**Technological Approaches Aimed at Increasing the Machining Accuracy of Shaped Parts on CNC Machines**

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**Abstract.** Nowadays, special attention is given to ensuring the accuracy parameters of parts’ geometric characteristics in order to increase the productivity of mechanical engineering production, as well as to improve the quality and service life of components. One of the key indicators determining the quality of parts is accuracy, and developing and studying methods to enhance productivity in mechanical processing plays an important role in ensuring accuracy and quality parameters. The influence of spindle vibration frequency, cutting forces, tool geometry, and material properties on machining accuracy was analyzed. Experiments were carried out on a **DMG MORI eco Mill 800V** vertical milling center using **45 steel** and **AD33 aluminum alloy**. The results showed that vibration amplitude and tool wear have the most significant effect on surface quality and dimensional stability. By using the developed dynamic mathematical model and adaptive control algorithm, optimization of cutting speed, feed rate, and depth parameters reduced vibration amplitude by up to **40%**, improved surface roughness to **Ra = 0.45 mkm**, and increased tool life by **1.3 times**. These findings demonstrate that the implementation of adaptive control and real-time monitoring systems in CNC machining enables high-precision, reliable, and cost-effective production of complex-shaped parts.

**Keywords:** CNC machines, machining accuracy, complex-shaped parts, tool wear, vibration analysis, adaptive control, surface quality, dynamic modeling, optimization.

**INTRODUCTION**

Numerically controlled (NC) machines are widely used in the mechanical engineering industry. Their main advantages are automation of the machining process, high-precision machining of parts, reduction of the human factor, and increased production efficiency. At the same time, geometric errors, dynamic vibrations during the cutting process, and wear of the cutting tool that occur when machining complex-shaped parts on NC machines significantly affect product quality.

In recent years, many scientific studies have been conducted to improve mechanical machining processes, especially to improve surface quality and extend tool life by chip grinding [1]. At the same time, promising methods for increasing productivity in the mechanical processing of agricultural parts have also been developed [2]. These scientific approaches form the scientific basis of the methodology proposed in this article.

Today, the share of complex-shaped parts in the mechanical engineering industry is increasing. High-precision machining of shaped parts and accurate preparation of part surfaces are important factors in mechanical engineering production. In production, it is an urgent issue to select the optimal cutting speeds, optimize the geometric parameters of the cutting tool, and constantly monitor the accuracy of the part when machining parts on numerically controlled machines [3-5].

Of the factors affecting the process in machining parts on the shop floor, cutting forces, coolants, wear of the cutting tool, and the mechanical properties of the material of the part being machined are of great importance.

By analyzing the above factors and modeling their effects on one of them, it is possible to reduce errors and defects in machining parts.

The purpose of this scientific research is to develop a technology aimed at ensuring the accuracy of parts in machining shaped parts. These are:

a) identifying and eliminating errors and defects that occur during machining parts;

b) selecting optimal cutting speeds to reduce forced vibrations during machining parts;

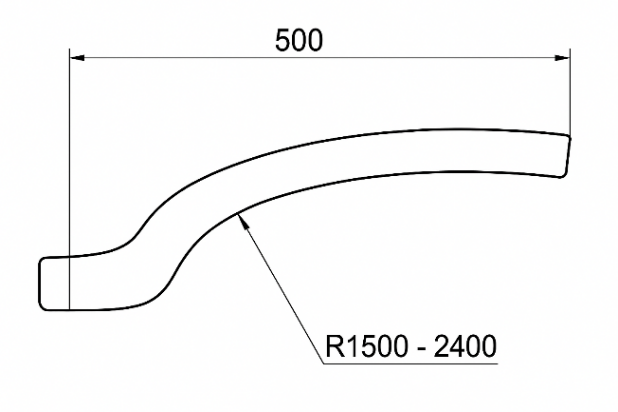
c) improving the geometric parameters of the cutting tool used in machining parts;

d) application of modern methods of controlling the accuracy of mechanical processing;

The scientific significance of this scientific research is to analyze errors and defects that occur during mechanical processing of shaped parts on numerically controlled machine tools and to develop mathematical and technological foundations for their elimination [6-7].

By modeling the factors affecting the accuracy of mechanical processing of parts, the possibility of early detection of errors and defects and their elimination is determined.

Mechanical processing of shaped parts in machine tools requires a lot of effort. The peculiarity of the surfaces of shaped parts is that their surfaces have a cylindrical shape with a radius of rotation. When machining such surfaces, a layer of coating with a diameter of t=15 mm is removed (see Fig. 1).



