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ANALYSIS AND OPTIMIZATION OF CUTTING PARAMETERS AND MACHINING TIME FOR ALUMINUM ALLOYS

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Abstract - This article examines the determination of the basic cutting parameters with a view to minimizing the machining time of aluminum alloys in CNC machining centers while ensuring the required workpiece quality. The optimal selection of these parameters is of great importance for the productivity improvement and energy-efficient processing of aluminum alloys in such machine tools. The research is conducted for a type of serially produced workpieces. Taking into account the features of the machining center used, a 3D geometric model of the machining workpiece has been developed using the SolidWorks software. Based on the functional requirements for the workpiece, a type of aluminum alloy is chosen as the appropriate material. The properties of this material, the geometry of the tools used and the machining conditions are discussed in detail. After the analysis conducted, the main practical approaches to improving productivity have been formulated, which are reduced to: using the capabilities of the CNC system, developing a special device for clamping the workpiece, optimizing the control and positioning system of the tool magazine, selecting appropriate cutting parameters, designing specialized tools, implementing control algorithms and applying effective auxiliary functions. The research carried out and the results obtained can be used in the adjustment of the considered type of machining centers for the production of aluminum alloy workpieces. The proposed analytical–experimental approach can be integrated into CNC machine tools monitoring systems to support real-time diagnostics and condition-based maintenance.

Keywords: CNC machine tools, Machining center, 3D modelling, Cutting parameters, Productivity improvement, Energy efficiency.

1. Introduction

The modern machining centers with computer numerical control (CNC) are multi-operation machine tools widely used to process workpieces with complex geometric shapes. They allow for a variety of mechanical processing operations, such as: milling, drilling, thread cutting, reaming, boring, grinding, etc. [1, 2]. The analysis and optimization of cutting parameters and machining time in these machines are essential for improving the processing quality, productivity and energy efficiency.

The basic cutting parameters in machining centers include cutting speed, spindle speed, feed rate, axial depth of cut, and radial width depth. Additional factors affecting the efficiency of the metal cutting process are the geometry and specialized coatings of the tools, as well as the cooling methods.

Aluminum alloys are distinguished by a unique combination of lightness, strength and processability. They are characterized by low density and lightness; corrosion resistance; good conductivity and high thermal conductivity; ductility and machinability; low melting point and recyclability [3]. At the same time, these materials also exhibit a tendency to form deposits on the cutting tool under unfavorable cutting conditions [4]. Therefore, the specific physical and mechanical characteristics of these alloys must be carefully considered when choosing processing modes.

Numerous studies have focused on the influence of the respective cutting parameters on machining performance. A detailed review of cutting force and temperature modeling methods, tool path planning approaches, and vibration suppression is made in [5].

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In [6], a review of approaches to optimizing machining process parameters and their influence on surface roughness and material removal rate for various aluminum alloys is presented. In [7], the influence of different geometric tools on the forces and temperature during cutting of aluminum alloys is investigated.

In [8], the influence of five essential machining parameters on dimensional accuracy during milling of curved surfaces of aluminum alloys are studied. In [9, 10], the Taguchi method is used, focusing on spindle speed, feed rate, and depth of cut to optimize CNC turning parameters for aluminum alloys. The basic objective of these studies is to improve the surface roughness of the material. The main conclusion is that speed and depth have the strongest influence on wear and roughness.

The productivity and energy efficiency of machine tools are two closely related parameters and their comparison can be made according to various criteria such as cutting speeds and feeds, accuracy, reliability, environmental friendliness, etc. Energy-efficient machining and cost-oriented optimization of cutting parameters are studied in [11], where a multi-objective optimization model is presented considering spindle speed, feed per tooth, and milling speed.

Increasing the productivity of metal-cutting machines is associated with processing in the minimum possible time without loss of product quality and with optimal use of relevant resources. Generally, the productivity index of machines is complex and includes technological, technical, reliability, structural, service and organizational parameters. There are various approaches used for productivity improvement. Some practical decisions to increase the productivity of a class of CNC machining centres are proposed and analyzed in [12]. In [13] the main characteristics of the tool magazine drive are analyzed and on this basis an algorithm for searching for an optimal tool position.

In [14], the application of the TPM (total productive maintenance) approach to eliminating production losses through the maintenance of production equipment is illustrated to improve its performance and efficiency, while ensuring production quality. In [15] a new approach is presented for parallel analysis of machine processes and automated improvement or control of the current mode in terms of quality and productivity. The main idea is to integrate machine learning with data from the technological process for real-time optimization.

