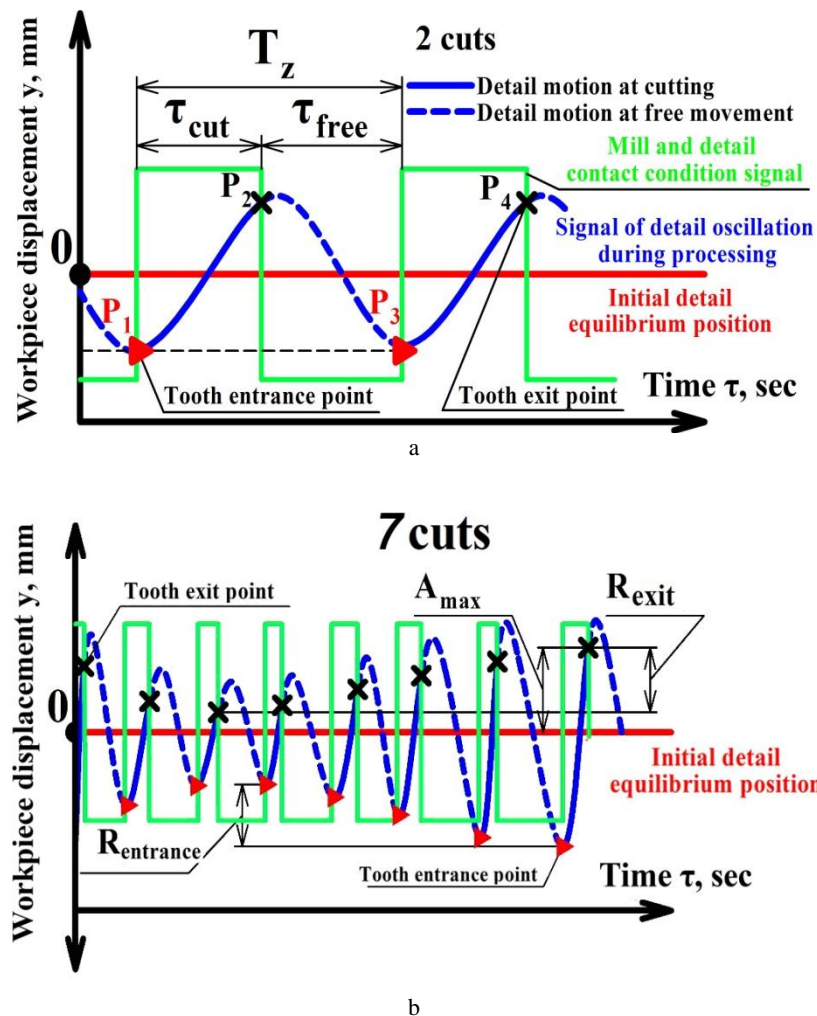


Fig 2. Fragments of the record of the machining process

To obtain a quantitative description of the conditions for milling thin-walled parts, the amplitude of the pierce point, R_{entry} , was estimated. This value characterizes the difference between the maximum and minimum deviation of a part at the beginning of cutting during the entire process of machining.

The experimental studies were carried out on a numerically controlled milling machine DMU 50., A knee-type clamped plate 6 mm thick ($h = 6$ mm) and 60 mm wide ($b = 60$ mm) was used as a springing element, the overhang of the plate was 80 mm, the material used was St 65 G. The sample made of the material St 3 was rigidly fixed at the exposed end of the plate. The metalworking was carried out with a carbide end cylindrical 4-tooth milling cutter, with the diameter of 20 mm, the flank angle of the helical cutting rim ω was equal to 330. The frequency of natural oscillations of the springing system (SS) of a thin-walled part f_{no} was equal to 565 Hz, the damping coefficient ξ was equal to 0.02, the stiffness C was equal to 1000 N/mm.