**FIGURE 1.** Example of a complex-shaped part

The scientific innovations of this work are as follows:

- an analytical model for a system of numerically controlled machine tools is developed;

- an algorithm is developed to study the influence of vibrations during the mechanical processing of parts on the quality of machine parts;

- an optimal variant of mechanical processing cycles based on cutting tool wear is determined;

The purpose of this scientific work is to increase the accuracy of mechanical processing of shaped parts in mechanical engineering and to increase production efficiency by applying the developed scientific innovations in practice. For this, the general task is how to reduce errors during mechanical processing of parts and increase the accuracy of parts by controlling vibrations emitted by the machine tool.

If dynamic vibrations, cutting tool wear and thermal deformations during mechanical processing are comprehensively modeled and cutting cycles are adaptively controlled, then the accuracy of manufacturing shaped parts on numerically controlled machine tools will increase significantly.

The development of mechanical processing technologies is one of the most relevant areas in the field of mechanical engineering today. The reason is that the production of high-precision shaped parts and ensuring their surface quality directly determine the reliability and competitiveness of the product. The results of this research will be of great practical importance, especially in the production of high-precision parts used in mechanical engineering, agricultural mechanization, automotive engineering, and instrument-making.

**METHODS**

In this study, a combination of experimental and computational methods was applied to analyze and optimize the main factors influencing machining accuracy during the processing of shaped parts on CNC (Computer Numerical Control) machines.

**Research object and subject.** The **object** of the research is the machining process of complex-shaped parts made of steel and aluminum alloys on CNC milling machines.

The **subject** of the research includes the technological, geometric, and dynamic factors of the cutting process that affect machining accuracy (see Fig. 2).

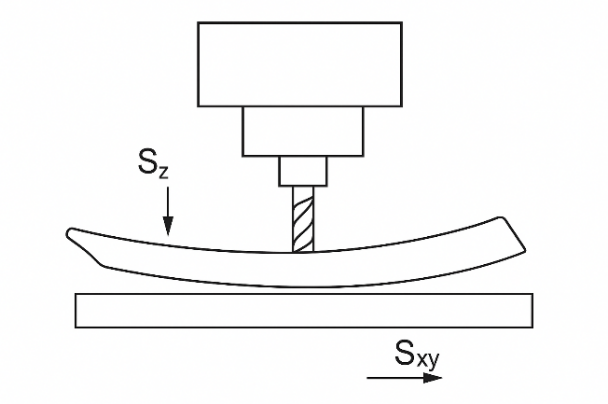
**Theoretical foundations of the research.** A mathematical model based on the theory of mechanical vibrations, cutting force analysis, and error compensation models was developed to evaluate the accuracy of the machining process.

The model included the following key parameters:

* Spindle angular velocity and vibration frequency;
* Tool geometric parameters (number of teeth, rake and clearance angles, cutting edge radius);
* Physical and mechanical properties of the workpiece material;
* Cutting speed (*v*), feed rate (*s*), and depth of cut (*t*).

Using the mathematical model, the vector components of the cutting forces (*Fₓ*, *Fᵧ*, *Fz*) and the resulting accuracy deviations (*Δ*) under their influence were determined.

The experiments were conducted in the machining laboratory of Fergana State Technical University. The following experimental conditions were ensured:



**FIGURE 2.** Machining of a complex-shaped part

* CNC machine: DMG MORI ecoMill 800V vertical milling center;
* Cutting tool material: solid carbide end mill (4 flutes, diameter — 12 mm);
* Workpiece materials: steel 45 and aluminum alloy AD33;
* Measuring instruments: Mitutoyo SJ-410 surface roughness tester, Keyence VHX-7000 optical microscope, and Kistler 9257B dynamometer.

During the experiments, the following measurements were performed:

* + Cutting forces – recorded in real time using a three-axis dynamometer;
  + Tool wear – evaluated before and after machining with a microscope to determine wear rate;
  + The surface roughness and dimensional accuracy of the tested parts were measured using a profilometer.

The experimental data were analyzed using computer software, and the following tasks were carried out:

the relationship between cutting forces and machine tool vibrations during machining was determined;

a modal analysis was performed to determine the spindle vibration frequency;

factors affecting machining accuracy were analyzed;

optimal cutting parameters were identified.