In [16], a method for optimizing the cutting parameters of a CNC machining center is proposed, which takes into account both energy saving and low cost. The productivity improvement and cost optimization are discussed in [17] where a cost optimization model for relevant machine operations is presented.

In [18], the potential of machine learning techniques to improve energy efficiency during milling with a CNC 5-axis machining center is discussed.

Productivity is an important indicator of machine efficiency. It depends on the reliability of the machine and the quality of its operation. In [19], the contradictions between productivity and technological flexibility of machine systems are analyzed and approaches are proposed to resolve these contradictions based on scientific achievements in the field of components, mechatronics and CALS technologies.

Overall, the literature indicates that feed rate is the most influential parameter on surface roughness, while cutting speed plays a crucial role in improving machining efficiency. The depth of cut, on the other hand, strongly affects material removal rate and machining time. Therefore, the optimization of machining parameters requires a multi-criteria approach that considers both quality and productivity. The literature review shows that research on machining center productivity focuses on reducing cycles, optimizing maintenance, and using modern technologies such as 5-axis machining and automation.

In this work, the main approaches to increasing the productivity in machining centers are analyzed and discussed. The main objective of this research is to achieve a balance between surface quality, machining time and tool life in the processing of a type of aluminum alloy workpieces.

2. Machining Center Specification and Cutting Methodology

The machining center used in this study provides the ability to perform mechanical operations such as milling, drilling, reaming, boring, etc. Its drive subsystems perform part positioning, tool selection, spindle rotation at the desired speed, and auxiliary machine functions such as cooling and lubrication.

General-purpose machining centers are often equipped with a two-stage drive with an efficient toothed belt transmission [20]. The rotary tables of such machines are equipped with a worm gear [21] with a screw-and-nut rolling transmission.

The machining center control is implemented through a CNC system with integrated ladder logic programming, enabling coordinated operation of all subsystems and ensuring reliable execution of both primary machining and auxiliary functions. The main components and technical characteristics of the machining center are summarized in Table 1.

The specification presented in Table 1 defines the kinematic structure, drive capabilities, and control architecture of the machine, which directly determine the achievable machining strategies and constraints during process planning.

Taking into account the technical capabilities of the machine, the geometric model of a practically machined workpiece is developed in the SolidWorks software (Fig. 1). The resulting three-dimensional model is used as a basis for generating tool paths, simulating machining and preparing NC code. In this way, consistency between the machine configuration, process planning and subsequent experimental validation is ensured.

Table 1. Components and technical characteristics of the machining center

Drive system	Mechanical transmission	Motor	Sensor	Description	Control type
Linear feed	Ball screw	DC motor, 5.4 Nm, 2000 rpm	Encoder	Linear motion along *x*, *y*, *z* axes	CNC position control
Rotary feed	Worm gear	DC motor, 1.6 Nm, 3000 rpm	Encoder	Linear motion along *a*, *c* axes	CNC position control
Spindle	Gear train	DC motor, 11 kW, 1000 rpm	Tachogenerator	Provides rotational cutting motion	CNC speed control
Positioning device	Worm gear	Induction motor, 200 W	Limit switch	Provides indexed positioning of 30 °	CNC control system with ladder logic
Tool magazine	Maltese cross	Induction motor with conical rotor, 500 W	Limit switch	Enables automatic tool selection	CNC control system with ladder logic
Hydraulics	-	Induction motor, 350 W	-	Provides fixing of the tool magazine	CNC control system with ladder logic
Cooling	-	Induction motor, 750 W	-	Supplies coolant to the cutting zone	CNC control system with ladder logic
Lubrication	-	Induction motor, 150 W	Pressure and level	Ensures proper lubrication of machine components	CNC control system with ladder logic

Based on the functional requirements for the workpiece, an aluminum alloy is chosen as the appropriate material. The blank is first obtained by casting and then subjected to machining by the machine. The technological process includes the drilling and reaming processes to achieve the desired hole sizes.

