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МОДЕЛЮВАННЯ ПРОЦЕСІВ В МЕТАЛУРГІЇ ТА МАШИНОБУДУВАННІ

MODELING OF PROCESSES IN METALLURGY AND MECHANICAL ENGINEERING

UDC 621.941.08

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INFLUENCE OF DISCONTINUOUS CHIP FORMATION ON THE EXCITATION OF REGENERATIVE SELF-OSCILLATIONS DURING TURNING

Purpose. *The objective of this study is to investigate the influence of discontinuous chip formation on the excitation of regenerative self-oscillations during turning, to compare the vibration for continuous and discontinuous chip formation mechanisms, and to improve the prediction of machining stability for brittle materials.*

Research methods. *The study was carried out under conditions of continuous orthogonal turning using a CNC lathe. Vibration was investigated with a single degree of freedom cutter–oscillator designed in the direction of chip thickness variation. The displacement of the cutting edge during machining was measured using an inductive sensor, and the signals were recorded through a multi-channel data acquisition system and processed on a computer. Oscillograms were analyzed to determine vibration amplitude and static deflection.*

Results. *The experimental results showed that the type of chip formation has a significant influence on vibration during turning. When machining steel AISI 1045, characterized by continuous chip formation, pronounced regenerative chatter was observed in the cutting speed range of v=100–250 m/min, with vibration amplitude increasing as cutting speed increased. In contrast, during machining of gray cast iron GG35, which produces discontinuous chips, no regenerative chatter was detected; only low-amplitude random vibrations were present, and their level remained nearly constant over the entire cutting speed range. For bronze CuSn3Zn13Pb4, also characterized by discontinuous chip formation, regenerative chatter occurred only at higher cutting speeds (v=150–250 m/min), and the vibration amplitude increased with cutting speed similarly to steel.*

Scientific novelty. *The scientific novelty of this study lies in establishing the influence of discontinuous chip formation on the suppression and excitation conditions of regenerative self-oscillations during turning.*

Practical value. *The practical significance of this study lies in improving the prediction of machining stability when processing materials with different chip formation mechanisms. The obtained results can be used to select optimal cutting conditions that reduce or prevent regenerative self-oscillations, especially when machining brittle materials.*

Key words: *vibration, regenerative self-oscillations, chip formation, cutter-oscillator, chip type.*

Introduction

Vibration during turning remains a key problem in machining, as it significantly impacts surface quality, part accuracy, and cutting tool life [1]. The most undesirable type of vibration during machining is considered to be regenerative self-oscillations, the mechanism of which is associated with cutting along a vibrational wavy trace that arose during the previous revolution of the part, leading to a change in the thickness of the cut layer over time during cutting [2].

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Chip formation can also significantly influence cutting dynamics. Depending on the properties of the workpiece material and machining conditions, chip formation varies significantly, resulting in the formation of various chip types: continuous, discontinuous, and segmental chips [3]. In continuous chip formation, plastic deformation of the material occurs more continuously. Segmented chip formation is accompanied by the periodic formation of shear segments and the occurrence of high-frequency oscillations in cutting force. In discontinuous chip formation, the cutting process has a pronounced intermittent nature, caused by brittle fracture of the material and the formation of individual chip fracture elements. In this case, chip formation is accompanied by sharp surges in cutting forces and brief unloading of the cutting tool, which leads to pulsed excitation of oscillations. This specificity of the interaction between the tool and the workpiece can both limit the development of classical regenerative self-oscillations due to the break in feedback and, under certain conditions, initiate complex non-stationary vibration modes that require separate theoretical and experimental analysis.

Different chip formation types differ significantly in the mechanism of plastic deformation of the material, the frequency of chip formation, and the nature of cutting force changes. Most existing theoretical and experimental studies focus on the machining of plastic materials, which are characterized by continuous chip formation. Meanwhile, when machining brittle materials, such as gray cast iron, discontinuous chip formation occurs. Despite this, the influence of discontinuous chips on the excitation of regenerative self-oscillations has been insufficiently studied, and the applicability of classical models developed for continuous chip formation remains controversial.

