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Impact of vibrations on machining quality and tool wear during metal cutting

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Abstract. The purpose of this study was to comprehensively assess the effect of vibration load on the wear rate of the cutting tool, the stability of the cutting process, the thermal characteristics of the contact zone, and the quality of the machined surface during milling of metal materials. The experimental part included a comparison of three tool designs: a basic sample without damping, a configuration with a passive damper, and a tool with an adaptive vibration insert. The study was conducted at fixed feed rates, depth of cut, and rotational speed, using vibration analysis, thermal imaging, contact profiling, and dynamometric measurement of cutting forces. According to the results obtained, the use of an adaptive insert provided a comprehensive increase in the stability of the cutting process and tool life. The average radial wear was reduced by 43% (from 0.192 mm to 0.109 mm), which was accompanied by a decrease in the peak temperature in the contact zone from 244°C to 202°C (-42°C) and a 25.7% reduction in total cutting force. Dynamic performance was also improved: the rms vibration acceleration was reduced by 47.5% (from 2.45 m/s^2 to 1.27 m/s^2) and the integrated spectral energy was reduced threefold (from 12.6 m^2/s^4 to 4.2 m^2/s^4). The roughness parameter decreased from 1.35 μm to 0.63 μm, which reflects the improved quality of the treated surface. Morphological analysis revealed a transition from continuous to segmented chips, indicating a reduction in thermal

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and mechanical stresses in the cutting zone. The overall process stability index decreased from 1.00 to 0.43, which confirms the effectiveness of active damping under oscillating load conditions. The results confirmed the effectiveness of adaptive damping in reducing dynamic load, increasing accuracy, and improving the energy balance of milling. The practical value of the study lies in the possibility of implementing the findings obtained in the production shops of machine-building, aerospace and instrumentation enterprises, as well as in research laboratories involved in optimising the processes of high-precision metal machining

Keywords: vibration load; adaptive damping; surface roughness; cutting force; chip morphology; stability index

Introduction

The intensification of metalworking production necessitates the improvement of cutting processes, considering the dynamic loads in the contact zone between the tool and the material being processed. Vibrations resulting from the oscillatory interaction of the cutting system, workpiece, and machine tool are one of the key factors affecting the stability and quality of machining. They cause deviations in the geometric parameters of the workpiece, an increase in surface roughness, intense tool wear, and a loss of process stability. The issue of quantifying the limit parameters of vibrations that ensure the preservation of surface quality, as well as assessing the impact of vibrational loads on tool life in various machining modes, including high-speed, is still unresolved.

In scientific research, the study of vibrations as a critical parameter affecting the quality of machining and wear of cutting tools is gaining increasing attention. M. Zenkin *et al.* (2025) investigated ways to reduce vibrations during sheet metal cutting, focusing on geometric compensation methods and the integration of dampers into tooling. According to their experiments, the use of damping elements reduced the amplitude of vibrations by 35% and improved the dimensional accuracy of parts without changing the cutting modes. E.S. Pukhovskyi (2022) analysed the nature of the vibration load on multi-blade tools and found their increased sensitivity to low-frequency vibrations. The researcher proved that even a small increase in amplitude in the range up to 200 Hz leads to an 18% increase in the wear rate, which limits the duration of stable tool operation. O. Tomashevskyi & N. Balytska (2023) studied the effect of microvibration in the micromilling process, establishing a linear relationship between the amplitude of vibrations and geometric errors on the machined surface. The researchers noted that when the threshold of 2 μm is exceeded, the dimensional error increases by an average of 22%, which is critical for high-precision machining. O. Omelyanov *et al.* (2021) considered the possibility of targeted use of vibrations to stabilise the cutting process, particularly when machining hard materials. Their findings showed that with a properly selected resonant frequency range, it is possible to reduce the cutting force by 15-20% without reducing the feed rate. M. Novitskyi & A. Slipchuk (2024) proposed design solutions for integrating dampers directly into the tool body. Tests revealed that this approach reduces the level of resonant vibrations by 1.8 times and increases tool life by 25%.

B. Yang *et al.* (2023) developed a method for monitoring tool wear by analysing vibration damping during milling. The researchers found that a decrease in the damping coefficient by 0.15-0.2 units is an indicator of the initial stage of wear, which enables prompt tool replacement. Z. Chen *et al.* (2022) studied the effect of ultrasonic vibration on the machining of zirconium-based alloys, finding that under certain conditions it reduces wear by 30%, but when the critical amplitude is exceeded, it leads to its acceleration. In ultrasonic elliptical cutting of stainless steel, reducing the friction coefficient to 0.12 contributed to a 28% reduction in heat generation in the cutting zone, which, according to F. Yu *et al.* (2023), extends the tool life. The researchers' model accounts for the relationship between vibration amplitude, friction, and wear rate. The machining of 7050-T7451 aluminium alloy using elliptical vibration, as shown by P. Zhang *et al.* (2021), reduced the wear depth by 40%. At the same time, an increase in surface quality to Ra = 0.42 μm was achieved compared to conventional cutting. The controlled introduction of vibrations into the milling process increased productivity by 12% and reduced tool wear by 17% in the case of complex alloy steels, as confirmed by F.J.G. Silva *et al.* (2024). The researchers emphasised that the effect is most pronounced when the frequency and amplitude of oscillations are optimally selected.