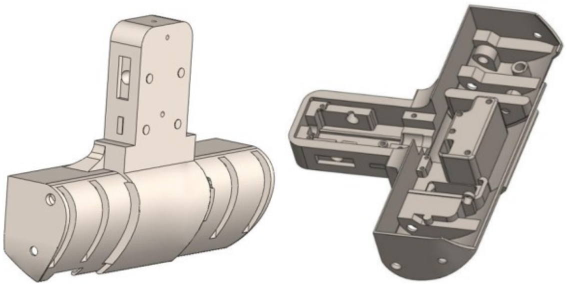


Figure 1: 3D Geometric model of the workpiece, developed in SolidWorks, on the both side

Following the analysis of the workpiece geometry and required machining operations, it is determined that several machining processes are necessary to obtain the desired final geometry. These include reaming of two holes using 15 mm and 13 mm reamers, as well as drilling operations for multiple hole diameters, specifically 4.2 mm, 5 mm, 6 mm, 8.5 mm, 10 mm, 10.5 mm, and 12 mm.

The presence of a large number of holes with different diameters significantly increases the complexity of the machining process and leads to a considerable amount of tool changes and auxiliary movements. Consequently, this operational structure imposes requirements for improving machining productivity. Therefore, attention is directed toward optimizing the drilling strategy, reducing non-productive time, and enhancing overall process efficiency through appropriate selection of tooling, machining parameters, and CNC programming approach.

In order to address these productivity limitations, an operation grouping strategy is applied during process planning. Tool grouping is implemented by organizing drilling and reaming operations according to tool diameter similarity and tool change minimization. This approach allows multiple holes to be machined sequentially using the same tool before switching to the next diameter, thereby reducing the number of tool changes and associated non-productive time.

Additionally, operations are sequenced to minimize rapid traverse movements between spatially distant holes, further improving machining efficiency.

The grouping strategy is integrated into the CAM planning stage, ensuring that the generated toolpaths reflect an optimized machining sequence consistent with the capabilities of the tool magazine and CNC control system. As a result, the overall machining cycle time is reduced while maintaining the required geometric accuracy and surface quality.

The described configuration of the machining center and machined workpiece provides the necessary basis for the analysis and implementation of productivity improvement approaches presented in the following section.

3. Research Approaches

3.1 Cutting Parameters Selection and Calculation

The determination of cutting parameters is related to the technological requirements of mechanical machining processes such as the geometry of the hole, the depth of penetration and the surface characteristics of the workpiece. For the correct determination of specific values, data from the tool manufacturer are used [4, 22]. For the aluminum alloys considered in this study, the material behavior is characterized by a reference specific cutting force $k_{c1} = 700\ \mathrm{N/mm}^2$ - representing the specific cutting force at a maximum chip thickness of 1 mm; and $m_c = 0.25$ – defining the relationship between chip thickness and the corresponding increase in specific cutting force.

Due to the different cutting conditions associated with different drill diameters, the parameter evaluation is carried out individually for each diameter. The rotation speeds are determined experimentally for each operation. The cutting parameters are calculated for drills with diameters of Ø6, Ø8.5 and Ø10 mm, respectively (designated with indices 1, 2 and 3 in further calculations). The experimentally obtained spindle speeds are 2000 rpm, 1500 and 1400 for the corresponding drills.

The cutting speeds are calculated using the following machining relationship:

$$V_{cd1} = (\pi \times D_{d1} \times n_1)/1000 \approx 37.7\ \mathrm{m/min}; \tag{1}$$

$$V_{cd2} = (\pi \times D_{d2} \times n_2)/1000 \approx 40\ \mathrm{m/min}; \tag{2}$$

$$V_{cd3} = (\pi \times D_{d3} \times n_3)/1000 \approx 43.4\ \mathrm{m/min}, \tag{3}$$

where $n_1 = 2000\ [\mathrm{min}^{-1}]$, $n_2 = 1500\ [\mathrm{min}^{-1}]$ and $n_3 = 1400\ [\mathrm{min}^{-1}]$ – the respective spindle speeds.

The material removal rates are determined using the following expressions:

$$Q_{d1} = \frac{\pi \times D_{d1}^2 \times f_{nd1} \times n_1}{4} \approx 5.65\ \mathrm{cm}^3/\mathrm{min}; \tag{4}$$

$$Q_{d2} = \frac{\pi \times D_{d2}^2 \times f_{nd2} \times n_2}{4} \approx 11.1\ \mathrm{cm}^3/\mathrm{min}; \tag{5}$$

$$Q_{d3} = \frac{\pi \times D_{d3}^2 \times f_{nd3} \times n_3}{4} \approx 16.5\ \mathrm{cm}^3/\mathrm{min}. \tag{6}$$

where $f_{nd1} = 0.1\,[\mathrm{mm/rev}]$, $f_{nd2} = 0.13\,[\mathrm{mm/rev}]$ and $f_{nd3} = 0.15\,[\mathrm{mm/rev}]$ – feeds per revolution.