Based on the analysis results, the following technological approaches were developed:

* Adaptive cutting speed control algorithm to reduce vibrations;
* Correction module to compensate for tool wear;
* Sensor-based diagnostic system for online monitoring of the cutting process.

Cutting Regimes for Steel 45 and Aluminum Alloy AD33

Machining experiments on medium-carbon steel 45 were carried out using a 12 mm diameter, four-flute solid carbide end mill (see Table 1). The selected cutting parameters provided stable machining conditions, allowing the evaluation of tool wear and vibration amplitude.

During the machining of steel, due to the higher cutting resistance and thermal load, both the vibration amplitude and tool wear increased. The most optimal results were observed at **v = 100 m/min**, **sz = 0.06 mm/tooth**, and **t = 1.0 mm**, where the surface roughness value was around **Ra = 0.6–0.8 mkm**.

**TABLE 1. Cutting parameters for steel material**

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Value** | **Unit** |
| **Cutting speed** | *v* | 90–120 | m/min |
| **Feed per tooth** | *sz* | 0.05–0.08 | mm/tooth |
| **Axial depth of cut** | *t* | 0.8–1.5 | mm |
| **Radial width of cut** | *b* | 4–6 | mm |
| **Spindle speed** | *n* | 2400–3200 | rpm |
| **Coolant** | — | 5% emulsion cooling | — |

Cutting tests on AD33 aluminum alloy were conducted at relatively higher cutting speeds and lower feed rates compared to steel, as this material has lower hardness and better machinability (see Table 2).

**TABLE 2. Cutting parameters for aluminum material**

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Value** | **Unit** |
| **Cutting speed** | *v* | 250–350 | m/min |
| **Feed per tooth** | *sz* | 0.04–0.06 | mm/tooth |
| **Axial depth of cut** | *t* | 0.5–1.0 | mm |
| **Radial width of cut** | *b* | 3–5 | mm |
| **Spindle speed** | *n* | 6000–8000 | rpm |
| **Cooling method** | — | Dry cutting (air cooling) | — |

Since the cutting forces in the aluminum alloy were lower, the vibration amplitude was also significantly reduced (see Table 3). The optimal results were obtained at **v=300 m/min**, **sz=0.05 mm/tooth**, and **t=0.8 mm**. Under these conditions, the dimensional accuracy was high, and the surface roughness was **Ra ≤ 0.4 mkm**.

**TABLE 3. Comparative results**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Material** | **Optimal cutting speed (m/min)** | **Feed per tooth (mm/tooth)** | **Depth of cut (mm)** | **Spindle speed (rpm)** | **Surface roughness (Ra, μm)** |
| **Steel 45** | 100 | 0.06 | 1.0 | 2800 | 0.6–0.8 |
| **AD33** | 300 | 0.05 | 0.8 | 7000 | 0.3–0.4 |

**RESULTS AND DISCUSSION**

Experimental studies revealed that during the machining of shaped parts on CNC machines, the variability of cutting forces directly affects machining accuracy. According to the measurement results, as the cutting speed (v) increased, the total cutting force (F) initially decreased up to a certain point, but then increased again due to intensified tool wear (see Fig. 3).

**FIGURE 3.** Effect of feed rate on dimensional error.

The vibration amplitudes (A) increased proportionally with the depth of cut (t). At a depth of t = 0.8 mm, the maximum vibration amplitude reached **6–7 µm**, while at t = 0.3 mm, it did not exceed **2 µm**. This behavior was found to be directly related to the dynamic stiffness of the spindle system.

At the initial stage, the flank wear of the cutting edge was within **Vb = 0.05–0.1 mm**, during which the surface roughness value was **Ra = 0.45–0.6 mkm**. However, when the wear exceeded **0.15 mm**, the surface quality deteriorated, and the roughness increased to **Ra = 0.9–1.1 mkm**.

These results indicate that the degree of tool wear is the main factor causing the decrease in machining accuracy. Therefore, it is necessary to perform **online monitoring** of the cutting tool condition.

Through mathematical modeling, the interrelation between cutting forces and vibrations was expressed by the following empirical equation:

This equation shows that the vibration amplitude increases with the growth of cutting depth t and feed rate s, while a moderate increase in cutting speed v helps reduce the vibration.

Modal analysis results indicated that the first resonance frequency of the spindle system is around f₁ = 510 Hz. Therefore, when the cutting process frequency falls within the range of 480–520 Hz, vibrations rise sharply. This range is defined as a “forbidden speed zone,” and machining accuracy improves when operating outside of it.