In all experiments, the axial depth of cutting a_p was equal to 2 mm, the radial depth varied from $a_e = 0.25$ mm to a $a_e = 0.5$ mm, the feed to the tooth was from

$S_z = 0.3$ mm per tooth to $S_z = 0.05$ mm per tooth, the feed direction was trailing. The lubricating-cooling technological medium was not used. That is, the experimental studies were carried out under the conditions that correspond to the modes of machining complex shaped parts, where the allowance is cut with small radial and axial depths.

Two series of experiments were conducted to consider the impact of the radial depth of cutting and feeding on the machining process. The milling dynamics was measured in the speed range from $n = 500$ rpm to $n = 10,000$ rpm. The step of changing the rotational speed of the spindle was 100 rpm. The analyzed parameter was the amplitude of a part position at the beginning of cutting.

The results of the research and discussion

Fig. 3 shows the change of the amplitude of the pierce point R_{entry} obtained experimentally depending on the frequency of a spindle rotation when the radial depth a_e is equal to 0.5 mm and a_e is equal to 0.25 mm.

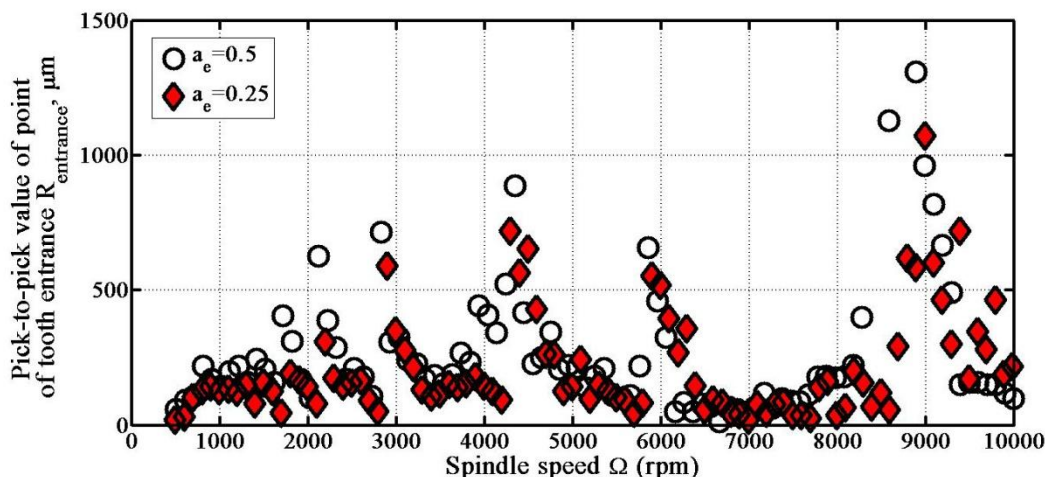


Fig. 3. The amplitude of the pierce point over a full range of radial depths

The results of the experimental study show that for both depths in the considered speed range, vibration-resistant machining conditions are observed ($n = 1900$ – 2000 rpm, $n = 2500$ – 2800 rpm, $n = 3300$ – 3900 rpm, $n = 4700$ – 5700 rpm, $n = 6300$ – 8000 rpm), as well as less vibration-resistant ones. Changing the speed of the spindle rotation helps change the amplitude of the pierce point by 10 or even more times. It should be noted that the speed ranges of stable and unstable cutting for both depths are equal because of the fact that during the high-speed milling the areas of optimal modes of machining depend on the characteristics of the system and on the excitation frequency. The areas of optimal machining occur when the frequencies of the spindle rotation are equal, taking into account the fact that the elastic system of a thin-

walled part and an instrument were the same in both experiments. The values of the pierce point amplitude of the considered radial depths, when the frequencies of the spindle rotation are equal, vary insignificantly (no more than 10 % in 95% of cases). If considering unstable conditions of machining, the amplitude of the pierce point for a greater radial depth would have higher values.