The feed speeds, representing the linear feed of the drill along its axis, are calculated according to the following equations:

$$v_{fd1} = f_{nd1} \times n_1 \approx 200\ \mathrm{mm/min}; \tag{7}$$

$$v_{fd2} = f_{nd2} \times n_2 \approx 195\ \mathrm{mm/min}; \tag{8}$$

$$v_{fd3} = f_{nd3} \times n_3 \approx 210\ \mathrm{mm/min}. \tag{9}$$

The specific cutting forces are determined using the next formulas:

$$k_{cd1} = k_{c1} \times (f_{nd1} \times \sin k_{r1})^{-\mathrm{m_c}} \times \times (1 - \gamma_0/100) \approx 1285\ \mathrm{N/mm}^2; \tag{10}$$

$$k_{cd2} = k_{c1} \times (f_{nd2} \times \sin k_{r2})^{-\mathrm{m_c}} \times \times (1 - \gamma_0/100) \approx 1200\ \mathrm{N/mm}^2; \tag{11}$$

$$k_{cd3} = k_{c1} \times (f_{nd3} \times \sin k_{r3})^{-\mathrm{m_c}} \times \times (1 - \gamma_0/100) \approx 1160\ \mathrm{N/mm}^2. \tag{12}$$

where $k_{r1} = k_{r2} = k_{r3} = 60°$ – lead angles; $\gamma_0 = 0$ – orthogonal rake angle at maximum cutting speed.

The cutting powers are calculated as follows:

$$P_{cd1} = \frac{(f_{nd1} \times V_{cd1} \times D_{d1} \times k_{cd1})}{240 \times 10^3} \approx \approx 0.121\ \mathrm{kW}; \tag{13}$$

$$P_{cd2} = \frac{(f_{nd2} \times V_{cd2} \times D_{d2} \times k_{cd2})}{240 \times 10^3} \approx \approx 0.221\ \mathrm{kW}; \tag{14}$$

$$P_{cd3} = \frac{(f_{nd3} \times V_{cd3} \times D_{d3} \times k_{cd3})}{240 \times 10^3} \approx \approx 0.315\ \mathrm{kW}. \tag{15}$$

The respective torques are determined as follows:

$$M_{cd1} = \frac{P_{cd1} \times 30 \times 10^3}{\pi \times n_1} \approx 0.58 \text{ Nm}; \tag{16}$$

$$M_{cd2} = \frac{P_{cd2} \times 30 \times 10^3}{\pi \times n_2} \approx 1.41 \text{ Nm}; \tag{17}$$

$$M_{cd3} = \frac{P_{cd3} \times 30 \times 10^3}{\pi \times n_3} \approx 2.15 \text{ Nm}. \tag{18}$$

The results highlight the variations in cutting conditions in the three stages of the step drilling process. As the drill diameter increases, cutting speeds and material removal rates increase, leading to increased power and torque requirements during machining. On the other hand, the use of a step drill allows for multiple diameter operations to be performed within a single tool set, thereby reducing the number of tool changes and minimizing unproductive time.

3.2 Productivity Improvement

Productivity improvement of the CNC machines is a process related to the optimization of machining processes, tool selection, positioning strategies, control algorithms, etc. These approaches can be categorized into several interrelated areas: the CNC system, the drive system, the tooling, the control strategies, and the auxiliary subsystems.

The main factors influencing the productivity of CNC machine tools are summarized in Table 2. The presented approaches to improve productivity can be divided into several interrelated areas, such as CNC system, drive system, tooling, control strategies and auxiliary subsystems.

The CNC control system allows for full process automation, providing the ability to simultaneously position the tools and process the workpiece, thus reducing idle time and compensating for the effects of mechanical wear through adaptive or corrective control strategies.

Optimization of the drive system (feed drives, spindle drives and auxiliary drives) allows for a reduction in the time for positioning the workpiece and the tool, ensuring high dynamics and acceleration.

Another important factor affecting productivity is the workpiece clamping and processing system. The design of the fixture directly affects the setup time and the duration of the workpiece change operations. Inefficient clamping solutions can significantly increase non-productive time, especially in series production. The implementation of automated processing systems, such as industrial robots, further increases productivity by reducing manual intervention and allowing continuous machine operation.