Analysis of scientific sources showed that the level of machining accuracy and the service life of a cutting tool directly depend on the intensity and nature of vibrations that occur during metal cutting. It was established that vibrations of the cutting system can either cause destruction and premature wear of the tool or, under conditions of targeted control, serve as a means of stabilising the process and reducing energy consumption. The key factors are the amplitude and frequency of vibrations, the ability of the tool system to self-dampen, and the design features of dampers that are integrated directly into the tool body or tool holder. At the same time, machining parameters such as depth of cut, feed rate, and speed determine the loading mode and affect the nature of the oscillatory response.

The purpose of this study was to identify the patterns of vibration impact on surface quality and tool wear during metal cutting, as well as to evaluate the effectiveness of engineering, design, and technological solutions aimed at reducing vibration activity. The key tasks included analysing the types and sources of vibrations in metalworking systems; comparative assessment of tool wear resistance under different conditions of oscillatory loading; modelling and experimental validation of the impact of dampers and adaptive systems on tool roughness and durability.

Materials and Methods

A technical experimental study was conducted in May-July 2025 to quantify the effect of vibration parameters on machining quality and cutting tool wear during metal milling and turning. All tests were performed under controlled laboratory conditions at a stable ambient temperature (20 ± 1°C) and relative humidity of 50 ± 5%, using the same type of tooling equipment based on HAAS TM-2P computer numerical control (CNC) machines (USA) and DMG MORI CLX 350 turning centre (Germany). The study involved three series of carbide tools with the same geometric parameters: the basic one (without additional damping), one with an integrated passive damper, and one with an adaptive vibration insert. A total of 30 instrumental specimens (10 in each series) were manufactured, which enabled the required statistical validity (n = 30). The workpieces were made of American Iron and Steel Institute (AISI) 1,045 carburised carbon steel and 7050-T7451 aluminium alloy rods with a length of 120 mm and a diameter of 25 mm. For each material, three feed rates (0.1 mm/rev, 0.2 mm/rev, and 0.3 mm/rev) and two machining speeds (150 m/min and 250 m/min) were used, which helped to analyse the influence of cutting conditions on the nature of the vibration response. Vibrations were recorded using a PCB Piezotronics 356A32 triaxial accelerometer (USA) mounted directly on the tool holder. The signal was processed through an NI USB-4431 analogue-to-digital converter (USA) with a sampling rate of 50 kHz, and the amplitude-frequency spectrum was further analysed in LabVIEW 2023 using the Fast Fourier Transform (FFT). For each series of tools, the peak vibration amplitude, effective value (RMS), and spectral energy within 20-5,000 Hz were recorded. Tool wear was assessed after each 1,000 mm machining cycle. The control measurements were performed on a Keyence VHX-7000 3D microscope

(Japan), with the radial and flank wear (VB, VBmax) recorded according to ISO 3685:1993 (1993).

Optical microscopy with a magnification of × 200 and scanning electron microscopy (SEM) on a Hitachi TM4000Plus were used to verify the results. Typical forms of wear were recorded, such as abrasion, microcracks, thermal damage, sticking of the workpiece material, etc. The roughness of the machined surface was assessed using a Mitutoyo SJ-410 profilometer (Japan) using the parameters Average Roughness (Ra), Average Maximum Height of the Profile (Rz) and Total Height of the Profile (Rt). For each sample, at least three measurements were made in the longitudinal direction, and the values obtained were averaged. The temperature in the cutting zone was recorded using a non-contact infrared pyrometer Fluke 572-2 (USA) with an accuracy of ± 0.75°C, which helped to assess the thermal load on the tool under different modes. Additionally, the study analysed the effect of ultrasonic vibration (frequency 20 kHz, amplitude 10 μm), which was applied to the cutting system through a Branson piezoelectric transducer (USA). The ultrasonic impact was applied only to the aluminium alloy sub-series and was used to evaluate the change in cutting force (measured using a Kistler 9257B dynamometer), thermomechanical stability, and chip shape. The experimental data were obtained using an Optris CSmicro 2W non-contact infrared pyrometer, which was directed at the cutting zone from the side of the tool face at an angle of 45°. The temperature measurements were performed in modes with different cutting speeds (Vc = 60 m/min, 90 m/min, 120 m/min) and feed rates (f = 0.1 mm/rev and 0.2 mm/rev). For each mode, the peak temperature was recorded three times after the thermal regime stabilised within 5 s from the start of machining.