Thus, the right choice of the spindle rotation frequency which corresponds to the vibration-resistant range of frequencies of a spindle rotation enables increasing radial depths saving the low level of vibrations.

Fig. 4 shows the change of the pierce point position depending on the frequency of a spindle rotation when the feeds to the tooth are equal: $S_z = 0,3$ mm per tooth and $S_z = 0,5$ mm per tooth.

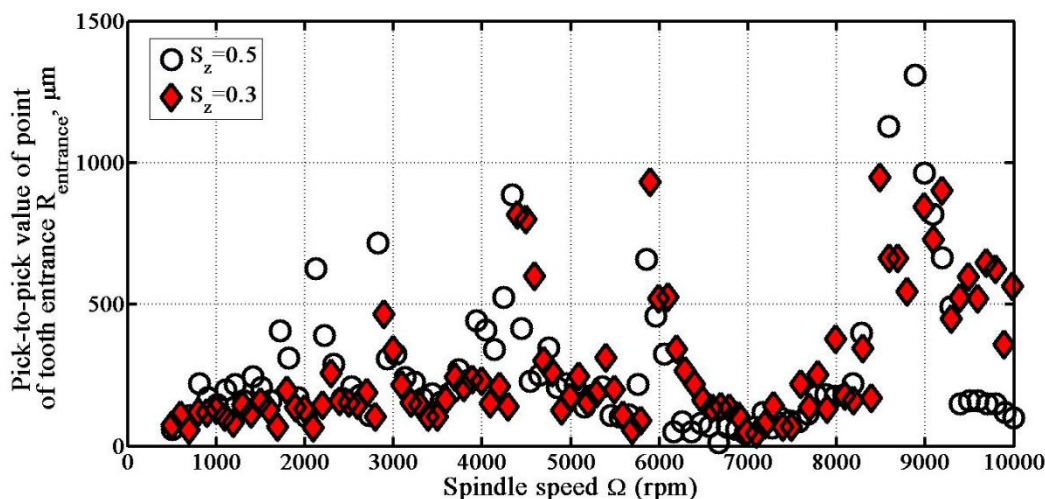


Fig. 4. The amplitude of the pierce point at various values of feeding to a tooth

Like in fig. 3, the vibration-resistant conditions of machining for the both considered values of changing the modes of cutting lie within the same speed ranges. They correspond to the ranges of the frequencies of the spindle rotation given for fig. 3 as the dynamic characteristics of a thin-walled part and the milling cutter remained the same.

In the majority of experiments, the amplitude of the pierce point for equal frequencies of a spindle rotation varied within the limits of 10% when the feed and the radial depth changed. At the same time, a change in the

spindle speed contributed to a significant change in the amplitude of the pierce point.

Thus, the results of the experimental studies show that the fundamental factor for achieving optimal machining conditions is the spindle rotation frequency (the frequency of forced oscillations). At the same time, achieving vibration-resistant milling conditions enables increasing the feed rate, thereby increasing the machining efficiency.

Conclusions

The article considered the possibility of increasing the radial depth of cutting and feeding at high-speed milling of thin-walled parts. The experimental conditions corresponded to the modes of machining parts with a complex geometric shape of surfaces; particularly, small cutting depths and intermittent cutting were used.

The results of experimental studies show that changing the speed of the spindle rotation contributes to multiple changes in the amplitude of the pierce point. The

speed of the spindle rotation is crucial for achieving a low level of vibrations and favourable quality of the machined surface of thin-walled parts.

Both the radial depth and feeding can be increased without any loss in the quality of machining while milling in the vibration-resistant range of the frequencies of the spindle rotation. Thus, the fundamental task is to improve the efficiency of machining significantly. The experimental studies have shown the capability of a twofold increase in the radial depth of cutting and half as much increase in feeding.