A specially designed angular positioning mechanism controlled by CNC ladder logic is implemented in the machine. The optimization of angular positioning is achieved by searching for the shortest path to the corresponding position.

The productivity of the machine using the tool magazine can be improved in the following directions: minimizing the time for tool changes by selecting a tool along the shortest path in the tool magazine; optimizing the sequence of tools, taking into account geometric and collision constraints; reducing the machining time by applying specially designed step drills according to the geometry of the workpiece.

4. Results and Discussion

4.1 Practical Approaches for Productivity Improvement and Machine Time Optimization

The workpiece is intended for serial production, which imposes requirements for optimizing the technological process in order to increase productivity and reduce the total machining time. This includes both the optimization of cutting parameters and the reduction of non-productive time associated with tool changes, positioning, and auxiliary operations.

Based on the analysis presented in Table 1, the main practical approaches for improving productivity and optimizing machining time for the considered workpiece include: utilization of the CNC system capabilities, development of a dedicated workpiece clamping device, optimization of tool magazine management and positioning subsystem, selection of cutting parameters, design of specialized tools, implementation of control algorithms, and application of efficient auxiliary functions.

In this context, the following solutions have been implemented:

1. CNC system - the developed workpiece program enables parallel execution of operations, where tool selection is performed simultaneously with the positioning of the workpiece. This significantly reduces non-productive time.
2. Workpiece clamping device - a dedicated fixture has been designed to ensure fast clamping, high rigidity, and reduced vibration during machining (Fig. 2).
3. Tool magazine optimization - an algorithm for tool selection based on the shortest path in the tool magazine has been developed, minimizing tool change time [13].
4. Workpiece positioning – an algorithm for selecting the angular position of the workpiece using the shortest path has been implemented, reducing positioning time between operations [23].

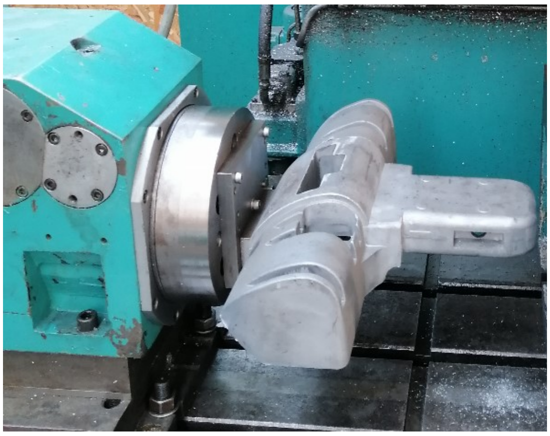


Figure 2: Workpiece clamping device.

5. Cutting parameters – based on experimental studies, the cutting parameters have been optimized in order to achieve the required dimensional accuracy and surface roughness.

6. Specialized tools – stepped drills have been designed to perform multiple operations in a single pass. This reduces the number of tools used and minimizes tool change time (Fig. 3).

7. Control algorithms – advanced control strategies are applied for simultaneous movement along the three axes, ensuring fast and accurate positioning of both the tool and the workpiece.

8. Auxiliary systems – an appropriate coolant is used according to the material properties, ensuring efficient chip evacuation, preventing adhesion, and increasing tool life.

Figure 3: Stepped drills with diameters 6/8.5/10 mm and 4.2/5 mm.

9. The primary constraint considered in the optimization process is the avoidance of collisions between the tool and the workpiece. For this reason, the tools are not arranged sequentially in the tool magazine, but are positioned according to safety and collision-free operation requirements.

Based on the applied approaches for optimization of machine time, Table 3 gives results from the practical processing of one workpiece.

Table 2. Factors influencing the productivity of CNC machines

Factor Group	Key Parameters / Approaches	Effect on Productivity	Time Component
CNC System	Automation; parallel operations	Reduces idle and auxiliary time	Non-productive
Drive System	Rapid traverse; high dynamics; acceleration	Reduces positioning time	Non-productive
Cutting Regimes	Cutting speed; feed; depth of cut	Increases material removal rate	Productive
Tooling System	Tool geometry; tool material; stepped drills	Improves efficiency; reduces operations	Both
Tool Control	Tool sequence optimization; tool change minimization	Reduces tool change time	Non-productive
Workpiece Handling	Fixture design; quick clamping; robotized handling	Reduces setup and workpiece change time	Non-productive
Positioning System	Indexing device (30°); shortest path rotation	Reduces positioning movements	Non-productive
Constraints	Collision avoidance; tool length limitations	Ensures safe and feasible machining	Indirect
Control Algorithms	Trajectory optimization; adaptive control	Reduces positioning time; stabilizes process	Both
Auxiliary Systems	Cooling; chip evacuation	Improves process stability	Productive