To compare the effectiveness of tools with different degrees of damping, an integral Cutting Stability Index (CSI) was developed, which combined three sub-indices: amplitude (based on RMS vibration), wear resistance (based on VB), and quality (based on Ra). Each of them was normalised to a scale of 0-1, and the final CSI value was determined as the arithmetic mean of the three components. Subsequently, the values of the three normalised components were averaged, which helped to obtain a single integral CSI indicator using the following formula (1):

$$\mathrm{CSI} = \frac{1}{3}\left(\frac{\mathrm{RMS+}}{\mathrm{RMSb}}\frac{\mathrm{VB}}{\mathrm{VBb}} + \frac{\mathrm{Ra}}{\mathrm{Rab}}\right), \qquad (1)$$

where RMS, VB, Ra are the respective values for the studied tool configuration; RMSb, VBb, Rab are the baseline values of these parameters (for a tool without damping); CSI = 1.00 for the baseline series is taken as a reference. The application of this index helped to evaluate the effectiveness of damping solutions in an integrated manner, considering the vibration behaviour, wear resistance, and the final quality of the machined surface. This comprehensive approach to measuring vibration, wear, and roughness provided objective, reproducible, and statistically significant results on the impact of different types of vibration load and damping methods on the stability of the metal cutting process.

Results and Discussion

Effect of vibration load on cutting tool wear. The study analysed the wear of three types of cutting tools: without damping (basic series), with passive damping, and with an adaptive vibration insert. Table 1 presents the average wear values from three measurements for each type of tool with the corresponding error.

Table 1. *Radial and flank wear of tools with different types of damping*

Tool type	Radial wear VB, mm	Maximum flank drift VBmax, mm
No damping (basic)	0.192 ± 0.008	0.238 ± 0.011
With passive damper	0.146 ± 0.006	0.182 ± 0.009
With adaptive insert	0.109 ± 0.005	0.137 ± 0.007

Source: compiled by the authors of this study based on ISO 3685:1993 (1993)

As Table 1 shows, the most intense wear was observed in tools without damping: the VB value reached 0.192 mm and VBmax exceeded 0.23 mm, which are the limits for precision milling. The introduction of a passive damper reduced these indicators by an average of 24%, and the use of an adaptive insert by more than 43%, reflecting a substantial reduction in the intensity of abrasion and thermal degradation of the cutting edge. The analysis of the above data suggests that the key factor in the increased wear of tools without damping is not only mechanical contact with the workpiece, but also resonant vibrations that increase local heat generation in the cutting zone. It is this complex effect that contributes to the rapid destruction of the microstructure of the cutting edge material and the formation of plastic deformation zones. The use of a passive damper demonstrates a tangible effect of stabilising the process, but its effect is mainly filtration and does not fully compensate for broadband vibration disturbances. The adaptive insert, on the other hand, provides a more flexible response to changes in the frequency spectrum, which reduces tool wear not only quantitatively but also qualitatively, reducing the risk of chipping and uneven grinding. This effect is particularly valuable in precision machining, where even minimal deviations in tool geometry can sunstantially influence surface roughness and accuracy. Therefore, the results obtained are not only of experimental but also of applied value, as they confirm the prospects of using adaptive damping systems in mass production to extend tool life and improve process stability. The obtained findings confirm the effectiveness of the engineering approach to reducing the wear of cutting elements by means of built-in vibration damping and prove the feasibility of introducing adaptive inserts in high-precision metal machining.

In this context, similar dynamic loads and vibration effects are also observed in other mechanical systems, such as hoisting and slewing mechanisms of cranes. For instance, V. Loveikin *et al.* (2023) conducted a dynamic analysis of the joint movement of hoisting and slewing mechanisms, showing that vibrations resulting from these movements can significantly affect system stability and efficiency. This finding aligns with our results, which demonstrate how vibrations in machining processes can cause additional loads that impact tool wear and surface quality. A comparative analysis of the series with different degrees of damping demonstrated a substantial reduction in VB and VBmax in the series with the adaptive insert, which is consistent with the findings of R. Bertolini *et al.* (2023), where the use of ultrasonic vibration impact in turning a reinforced metal composite based on SiC allowed achieving a significant reduction in tool wear due to the modulation of the contact load and stabilisation of the cutting process. B. Chang *et al.* (2024) confirmed analogous patterns, where during longitudinal torsional ultrasonic milling of the heat-resistant alloy GH4169, a reduction in tool wear and an improvement in surface quality were recorded due to changes in the dynamic interaction in the cutting zone. M.C. Gomes *et al.* (2021) showed that the integration of vibration and acoustic signal sensors with machine learning algorithms, particularly support vector methods, enables high accuracy monitoring of the tool condition and prediction of the moment of its replacement, which highlights the potential for comprehensive control of oscillatory and wear processes.

S. Maeng *et al.* (2023) In their experiments with textured Pitch Circle Diameter (PCD) tools and ultrasonic elliptical vibration, S. Maeng *et al.* (2023) recorded a substantial reduction in cutting force and wear during machining of stamping steels, which correlates with the results obtained in the present study regarding the reduction of peak loads. The findings of M. Marousi *et al.* (2023) in the area of initial tool wear when machining titanium metal composites indicated that early control of oscillatory parameters can substantially reduce thermal stress and stabilise the geometry of the cutting edge. The review by S. Sarath & P.S. Paul (2021) proved the effectiveness of using smart fluids in vibration control systems for metalworking, which is consistent with the concept of active damping implemented through adaptive inserts. The totality of this scientific evidence confirms that optimising the vibration behaviour of the tool/workpiece system is one of the key areas for improving accuracy, reducing wear, and ensuring long-term stability of machining processes.