Thus, there is need to expand the theory of cutting process dynamics to the class of brittle materials with discontinuous chip formation, which will allow for more accurate prediction of the stability of the turning process and the development of effective methods for vibration suppression.

Literature review

The problem of vibration during turning has been studied for a long time, but its physical nature still does not have an unambiguous interpretation. In early works, the main attention was paid to phenomena associated with contact processes on the cutting edge of the tool. In particular, one of the first explanations for the occurrence of vibrations was based on the periodic formation and breakdown of built up edge. In studies [4, 5] it was shown that the built up edge is cyclically formed and destroyed, causing a change in cutting forces and, as a result, excitation of vibrations of the technological system.

Most scientists associate the appearance of vibrations with the regenerative effect, which is considered the main source of self-oscillations during turning [6–9]. However, in work [10] it was established that waviness on the cutting surface is not the cause of regenerative self-oscillations, but rather their consequence. At the same time, vibrations occur as a result of the resonance of the frequency of chip formation and the natural frequency of the cutter during cutting.

In parallel with the development of the theory of regenerative self-oscillations, considerable attention was paid to the study of the chip formation process itself as a source of vibration excitation. It was found that chip segmentation is accompanied by fluctuations in cutting forces, which can act as a source of vibration excitation.

In [10], when turning steel AISI 1040, it was found that the frequency of formation of secondary and primary waves on the free side of the chip increases almost linearly with cutting speed. The vibration amplitude increases sharply when the chip segmentation frequency curve approaches the corresponding curve of the natural frequency of the cutter (at approximately 100 m/min).

In [11], graphs of the dependence of chip type on cutting speed were constructed during a study of various steels and a titanium alloy. It was found that when the chip formation frequency coincides with one of the natural oscillation frequencies of the machine's elastic system, resonance can occur, leading to intense vibrations. To avoid instability of the chip formation process in the local shear plane, the tool oscillation frequency must exceed the segmental chip formation frequency.

In [12], vibrations during milling of gray cast iron were studied. Based on the results, a stability lobe diagram in the frequency domain was constructed. In the study, the oscillator was a component with one degree of freedom along the z-axis. Milling was performed using a multi-tooth face mill with a 45° cutting angle. This research method does not allow for the study of regenerative self-oscillations alone.

The study [13] presents a hybrid methodology based on an artificial neural network, specifically developed for predicting the surface roughness of GG-25 gray cast iron workpieces processed during turning. These studies did not consider the effect of vibration on roughness.

In [14], a comprehensive model for predicting vibrations during turning of cast iron brake discs was developed, and a stability lobe diagram was constructed. A test cutting method was proposed for identifying vibrations during radial turning using continuous cutting at variable speed. It was established that the intensity of vibrations is affected by cutting speed; vibrations occur in a specific speed range in which the peak amplitude of oscillations is observed.

In [15], the influence of cutting parameters and the chemical composition of cast iron on the excitation of regenerative self-oscillations was established. It was found that a higher C-Si content in cast iron helps suppress the resulting vibrations; turning cast iron with a high carbon content with a lower C-Si content at low cutting speeds is accompanied by intense regenerative self-oscillations.

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Despite the considerable amount of research, most of them focus on continuous or segmented chip formation, or use a methodology that is not able to separately study only regenerative self-oscillations. At the same time, the processes characteristic of the processing of brittle materials with the formation of discontinuous chips remain less studied. This limits the possibilities of applying classical models of cutting dynamics and necessitates the further development of the theory taking into account the peculiarities of discontinuous chip formation.

The aim of the study is to investigate the influence of discontinuous chip formation on the excitation of regenerative self-oscillations during turning.

Research methodology

The experiments were carried out under continuous orthogonal turning conditions on a Zenitech WL 320 CNC lathe [16]. A cutter-oscillator with one degree of freedom in the direction of change in the thickness of the cut layer was used to study the vibrations [17]. The natural frequency of the cutter-oscillator oscillations was f_n=500Hz. The cutter-oscillator was installed in the tool holder of the machine using a special device, in the housing of which an inductive displacement sensor Schneider Electric XS4-P12AB110 was installed (Fig. 1). Vibrations of the cutting edge during the turning process were recorded by this sensor and fed to a multichannel analog-to-digital converter L-Card E140 and transmitted in digital form to a personal computer. Signal processing was performed in PowerGraph 3.3 software. The obtained oscillograms were used to determine the cutting edge oscillation amplitude A_x and the static deflection B_x. Additionally, a spectral analysis of the oscillograms was performed using the fast Fourier transform method to determine the frequency of self-oscillations f_{SO}.