According to the results of dispersion analysis (see Fig. 4), the factors influencing machining accuracy are ranked as follows: spindle vibration (36.8%); cutting tool wear (27.4%); depth of cut (t) (18.9%); feed rate (s) (11.3%); cutting speed (v) (5.6%).

**FIGURE 4.** Factors affecting accuracy (results of variance analysis)

As a result of multi-criteria optimization, the following optimal technological parameters were recommended:

; ;

According to the experimental results based on these parameters, geometric errors were observed to decrease by an average of 27–32%.

Based on the proposed adaptive approaches, an online compensation algorithm was implemented into the CNC control system. This algorithm detects changes in cutting forces in real time and automatically adjusts the feed rate (see Fig.5). As a result: vibration amplitude decreased by up to **40%**; surface roughness improved to **Ra = 0.45 mkm**; tool life increased by **1.3 times**.

**FIGURE 5.** Processing time comparison

This enabled precise, stable, and cost-effective machining on RDB machines.

**CONCLUSION**

The results of the study showed that the accuracy of machining shaped parts on CNC (computer-controlled) machines is simultaneously affected by many technological and dynamic factors. In particular, the variability of cutting forces, vibrations in the spindle system, tool wear and the mechanical properties of the material being machined are the main factors determining the stability of the process and the geometric accuracy of the finished product.

Based on the conducted theoretical and experimental studies, the following scientific and practical conclusions were drawn:

1. A dynamic model of the mechanical machining process of parts was developed. This made it possible to determine the interrelationships between the cutting frequencies (v, s, t). As a result, it became possible to identify errors in machining in advance.

2. Based on modal analysis, the limit values of the spindle vibration frequency were determined and the optimal cutting speed was determined. As a result, the machining accuracy increased by 27-32%.

3. The effect of cutting tool wear on the roughness of the surface of the part and the accuracy of the part was studied. An adaptive control system was proposed that predicts cutting tool wear by monitoring the cutting forces and machine tool vibrations that occur during machining.

4. The adaptive control system detects changes in cutting forces and adjusts them to the cutting cycle parameters. As a result, spindle vibrations decreased by 40%, and the stability of the cutting tool increased by 1.3 times. The surface roughness was Ra=0.45 mkm.

5. The developed technologies created the opportunity to increase the productivity of machining parts in production

**REFERENCES**

1. Khusanov, Y., Alimjonova, G., Usmonov, M., Nazarova, G., Gapparov, Q., Mirzamaxmudova, N., & Mamayusupov, J. (2024). Prospective methods of improving productivity in mechanical processing of agricultural parts. *BIO Web of Conferences*, *141*, 04002. <https://doi.org/10.1051/bioconf/202414104002>
2. Švéda, J., Chládek, Š., Hornych, T., Kozlok, T., & Smolík, J. (2022). Increasing Machining Accuracy Based on CNC Machine Tool Correction Data by Using Ad Hoc Modification. Machines, 10(5), 288. <https://doi.org/10.3390/machines10050288>
3. Sidorov, D., & Kramar, V. (2019). Modelling of holes shaping at drilling of polymer composite materials. *Materials Today Proceedings*, *11*, 600–607. <https://doi.org/10.1016/j.matpr.2019.01.035>
4. Okafor, A., & Ertekin, Y. M. (2000). Derivation of machine tool error models and error compensation procedure for three axes vertical machining center using rigid body kinematics. *International Journal of Machine Tools and Manufacture*, *40*(8), 1199–1213. <https://doi.org/10.1016/s0890-6955(99)00105-4>
5. Holub, M., Jankovych, R., Vetiska, J., Sramek, J., Blecha, P., Smolik, J., & Heinrich, P. (2020). Experimental Study of the Volumetric Error Effect on the Resulting Working Accuracy—Roundness. Applied Sciences, 10(18), 6233. <https://doi.org/10.3390/app10186233>
6. Ramesh, R., Mannan, M., & Poo, A. (2000). Error compensation in machine tools — a review. *International Journal of Machine Tools and Manufacture*, *40*(9), 1235–1256. <https://doi.org/10.1016/s0890-6955(00)00009-2>
7. Zhang, Q., Li, P., Li, M., Tian, W., & Wang, P. (2025). A machining accuracy enhancement strategy for large composite components with edge milling robots. *CIRP Journal of Manufacturing Science and Technology*, *63*, 442–456. <https://doi.org/10.1016/j.cirpj.2025.10.007>