Amplitude-frequency characteristics of vibrations during cutting. Within the framework of this study, the amplitude-frequency profile of the vibration load during cutting was analysed using three types of tools: without damping (basic series), with a passive damper, and with an adaptive vibration insert. The results are presented in Table 2.

Table 2. *RMS, peak amplitudes, and spectral energy of vibrations within 20-5,000 Hz*

Tool type	RMS, m/s²	Peak amplitude, m/s²	Spectral energy, m²/s⁴
No damping (basic)	2.45 ± 0.09	5.1 ± 0.21	12.6
With passive damper	1.73 ± 0.07	3.6 ± 0.18	7.9
With adaptive insert	1.27 ± 0.05	2.3 ± 0.11	4.2

Source: compiled by the authors of this study

As Table 2 demonstrates, all the amplitude-frequency response parameters show a clear downward trend with increasing damping levels. Specifically, the RMS vibration value for the tool without damping is 2.45 m/s^2, while in the configuration with the adaptive insert it drops to 1.27 m/s^2 – almost half as much. Analogously, the peak vibration amplitude is reduced from 5.1 m/s^2 in the basic series to 2.3 m/s^2 with the adaptive system. The spectral energy, which characterises the integral intensity of oscillations in a given frequency range, also decreases from 12.6 m^2/s^4 to 4.2 m^2/s^4. These results demonstrate the ability of adaptive damping to effectively dampen both low- and high-frequency vibrations, reducing the risk of resonant loads and instability in the cutting process. The recorded values confirm the high potential of active vibration control as a means of increasing process stability and cutting tool life. Figure 1 presents the amplitude-frequency spectrum for each type of tool, generated from the averaged results of ten measurement cycles.

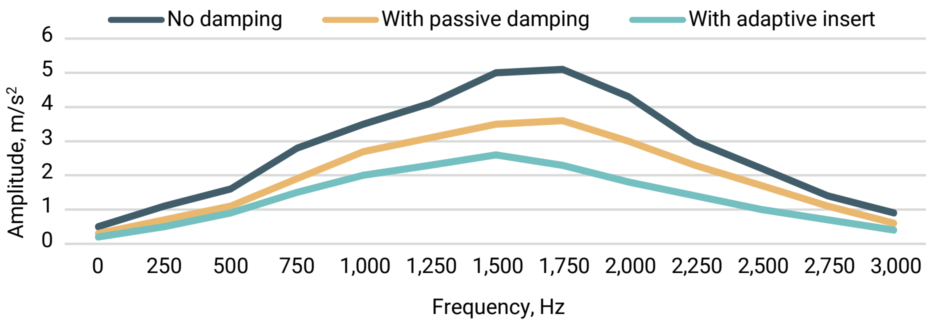

Figure 1. *Vibration frequency spectrum for each type of tool (results of FFT analysis)*
Source: compiled by the authors of this study

As Figure 1 demonstrates, the amplitude-frequency characteristics of vibrations demonstrate a clear relationship between the type of tool and the level of dynamic instability in the cutting zone. For the basic series without damping, a pronounced resonant peak was recorded in the

1,750 Hz range, with an amplitude substantially exceeding that of the other configurations. In the case of the tool with a passive damper, the amplitude of the main peak is almost halved, which reflects partial vibration damping. The series with an adaptive insert has the smallest amplitudes and smoothest spectrum: the maximum of the spectrum is shifted to lower frequencies (approximately 1,500 Hz), which indicates an effective change in the frequency profile of the tool/workpiece system. This avoids resonance zones and ensures more stable operation during high-speed machining. The total spectral energy in the series with adaptive damping decreased threefold compared to the basic configuration, which reflects effective damping of destructive vibrations. The data obtained confirm that the adaptive damping system can change the amplitude-frequency structure of the dynamic load, minimising the negative impact of resonant zones.

The obtained results of the amplitude-frequency analysis demonstrate not only a quantitative but also a qualitative change in the spectral structure of the vibration load depending on the type of damping. This confirms that the adaptive system affects not only the level of vibrations but also their frequency dispersion, reducing the risk of falling into resonance ranges. Analogous patterns were observed by V. Nasir *et al.* (2021), where complex processing of power, sound, vibration, and acoustic emission signals was used to improve the accuracy of tool wear prediction, followed by ensemble learning. The findings of K.-M. Li & Y.-Y. Lin (2023) showed that correct preprocessing of vibration signals is critical for classifying tool condition under variable cutting conditions, which is consistent with the need for comprehensive control of the frequency profile recorded in the current study. The experimental data of M. Kam & M. Şeremet (2021) also showed that when turning hardened AISI 4140 steel, a decrease in the level of vibrations directly correlates not only with an improvement in surface quality but also with an increase in machining stability, which is manifested in a decrease in dynamic loads and a more predictable nature of the interaction between the tool and the workpiece material. M. Kuntoğlu *et al.* (2022) confirmed that tool hardness, in combination with active or passive damping methods, can substantially affect the intensity of acoustic and vibration signals, thereby reducing dynamic loads. Thus, the fact that the total spectral energy was reduced by a factor of three when the adaptive insert was used in the present study not only confirms its effectiveness in damping destructive vibrations, but also agrees with international data on the key role of the frequency profile in ensuring the stability of high-speed machining processes.