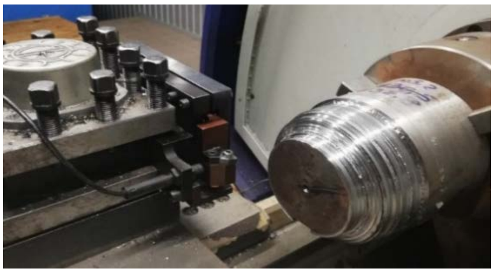

Figure 1. Workplace for vibration research [18]

The workpieces were cylindrical, D=120mm, L=100mm, ensuring high system rigidity during continuous turning. To compare the effects of different chip formation types on vibration excitation during turning, the following workpieces were used: grade steel AISI 1045 with continuous chips, gray cast iron GG35, and bronze CuSn3Zn13Pb4 – materials characterized by discontinuous chip.

Turning was performed under the following cutting conditions: cutting speed v=50-250m/min, feed rate S=0.2mm/rev, depth of cut t=1mm, without cooling.

The cutting carbide insert T15K6 (P30) has the following geometric parameters: $\gamma=0°$, $\alpha=10°$, $\varphi=90°$, $\lambda=0°$, r=0.15 mm. The wear area on the flank surface of the cutter was maintained in the range of 0.05...0.1 mm.

Results and discussion

As a result of the research during turning of different materials, oscillograms of the cutting edge oscillations were recorded (Fig. 2–4), according to which the oscillation amplitude A_x and the static deflection of the cutter-oscillator B_x and the frequency of self-oscillations f_{SO} were measured (Table 1–3).

When turning steel AISI 1045 with the cutter-oscillator, intense regenerative self-oscillations were observed in the cutting speed range of v=100–250 m/min. The oscillation amplitude increased with increasing cutting speed. When turning cast iron GG35, regenerative self-oscillations were absent; oscillograms showed random oscillations whose amplitude remained virtually unchanged with increasing cutting speed. When turning bronze CuSn3Zn13Pb4, regenerative self-oscillations were observed at cutting speeds of v=150–250 m/min. With increasing cutting speed, the oscillation amplitude increased, similar to that observed for steel AISI 1045.

Table 1 – Results of the study when turning steel AISI 1045

v, m/min	A_x, mm	B_x, mm	f_{SO}, Hz
50	0.03…0.035	0.25…0.283	-
100	0.040…0.048	0.18…0.216	625
150	0.050…0.063	0.16…0.2	625
200	0.066…0.075	0.16…0.183	625
250	0.075…0.091	0.166…0.2	625

Table 2 – Results of the study during turning of bronze CuSn3Zn13Pb4

v, m/min	A_x, mm	B_x, mm	f_{SO}, Hz
50	0.018…0.023	0.043…0.046	-
100	0.016…0.025	0.046…0.050	-
150	0.021…0.028	0.046…0.050	582
200	0.050…0.075	0.046…0.050	570
250	0.083…0.100	0.043…0.046	581

Table 3 – Results of the study during turning of cast iron GG35

v, m/min	A_x, mm	B_x, mm	f_{SO}, Hz
50	0.011…0.016	0.183…0.19	-
100	0.008…0.014	0.15…0.166	-
150	0.006…0.014	0.156…0.163	-
200	0.006…0.013	0.16…0.17	-
250	0.008…0.012	0.16…0.166	-

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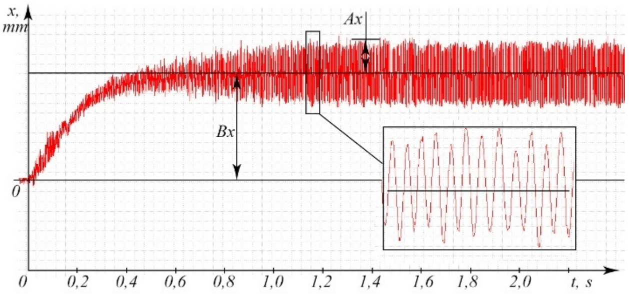