Table 3. Results from the practical processing of one workpiece

Step	Operation	Diameter Ø [mm]	Tool change	Workpiece rotation angle [°]	Tool change time [s]	Workpiece rotation time [s]	Machining time [s]	Total time [s]
1.	Positioning	-	-	0	-	0	-	3
2.	Workpiece clamping	-	-	-	-	-	-	33
3.	Reaming	15	-	90	-	4	20	60
4.	Center Drilling	3.2	T6→T7	90	3.5	0	7	70.5
5.	Drilling	6/8.5/10	T7→T4	90	5.5	0	35	111
6.	Drilling	10.5/12	T4→T3	90	3.5	0	62	176.5
7.	Reaming	13	T3→T6	90	5.5	0	9	191
8.	Drilling	4.2/5	T6→T8	180	4.5	4	64	263.5
9.	Drilling	3.2	T8→T7	270	3.5	4	7	278
10.	Drilling	6/8.5/10	T7→T4	270	5.5	0	35	318.5
11.	Drilling	10.5/12	T4→T3	270	3.5	0	62	384

The studied technological process for processing the considered workpiece includes sequentially the operations of drilling with a center drill, drilling with different diameter step drills and reaming, performed at different angular positions of the workpiece. The processing is carried out bilaterally, which requires the use of angular orientations (90°, 180° and 270°) in order to provide access to all machined surfaces. The total technological time of the process amounts to 384 s, which is the allocation for mechanical processing (~78%), followed by auxiliary times associated with tool changes, positioning and rotation of the workpiece. The share of the time for rotating the device is relatively small (~3%), which confirms the effectiveness of the selected positioning strategy.

The analysis of the tool change times shows that the frequency of tool changes has a significant impact on the total cycle time. It has been experimentally established that in the absence of tool search optimization (not using a minimum path algorithm in the tool magazine), the total machining time increases by 31 s, which represents approximately 8% of the entire technological cycle. This result emphasizes the importance of algorithms for controlling tool systems as a key factor in increasing productivity for serial parts. An essential element of the considered technological process is the use of step drills, which allow for the execution of consecutive diameters within one operation. This approach leads to a significant reduction in the number of tool changes and, accordingly, to a reduction in auxiliary times.

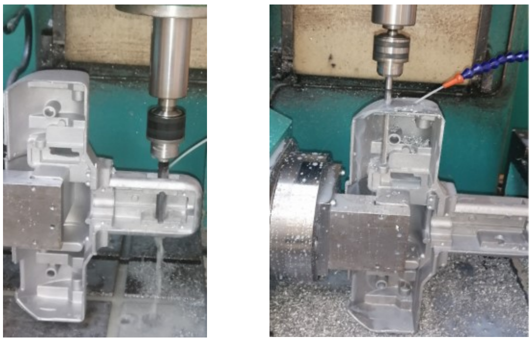
The conducted comparative analysis shows that when replacing step drills with separate standard tools for each diameter, the total machining time of the part on the one hand increases by approximately 57 s. The main reason for this is the need for significantly more frequent tool changes, which leads to the accumulation of unproductive time within the technological cycle.

In addition to the increase in machining time, a significant design limitation is also established. When using separate tools for each operation, the number of positions required in the tool magazine exceeds the available capacity of the machine. This makes the process practically unfeasible without additional intervention, such as manual tool change or the use of a different machine with a larger tool capacity. Therefore, the use of stepped drills not only optimizes the machining time (reducing the cycle time by tens of seconds), but also ensures the technological feasibility of the process within the available equipment. This result emphasizes the importance of the correct choice of tool configuration as a key factor for both productivity and machining feasibility.

Additionally, an assessment of the energy consumption during the mechanical processing of the studied workpiece is carried out. The calculated energy for the production of a single workpiece is approximately 0.214 kWh. In the absence of optimization in the search for the corresponding position from the tool magazine, the energy consumption increases by about 8%, while when using standard instead of stepped drills, the increase reaches approximately 15%. Therefore, the results obtained show that the optimization of the technological process leads not only to a reduction in processing time, but also to a significant increase in energy efficiency.