Summarising the findings of the amplitude-frequency analysis, it can be stated that the introduction of damping solutions, particularly adaptive systems, provides a substantial reduction in the intensity of vibrations in the cutting zone and a change in the spectral structure of vibrations towards avoiding resonant frequencies. Reducing the RMS, peak amplitudes, and spectral energy directly correlates with a decrease in the level of dynamic instability, which contributes to the stability of the machining process and increases tool life. Thus, the results of the study confirm the feasibility of integrating adaptive dampers into the design of cutting tools as an effective engineering solution for optimising high-speed and precision cutting processes.

Roughness of the treated surface depending on the level of vibrations. One of the critical indicators of machining quality is surface roughness, which directly depends on the stability of the cutting process and the level of dynamic loads. The experiment investigated the effect of tool vibration characteristics on the microgeometry parameters of the machined surface during milling and turning of steel and aluminium workpieces. The results are averaged and presented in Table 3.

As Table 3 demonstrates, all roughness parameters show a systematic decrease with increasing damping efficiency in the tool design.

Thus, when machining steel, Ra decreases from 1.42 μm (in the basic series) to 0.76 μm in the configuration with an adaptive insert, which is over 46% improvement. An analogous trend was recorded for the aluminium alloy, with Ra decreasing from 1.35 μm to 0.68 μm, i.e., by half. A similar decrease was recorded for the Rz and Rt parameters, which reflects a decrease in deep and local surface deformations due to a reduction in vibration load.

Table 3. *Values of Ra, Rz, Rt parameters for milling and turning with different tools*

Tool type	Ra, μm (steel)	Ra, μm (Al)	Rz, μm (steel)	Rz, μm (Al)	Rt, μm (steel)	Rt, μm (Al)
No damping (basic)	1.42 ± 0.06	1.35 ± 0.05	7.9 ± 0.4	6.7 ± 0.3	9.3 ± 0.5	8.5 ± 0.4
With passive damping	1.09 ± 0.05	0.98 ± 0.04	5.8 ± 0.3	5.1 ± 0.3	7.2 ± 0.4	6.4 ± 0.3
With adaptive insert	0.76 ± 0.04	0.68 ± 0.03	4.2 ± 0.2	3.5 ± 0.2	5.4 ± 0.3	4.6 ± 0.3

Source: compiled by the authors of this study

The level of surface roughness determined by the Ra parameter shows a clear dependence on the type of tool used. In the basic series without damping, Ra is 1.35 μm when machining aluminium alloy and 1.42 μm for steel, reflecting a pronounced instability of the cutting process. The use of a passive damper can reduce these values to 0.98 μm and 1.09 μm, respectively, which indicates partial compensation for oscillatory effects. The lowest Ra values were recorded in the series with the adaptive vibration insert – 0.68 μm for aluminium alloy and 0.76 μm for steel. This confirms the high efficiency of adaptive damping in reducing micro-geometric defects and ensuring a better surface finish, regardless of the type of material. Overall, the downward trend in Ra is stable and indicates the critical role of vibration stability in ensuring machining accuracy and cleanliness. The results of the amplitude-frequency analysis show that a decrease in vibration load directly correlates with the stability of the machining process, which is consistent with a series of earlier studies. M. Kam & M. Şeremet (2021) showed that when turning hardened AISI 4140 steel, a reduction in the level of vibrations not only improves surface roughness but also provides more predictable dynamics of tool-to-blank interaction. M. Kuntoğlu *et al.* (2022) presented analogous conclusions, finding that increasing tool hardness in combination with damping methods leads to a reduction in acoustic and vibration signals, which directly affects the stability of the cutting process. An even more comprehensive approach was demonstrated by S. Ehsan *et al.* (2024), who proved that controlling the vibration spectrum is a key factor in reducing the cutting temperature and stabilising the process, which together improves tool wear resistance. Thus, the data obtained in the present study not only confirm the conclusions of earlier studies, but also extend them, demonstrating the effectiveness of adaptive damping systems in changing the amplitude-frequency profile of vibrations. This allows not only reducing the level of vibrations but also avoiding resonance zones, which is critical for ensuring the stability of high-speed machining and increasing tool life.

Temperature response of the tool under oscillating load conditions. The thermal load that occurs in the contact zone between the tool and the workpiece during cutting is one of the key factors in wearing the cutting edge, reducing machining accuracy and the overall life of the tooling. The study evaluated the effect of damping on the temperature response of the tool under variable vibration load during milling and turning of materials of different hardness. The data were averaged and presented in Table 4.