Figure 2. Oscillogram of steel AISI 1045 turning at a speed of v =150 m/min

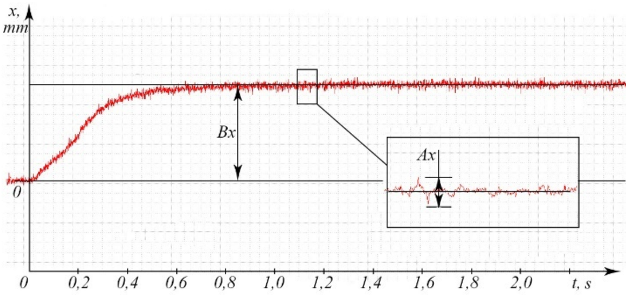


Figure 3. Oscillogram of turning cast iron GG35 at a speed of v =150 m/min

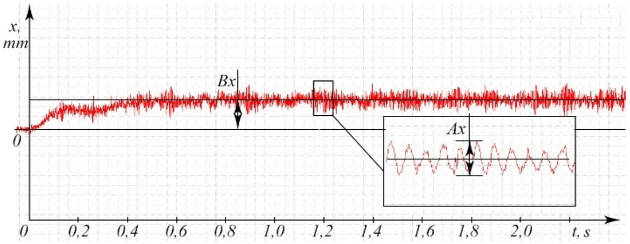
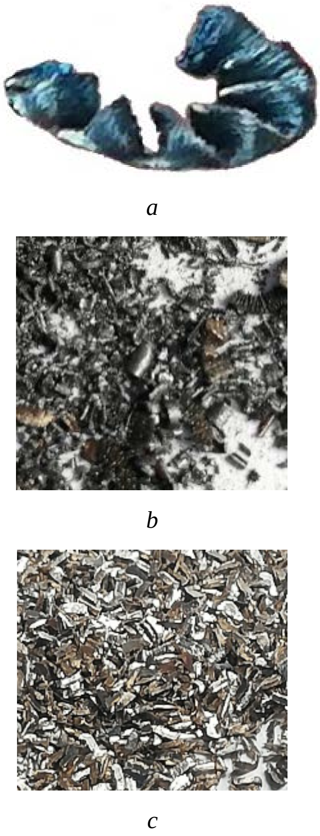


Figure 4. Oscillogram of turning bronze CuSn3Zn13Pb4 at a speed of v =150 m/min

The chips when turning steel AISI 1045 had a wave on the free surface, which confirmed the presence of regenerative self-oscillations (Fig. 5*a*). And the chips of cast iron GG35 and bronze CuSn3Zn13Pb4 were formed from numerous pieces of irregular shape, not connected or weakly connected with each other, from which it was not possible to decide the nature of vibration (Fig. 4*bc*).

The amplitude of the regenerative self-oscillations of the cutting edge of the cutter-oscillator was reflected in the vibration patterns of the machined surface (Fig. 6). On the surface of steel AISI 1045, there was a clear wave from the oscillations of the cutter tip; on bronze CuSn3Zn13Pb4, the wave was much smaller, and on cast iron GG35, the wave was absent.

An analysis of the amplitude-frequency spectra (Fig.7) revealed that a dominant oscillation frequency was observed when turning steel AISI 1045 at cutting speeds of 100-250 m/min and bronze CuSn3Zn13Pb4 at cutting speeds of 150-250 m/min. The dominant frequency in the spectrum was slightly higher than the natural frequency of the cutter-oscillating. This confirms that the observed vibration is regenerative self-oscillation. When turning cast iron GG35 the dominant frequency was absent across the entire cutting speed range, indicating the absence of regenerative self-oscillations.


a

b

c

Figure 5. Chips during turning of steel AISI 1045 (*a*), cast iron GG35 (*b*), bronze CuSn3Zn13Pb4 (*c*) at a speed of v=150 m/min