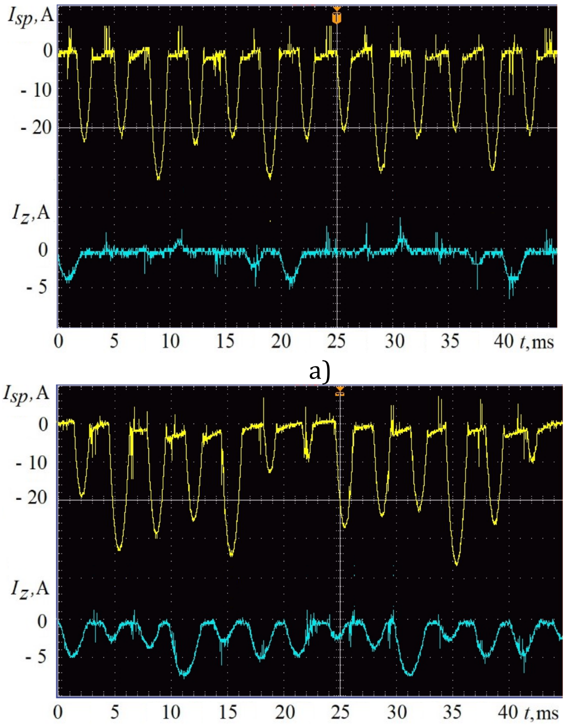
4.2 Machining Processes and Analysis

Based on the calculations performed, the research and processing presented in the previous points, the results of real mechanical processing and experimentally recorded current pulses in the relevant processes are illustrated. The analysis of the cutting parameters is carried out by evaluating the current pulses in real time, recorded from the drives of the relevant axes and spindles. This approach allows for indirect assessment of the cutting forces, torque and overall dynamics of the process without the need for external measuring instruments.



a) b)

Figure 4: Reaming process with diameter 15 mm and drilling process with stepped diameter with diameters Ø 6/ Ø 8.5/ Ø 10 mm.



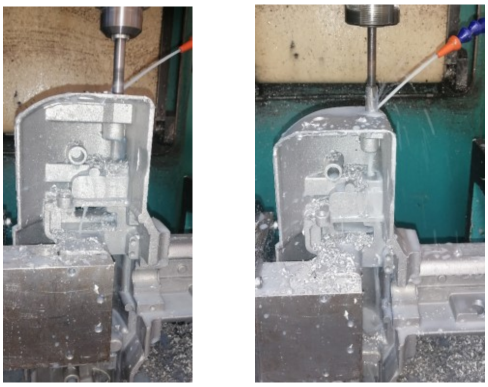
b)

Figure 5: Current signals in reaming process with diameter Ø 15 mm and drilling process with stepped diameter with diameters Ø 6/ Ø 8.5/ Ø 10 mm.

Fig. 4a and 4b present respectively the photos of the mechanicals processing of the workpiece during reaming with reamer 15 mm, drilling with stepped diameter with diameters Ø 6/ Ø 8.5/ Ø 10 mm.

Fig. 5a and 5b illustrates the experimentally measured spindle (I_{sp}) and z axis (I_z) current signals during the respectively mechanical operations from Fig. 4.

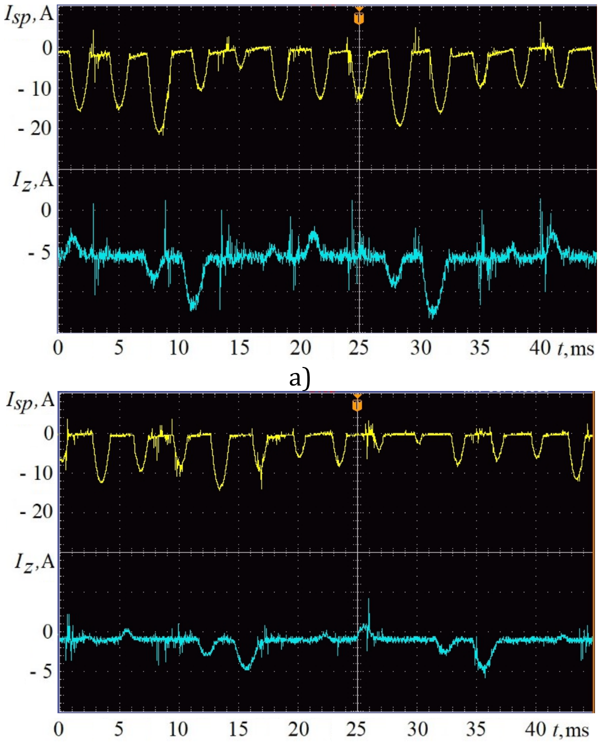
Fig. 6a and 6b demonstrates the pictures of the mechanicals processes during drilling process with stepped drill with diameters 10.5/12 mm and reaming process with reamer 13 mm respectively.



a) b)

Figure 6: Drilling process with stepped diameter with diameters Ø10.5/ Ø12 mm and reaming process with reamer Ø13 mm.