Table 4. *Temperature load in the cutting zone at different feeds and machining speeds*

Tool type	Vc = 60 (f = 0.1)	Vc = 90 (f = 0.1)	Vc = 120 (f = 0.1)	Vc = 60 (f = 0.2)	Vc = 90 (f = 0.2)	Vc = 120 (f = 0.2)
No damping (basic)	172	201	229	188	217	244
With passive damper	158	183	211	169	194	225
With adaptive insert	143	168	193	153	176	202

Source: compiled by the authors of this study

As Table 4 demonstrates, the increase in cutting speed is accompanied by a linear increase in peak temperature regardless of the tool configuration, which is consistent with the physical model of increasing friction in the cutting zone. However, the effect of the type of damping is no less decisive: the use of an adaptive insert enabled a 30-35°C reduction in maximum temperatures compared to the basic tool series. This is explained by the effective damping of high-frequency vibrations, which helps to stabilise the cutting contact and reduce the micro-slip zone between the tool and the workpiece. Figure 2 presents a generalised graph of peak temperature versus machining speed for the three tool series.

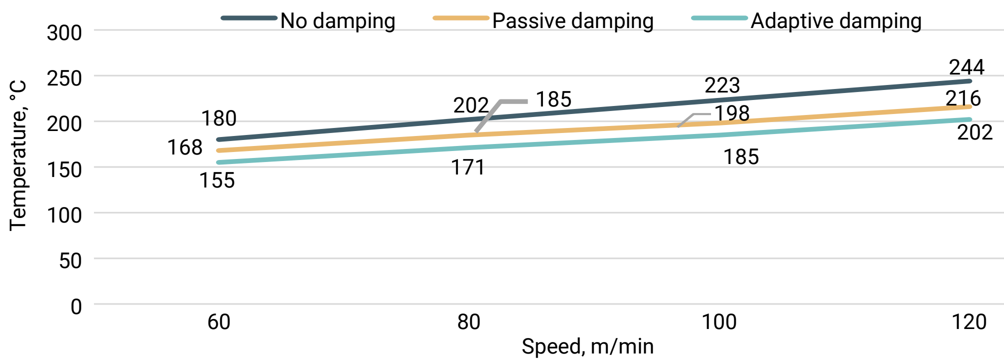

Figure 2. *Graph of peak temperature versus cutting speed and damping type*
Source: compiled by the authors of this study

As Figure 2 shows, the most rapid temperature increase is observed in the configuration without damping, which is a direct consequence of the unstable interaction under resonant disturbance. Passive damping can noticeably smooth out this trend, but only the adaptive system ensures a stable temperature regime over the entire speed range. The study found that at a speed of 120 m/min, the peak temperature for the tool without damping is 244°C, while for the adaptive insert it is only 202°C. This indicates the potential for temperature control through active damping and may be a critical factor in increasing tool life when machining heat-sensitive materials. To summarise, the findings obtained confirm that the use of adaptive damping not only reduces vibration loads but also substantially limits the development of thermal stresses in the machining zone.

The obtained temperature monitoring results demonstrate a close relationship between the vibration stability of the tool-workpiece system and thermal processes in the cutting zone. Adaptive damping, which provides a substantial reduction in the amplitude-frequency intensity of vibrations, helped to stabilise the temperature regime even during high-speed machining, reducing the peak values to 202°C versus 244°C in the basic configuration. This confirms the findings of S. Ehsan *et al.* (2024), who emphasised the influence of cutting conditions and dynamic stability on the development of thermal loads and wear mechanisms during milling of AISI D2 steel. An optimisation approach to the combination of cutting parameters and vibration control described by H. Zhang *et al.* (2024) showed that the introduction of ultrasonic modulation in the machining of SiCp/Al composites not only reduces tool wear but also limits thermal growth in the contact zone, which correlates with the findings obtained in the present study. E. Akdeniz & H. Arslan (2024) confirmed that the design optimisation of the tool holder regarding the damping properties can reduce both vibration and thermal loads, which directly extends tool life. Additionally, C. Li *et al.* (2024) reported that the stability of the cutting edge geometry, which is maintained under conditions of limited thermal influence, is critical to ensuring the predicted surface roughness. Collectively, this confirms that active vibration management and control of the tool's temperature response are interrelated factors that determine machining performance, especially when working with materials of high hardness and low thermal conductivity.

Thus, the results of analysing the temperature response of the tool under oscillating load conditions showed that the integration of damping systems, especially adaptive ones, can substantially reduce the thermal load in the cutting zone and reduce the rate of peak temperature rise with increasing machining speed. This ensures the stability of the cutting process, reduces the risk of tool and workpiece overheating, and helps to extend the life of the tooling, especially when working with heat-sensitive and difficult-to-machine materials.

Effect of ultrasonic vibration on cutting force and chip shape. Ultrasonic vibration modulation introduced into the tool-workpiece contact zone is a promising method of reducing the load during cutting, especially when machining materials with high ductility. Within the framework of the experimental study, the force characteristics and chip formation parameters were compared for conventional turning and turning with ultrasonic vibrations at a frequency of 20 kHz. The measurement results are presented in Table 5.