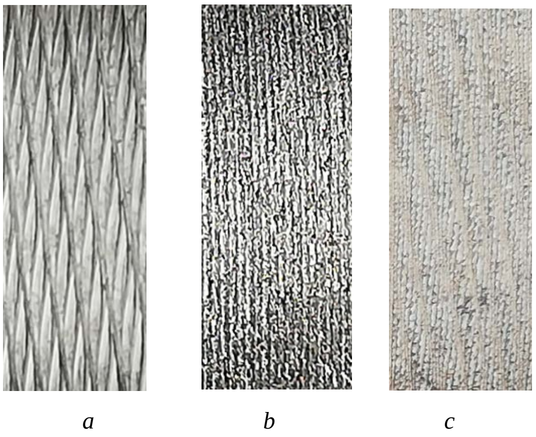

a b c

Figure 6. Vibration pattern on the machined surface of steel AISI 1045 (*a*), cast iron GG35 (*b*), bronze CuSn3Zn13Pb4 (*c*) at a speed of v=150 m/min

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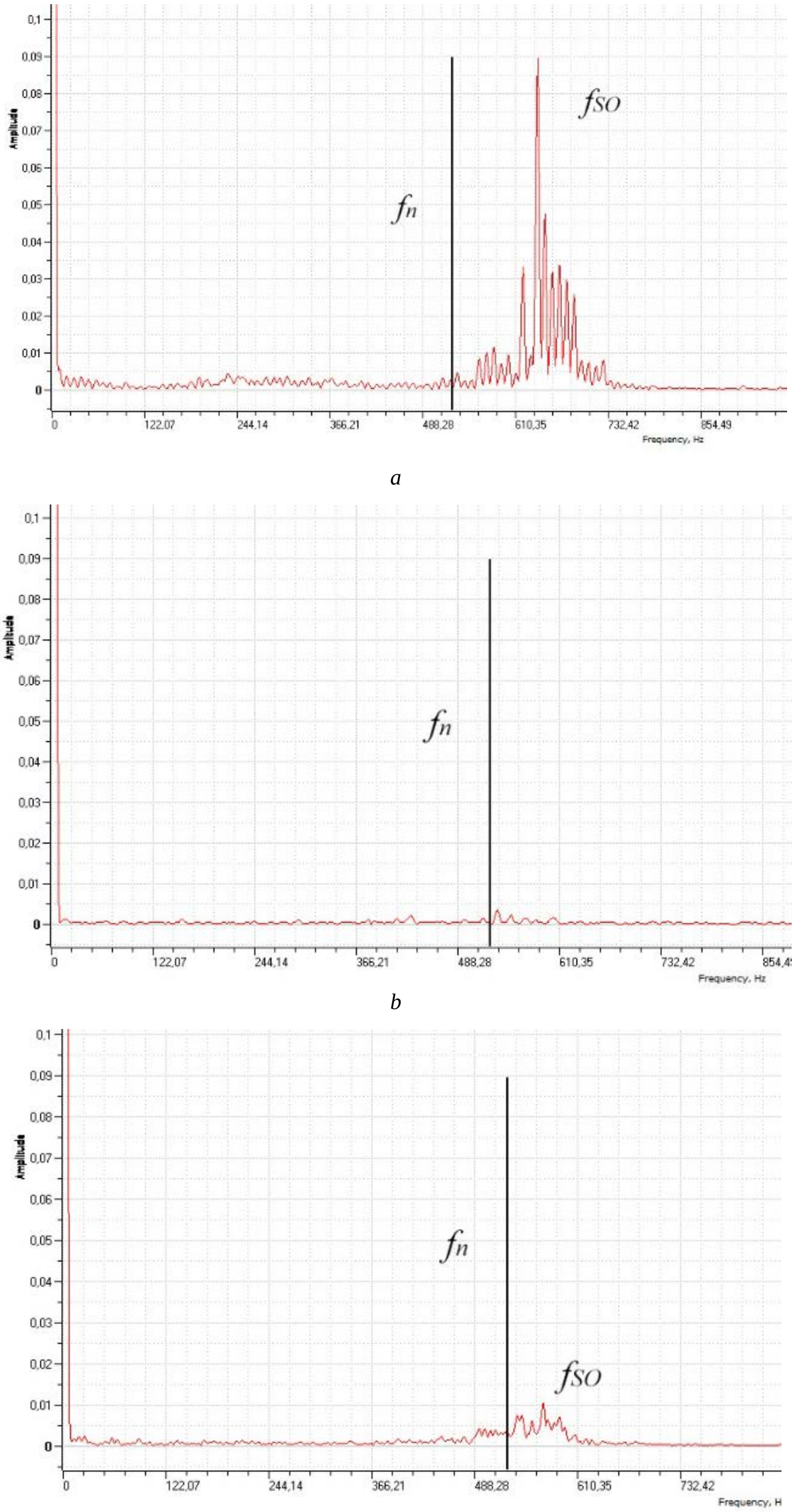