Fig. 7a and 7b shows respectively measured spindle (I_{sp}) and z axis (I_z) current signals for the mechanical operations from Fig. 6.



b)

Figure 7: Current signals with stepped diameter with diameters Ø10.5/ Ø12 mm and reaming process with reamer Ø13 mm.

From the recorded current pulses, a strong correlation between the type of machining operation and the tool geometry (diameter) is observed. The spindle current reflects the main cutting load, while the feed axis drive current is related to axial resistance and the dynamics of material removal.

When analyzing the reaming processes, the current signals show a relatively stable behavior with a continuous cutting mode with uniform load distribution and minimal dynamic disturbances. Such characteristics are typical for this type of operation, where the cutting conditions remain constant and the process stability is relatively high.

The drilling process, unlike reaming, is characterized by abrupt changes in both spindle and feed currents, corresponding to transitions between different tool diameters and reduced process stability. Drilling at larger diameters (Fig. 7a) results in increased current levels and noticeable oscillations, reflecting increased cutting forces and higher energy consumption. From an optimization perspective, the analysis confirms that real-time monitoring of drive currents serves as an effective tool for process control and parameter adjustment. By identifying signal irregularities and load peaks, it becomes possible to optimize cutting parameters, such as feed rate, spindle speed, and depth of cut, in order to improve surface quality and extend tool life.

The photos of remaining operations, presented in Fig. 8, are associated with drilling processes performed using a stepped drill with diameters of Ø 4.2 and Ø 5 mm.

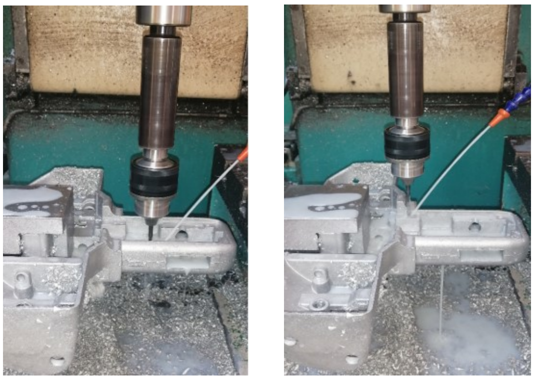


Figure 8: Drilling processes performed using a stepped drill with diameters of 4.2 and 5 mm.

Fig. 9 shows the machined workpiece after all mechanical operations have been performed.

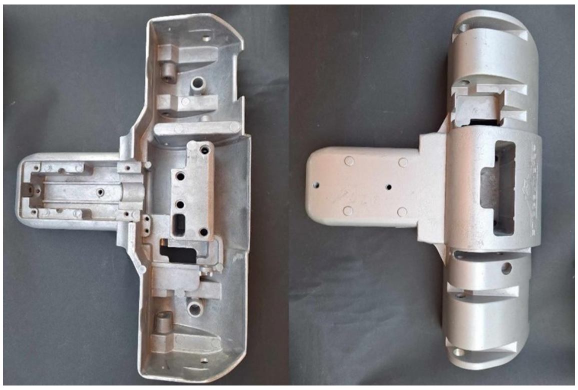


Figure 9: The machined workpiece.

5. Conclusions

This article discusses the determination of the basic cutting parameters and the machining time minimization of aluminum alloy workpieces, while ensuring their quality.

Based on the functional requirements for the workpieces, a certain type of aluminum alloy is selected as a suitable material. The properties of this material, the geometry of the tools used, and the machining conditions are discussed in detail. The analysis of the cutting parameters is performed by evaluating the real-time electrical responses of the corresponding electric drives of the machining center used.

The conducted study and the obtained results can be used in the tuning of this type of metal-cutting machines for the production of aluminum alloy parts. Furthermore, the presented analytical-experimental approach can be integrated into CNC machine tools monitoring systems to provide real-time diagnostics and condition-based maintenance, which will be a subject of our future research.

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