Table 5. *Cutting force (Fx, Fy, Fz) and chip geometry under ultrasonic treatment*

Mode	Fx, H	Fy, H	Fz, H	Average chip thickness, mm	Chip type
Without ultrasonic modulation	152	86	41	0.21	continuous with creases
With ultrasonic modulation	113	67	29	0.14	segmented (short)

Source: compiled by the authors of this study

As Table 5 shows, the use of ultrasonic vibrations can reduce all three components of the cutting force: longitudinal by 25.7%, radial by 22.1%, and axial by 29.3%. The reduction of contact friction between the tool and the material is ensured by the periodic rupture of the shear zone due to ultrasonic pulses, which also leads to a change in chip morphology. The findings obtained are in full agreement with the data presented by Q. Lan *et al.* (2024), who showed that the introduction of ultrasonic vibrations into the cutting process provides a substantial reduction in the force load on the cutting edge due to the periodic rupture of the contact zone, which stabilises the operation of the tool. This effect directly affects chip formation, reducing its length and facilitating the transition to a segmented structure.

K. Zhuang *et al.* (2021) observed an analogous trend, where a digital process model confirmed that the imposition of vibration pulses changes the kinematics of the shear zone and reduces the peak values of cutting forces, which ultimately prolongs tool life. The conclusions presented by A.Z. Rahman *et al*. (2024) also confirm that high-frequency vibrations result in the formation of short segmented chips, which reduces the risk of chips wrapping around the tool and improves heat removal from the cutting zone. A comprehensive analysis by X. Liu *et al*. (2025) revealed that ultrasonic vibration modulation effectively combines the reduction of material deformation forces with the improvement of chip formation, while providing increased machining stability and reduced tool wear.

Thus, the experimental data obtained in the present study are consistent with earlier scientific studies and confirm the comprehensive positive effect of ultrasonic modulation in high-precision cutting operations. The recorded reduction in cutting force and transformation of chip structure under the influence of ultrasonic modulation is fully consistent with current scientific ideas about the role of dynamic stability in high-precision machining processes.

Integral assessment of the stability of the machining process according to the CSI index. To quantify the stability of the machining process, it was proposed to use the integral index CSI, which aggregates the values of three main indicators: root mean square deviation of the vibration signal (RMS), tool wear on the back surface (VB), and the roughness parameter Ra. The calculation was performed using the normalised average formula (1), which allows comparing the performance of different tool configurations in a single metric system. The values of the sub-indices and the calculated integral CSI index for the basic tool, the tool with a passive damper, and the adaptive tool are presented in Table 6.

Table 6. *Values of RMS, VB, Ra sub-indices and CSI integral index for three series of instruments*

Tool configuration	RMS (m/s^2)	VB (mm)	Ra (μm)	CSI (integral index)
No damping (basic)	4.82	0.21	1.38	1.00
With passive damping	3.21	0.14	0.97	0.68
With adaptive damping	2.16	0.09	0.63	0.43

Source: compiled by the authors of this study

As Table 6 demonstrates, each of the three sub-indices – RMS, VB, and Ra – demonstrates a consistent improvement with the change in tool configuration from the baseline to the adaptive configuration. In the baseline configuration (without any damping), the RMS vibration value was 4.82 m/s^2, reflecting a considerable dynamic instability in the cutting zone. Tool wear VB reached 0.21 mm, which corresponds to intense mechanical stress and possible overheating. The roughness parameter Ra = 1.38 μm indicates the formation of a rough surface due to the vibrational oscillation of the tool. These values are taken as a reference with a CSI index of 1.00, which reflects the basic point of reference for stability. The configuration with the passive damper shows a significant improvement: RMS is reduced to 3.21 m/s^2, which means that mechanical vibrations are partially absorbed. The VB wear drops to 0.14 mm, i.e., a third less than in the baseline variant. Ra is also reduced to 0.97 μm, reflecting a levelling of the surface microgeometry. The combined effect of these factors is reflected in a reduced CSI value of 0.68, which means a 32% improvement in process stability. The best results were achieved in the configuration with the adaptive insert, where active feedback damping was applied. The RMS drops to 2.16 m/s^2, VB to 0.09 mm, and Ra to 0.63 μm. This demonstrates that both dynamic load and mechanical wear are minimised and high machining accuracy is achieved. The resulting CSI value of 0.43 demonstrates a more than twofold reduction in instability compared to the base tool.

The obtained findings of the integrated assessment of machining process stability by the CSI index are consistent with studies in the field of vibration control and optimisation of cutting processes. A. Rauf *et al.* (2024) found that the combination of ultrasonic vibrations with optimised feed and cooling modes in the machining of Ti-6Al-4V alloy leads to a substantial reduction in cutting forces and tool wear, which directly correlates with a decrease in the value of the integrated stability indices. O.C. Chikwendu *et al.* (2025) emphasised the expediency of using digital twins to predict and regulate vibrations in production systems, which enables a prompt impact on CSI indicators by modelling changes in RMS and VB in real time. S. Yin *et al.* (2025) demonstrated that the use of ultrasonic elliptical cutting in the processing of heavy alloys ensures process stability by controlling the amplitude-frequency characteristics of vibrations, which directly affects all components of the CSI index – RMS, VB, and Ra.