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ВИСОКОШВИДКІСНОГО ФРЕЗЕРУВАННЯ ТОНКОСТІННИХ ЕЛЕМЕНТІВ ДЕТАЛЕЙ СКЛАДНОЇ ГЕОМЕТРИЧНОЇ ФОРМИ

Тонкостінні елементи складної геометричної форми широко застосовуються в авіакосмічній та інших галузях промисловості. Отримують їх різними методами механічної обробки на сучасних верстатах з числовим програмним управлінням. Основними факторами при виготовленні деталей є продуктивність і якість обробки. **Предметом** даного дослідження є вібрації при високошвидкісному фрезеруванні тонкостінних елементів деталей складної геометричної форми. **Мета** статті - визначення можливості підвищення ефективності високошвидкісного фрезерування тонкостінних деталей шляхом знаходження вібростійких умов обробки. Для досягнення мети поставлені і реалізовані наступні **завдання**: розгляд особливостей високошвидкісного фрезерування тонкостінних елементів деталей зі складною геометричною формою, розробка методики дослідження процесу фрезерування, виявлення стабільних умов обробки при високошвидкісному фрезеруванні тонкостінних елементів деталей. Використано методи фіксації коливань в процесі обробки і статистичного аналізу експериментально отриманих результатів. Отримані наступні **результати**: для вивчення процесу фрезерування тонкостінних елементів деталей запропонована конструкція експериментального стенду, методика отримання кількісної характеристики умов фрезерування, яка ґрунтується на визначенні положення деталі в момент врізання зуба фрези, виявлені стабільні умови обробки при високошвидкісному фрезеруванні тонкостінних елементів деталей. **Висновки**. Експериментально доведено визначальна роль частоти обертання шпинделя в досягненні низького рівня вібрацій, в умовах високошвидкісного фрезерування в вібростійкого діапазоні частот обертання шпинделя можливо як збільшення радіальної глибини, так і збільшення подачі без втрат в якості обробки.

Ключові слова: тонкостінний елемент, пружна система, коливання, високошвидкісна обробка, точка врізання.

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ВЫСОКОСКОРОСТНОГО ФРЕЗЕРОВАНИЯ ТОНКОСТЕННЫХ ЭЛЕМЕНТОВ ДЕТАЛЕЙ СЛОЖНОЙ ГЕОМЕТРИЧЕСКОЙ ФОРМЫ

Тонкостенные элементы сложной геометрической формы широко применяются в авиакосмической и других отраслях промышленности. Получают их различными методами механической обработки на современных станках с числовым программным управлением. основополагающими факторами при изготовлении деталей является производительность и качество обработки. **Предметом** данного исследования является вибрации при высокоскоростном фрезеровании тонкостенных элементов деталей сложной геометрической формы. **Цель** статьи – определение возможности повышения эффективности высокоскоростного фрезерования тонкостенных деталей путем нахождения виброустойчивых условий обработки. Для достижения цели поставлены и реализованы следующие **задачи**: рассмотрение особенностей высокоскоростного фрезерования тонкостенных элементов деталей со сложной геометрической формой, разработка методики исследования процесса фрезерования, выявление стабильных условий обработки при высокоскоростном фрезеровании тонкостенных элементов деталей. Используются **методы** фиксации колебаний в процессе обработки и статистического анализа экспериментально полученных результатов. Получены следующие **результаты**: для изучения процесса фрезерования тонкостенных элементов деталей предложена конструкция экспериментального стенда, методика получения количественной характеристики условий фрезерования, которая основывается на определении положения детали в момент врезания зуба фрезы, выявлены стабильные условия обработки при высокоскоростном фрезеровании тонкостенных элементов деталей. **Выводы**. Экспериментально доказана определяющая роль частоты вращения шпинделя в достижении низкого уровня вибраций, в условиях высокоскоростного фрезерования в виброустойчивом диапазоне частот вращения шпинделя возможно, как увеличение радиальной глубины, так и увеличение подачи без потерь в качестве обработки.

Ключевые слова: тонкостенный элемент, упругая система, колебания, высокоскоростная обработка, точка врезания.