a

b

c

Figure 7. Amplitude-frequency spectrum during turning of steel AISI 1045 (*a*), cast iron GG35 (*b*), bronze CuSn3Zn13Pb4 (*c*) at a speed of *v*=150 m/min

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Conclusion

The conducted studies have shown that the type of chip formation has a significant impact on the excitation of regenerative oscillations during turning. It was found that regenerative oscillations are excited during turning of steel AISI 1045, which produces continuous chips. This is due to the relatively continuous nature of plastic deformation and the stable formation of the shear layer, which facilitates the development of positive feedback between the cutting process and the cutter-oscillator.

At the same time, materials characterized discontinuous chip formation (cast iron GG35, bronze CuSn3Zn13Pb4) dampen regenerative oscillations. The discontinuous, random nature of chip formation, caused by brittle fracture of the material, dampens the oscillator's oscillations via the feedforward coupling and prevents the oscillatory system from oscillating via the feedback coupling.

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ВПЛИВ СТРУЖКОУТВОРЕННЯ, ЩО СТВОРЮЄ СТРУЖКУ НАДЛОМУ, НА ЗБУДЖЕННЯ РЕГЕНЕРАТИВНИХ АВТОКОЛИВАНЬ ПРИ ТОЧІННІ

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Мета роботи. *Метою цього дослідження є вивчення впливу стружкоутворення на збудження регенеративних автоколивань при точінні, порівняння поведінки автоколивань при стружкоутворенні, яке створює зливну стружку та стружку надлому, а також прогнозування стабільності обробки крихких матеріалів.*

Методи дослідження. *Дослідження проводилося в умовах безперервного ортогонального точіння на токарному верстаті з ЧПК. Вібрацію досліджували за допомогою різця-осцилятора з одним ступенем свободи в напрямку зміни товщини шару, що зрізається. Зміщення різальної кромки під час обробки вимірювали за допомогою індуктивного датчика, а сигнали записували за допомогою багатоканальної системи збору даних та обробляли на комп'ютері. Осцилограми аналізували для визначення амплітуди та статичного відхилення.*

Результати. *Експериментальні результати показали, що тип утворення стружки має значний вплив на вібрацію під час точіння. Під час обробки сталі 45, що характеризується зливним стружкоутворенням, у діапазоні швидкостей різання v = 100–250 м/хв спостерігалися регенеративні автоколивання, при цьому амплітуда їх зростала зі збільшенням швидкості різання. Натомість, під час обробки сірого чавуну СЧ35, який утворює стружку надлому, регенеративних автоколивань не виявлено; були наявні лише випадкові коливання низької амплітуди, рівень яких залишався майже постійним у всьому діапазоні швидкостей різання. Для бронзи БрОЗЦ13С4, що також утворює стружку надлому, регенеративні автоколивання виникали лише при вищих швидкостях різання (v=150–250 м/хв), амплітуда їх зростала зі швидкістю різання, подібно до сталі.*

Наукова новизна. *Наукова новизна цього дослідження полягає у встановленні впливу стружкоутворення на умови пригнічення та збудження регенеративних автоколивань при точінні.*

Практична цінність. *Практичне значення цього дослідження полягає в покращенні прогнозування стабільності при обробці матеріалів з різними механізмами стружкоутворення. Отримані результати можуть бути використані для вибору оптимальних умов різання, які зменшують або запобігають виникненню регенеративних автоколивань, особливо під час обробки крихких матеріалів.*

Ключові слова: *вібрація, регенеративні автоколивання, стружкоутворення, різець-осцилятор, форма стружки.*

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