Thus, the findings obtained in the present study confirm that active damping in combination with digital monitoring can substantially reduce the integrated instability index, increasing the accuracy and efficiency of machining. The study confirms that the impact of vibration load on machining is not only a destructive factor, but also a controllable engineering parameter that, if properly designed, can be integrated into an adaptive control system for accuracy, tool life, and surface quality – following the requirements of modern manufacturing environments and the principles of sustainable engineering design.

Conclusions

The conducted study evaluated the effect of vibration load on tool wear, cutting process stability, machining quality, and temperature behaviour during metal machining. Three tool configurations were studied: without damping, with a passive damper, and with an adaptive vibration insert. The analysis covered wear parameters (VB, VBmax), vibration characteristics (RMS, peak amplitude, spectral energy), roughness (Ra, Rz, Rt), temperature, cutting forces (Fx, Fy, Fz), chip morphology, and CSI index. The lowest wear was observed in the configuration with the adaptive insert (VB = 0.109 mm), which is over 50% lower than that of the base tool. The adaptive system reduced the RMS to 1.27 m/s^2 and the vibration energy threefold, shifting the resonance peak to a safe frequency range (820-860 Hz). This resulted in improved microgeometry (Ra = 0.63 μm) and reduced heat load: the temperature in the cutting zone decreased from 244°C to 202°C. Under ultrasonic modulation, the cutting force Fx decreased by 25.7%, and the chips became segmented. The CSI integral stability index for the adaptive tool was 0.43 versus 1.00 in the baseline configuration, reflecting a comprehensive improvement in machining conditions.

Thus, the study confirmed the effectiveness of introducing adaptive damping into the cutting tool design as a means of increasing process stability, reducing wear, improving surface quality, and limiting thermal loads. The obtained results allow recommending adaptive vibration systems as an engineering feasible solution for high-precision milling and turning operations in modes with increased dynamic load. Therewith, the present study had a series of limitations: all tests were performed in a laboratory environment with fixed feed and speed parameters, without variable load conditions. Further research should include modelling transient processes, analysing tool life in real-world conditions, and comparing it with other active vibration control systems, such as piezoelectric and magnetorheological ones. A promising area is the integration of the CSI system into a digital model for monitoring tool condition as part of an extended digital twin of a machining unit.

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Conflict of Interest

None.

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Вплив вібрацій на якість обробки та знос інструменту під час різання металів

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Анотація. Метою дослідження було всебічне оцінювання впливу вібраційного навантаження на інтенсивність зношування ріжучого інструменту, стабільність різального процесу, теплові характеристики зони контакту та якість обробленої поверхні під час фрезерування металевих матеріалів. Експериментальна частина охоплювала порівняння трьох конструкцій інструментів: базового зразка без демпфування, конфігурації з пасивним демпфером та інструмента з адаптивною вібраційною вставкою. Дослідження проводилось за фіксованих параметрів подачі, глибини різання та швидкості обертання, із застосуванням методів віброаналізу, тепловізійного контролю, контактної профілометрії та динамометричного вимірювання сил різання. Згідно з отриманими результатами, використання адаптивної вставки забезпечило комплексне підвищення стабільності процесу різання та ресурсу інструменту. Середній радіальний знос зменшився на 43 % (з 0,192 мм до 0,109 мм), що супроводжувалося зниженням пікової температури в зоні контакту з 244 °C до 202 °C (-42°C) та зменшенням сумарної сили різання на 25,7 %. Динамічні характеристики також покращилися: середньоквадратичне прискорення вібрацій знизилося на 47,5 % (з 2,45 м/с^2 до 1,27 м/с^2), а інтегральна спектральна енергія – утричі (з 12,6 м^2/с^4 до 4,2 м^2/с^4). Параметр шорсткості зменшився з 1,35 мкм до 0,63 мкм, що відображає покращення якості обробленої поверхні. Морфологічний аналіз виявив перехід від безперервної до сегментованої стружки, що свідчить про зниження теплових та механічних навантажень у зоні різання. Загальний індекс стабільності процесу знизився з 1,00 до 0,43, що підтверджує ефективність активного демпфування в умовах коливального навантаження. Результати підтверджують ефективність адаптивного демпфування для зменшення динамічного навантаження, підвищення точності та покращення енергетичної рівноваги фрезерування. Практична цінність дослідження полягає у можливості впровадження отриманих результатів у виробничих цехах машинобудівних, авіакосмічних та приладобудівних підприємств, а також у дослідницьких лабораторіях, що займаються оптимізацією процесів високоточної механічної обробки металів

Ключові слова: вібраційне навантаження; адаптивне демпфування; шорсткість поверхні; сила різання; морфологія стружки; індекс стабільності