MODELING AND OPTIMIZING THE TURNING PROCESS TO SUPPORT THE CIRCULAR ECONOMY

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ABSTRACT: This paper presents an integrated approach to the modeling and optimization of the turning process, with the aim of increasing resource efficiency and supporting the principles of the circular economy in the machining industry. The study focuses on developing mathematical and experimental models capable of describing the interdependencies between operating parameters (cutting speed, feed rate, cutting depth), energy consumption, machined surface quality, etc.
The paper demonstrates the relevance of integrating circular economy concepts into the design and management of machining processes, providing a methodological framework applicable in the industrial environment for the transition to more efficient and environmentally friendly production systems.

KEYWORDS: turning, energy consumption, surface roughness, sustainability, circular economy.

1. INTRODUCTION

In the current context of sustainable development, the circular economy represents an essential model for reducing resource consumption and minimizing environmental impact. The manufacturing industry, and in particular machining processes, are characterized by high energy consumption and the generation of significant amounts of waste in the form of chips [1, 2].

Turning is one of the most widely used machining processes, characterized by flexibility and broad applicability in the manufacture of mechanical components. However, the process involves significant energy consumption, the generation of waste in the form of chips, and the progressive wear of cutting tools. In the absence of appropriate optimization strategies, these issues lead to high production costs and a negative environmental impact [3, 4].

In this context, it becomes necessary to develop advanced methods for modeling and optimizing the turning process, which allow for the correlation of technological parameters with technical-economic and environmental performance indicators. The integration of predictive models and multi-objective optimization techniques offers the possibility of identifying optimal machining conditions that ensure a balance between productivity, surface quality, and resource consumption.

This paper aims to contribute to this line of research by analyzing and modeling the turning process from the perspective of the circular economy. The relationships between machining parameters, energy consumption, and the quality of the finished part are investigated, with the goal of identifying optimal solutions that lead to a reduction in material waste and an increase in the process’s sustainability. The results obtained are intended to establish a methodological framework applicable in the industrial environment, aimed at optimizing manufacturing processes in accordance with the principles of sustainable development.

2. MATERIALS AND METHODS

In this study, the turning process was investigated using an experimental and analytical approach, with the aim of modeling and optimizing technological parameters to increase efficiency and support the principles of the circular economy [5].

2.1. Materials used.

The base material subjected to machining was carbon steel (e.g., C45), commonly used in the machine-building industry due to its balanced mechanical properties and good machinability. The blanks were in the form of cylindrical bars with standardized diameters and lengths to ensure the repeatability of the experiments. The cutting tools used were indexable carbide inserts (WC-Co), coated with hard layers (TiN/TiAlN), mounted on standardized holders suitable for longitudinal turning operations.

2.2. Equipment and instrumentation.

The experiments were conducted on a precision CNC lathe capable of ensuring strict control of the cutting parameters: rotational speed, feed rate, and cutting depth (Figure 1).

Figure. 1 CNC lathe

Energy consumption was monitored using a power analyzer connected to the machine tool's power supply. A digital roughness tester was used to evaluate the quality of the machined surface.

2.3. Experimental Methodology.

The experimental design was based on a Design of Experiments (DoE) approach, using a factorial design to investigate the influence of the main technological parameters: cutting speed (vaș), feed rate (f), and cutting depth (ap). Each parameter was varied across multiple levels, determined based on recommendations from tool manufacturers and the technical literature. For each combination of parameters, repeated machining operations were performed to ensure data reproducibility.

During the experiments, the relevant response variables were recorded: specific energy consumption and surface roughness (Ra). Additionally, the amount of waste generated and the possibility of recycling the chips were evaluated as indicators of the process’s sustainability.

2.4. Cutting Process Parameters

The main parameters analyzed are:

- cutting speed (v);
- feed rate (f);
- cutting depth (ap).

The values for these three cutting parameters are given in Table 1.

Table 1. Cutting parameters used in the experiments:

Parameter	Level 1	Level 2	Level 3
Cutting speed, $v_{aș}$[m/min]	120	180	240
Advance, f [mm/rot]	0,10	0,20	0,30
Cutting depth, a_p [mm]	0,5	1	1,5

2.5. Process Modeling

The turning process was modeled by correlating the technological parameters with performance indicators:

- specific energy consumption (Es)
- machined surface quality (Ra), etc.

An empirical model based on regression and multiple objective functions was used to evaluate overall performance.

Optimization Method

Optimization was performed using a multi-objective method (genetic algorithm type), with the following objectives:

- minimizing energy consumption;
- improving the quality of the machined surface; etc.

Additionally, the possibility of recycling the resulting chips was analyzed by evaluating the degree of material recovery.

3. RESULTS AND DISCUSSION

Following the completion of the experimental program and the analysis of the obtained data, a number of significant correlations were identified between the operating parameters of the turning process and the analyzed performance indicators, namely specific energy consumption and the quality of the machined surface. The results confirm the complexity of the interdependencies among the process variables and the need for a multi-criteria approach to its optimization.

The Influence of Cutting Parameters on Energy Consumption

Analysis of the experimental data reveals that cutting speed (vaș) and feed rate (f) have a direct and significant influence on specific energy consumption. Increasing the cutting speed generally leads to a reduction in machining time, but is associated with an increase in instantaneous power consumption (Figure 2). However, the results show that there is an optimal range of cutting speeds within which specific energy consumption (relative to the volume of material removed) is minimized. This behavior is explained by the increased efficiency of the cutting process and the reduction of relative friction in the tool–workpiece contact zone.

The feed rate has a dual effect: increasing it leads to an increase in the volume of material removed per unit of time, which results in a decrease in specific energy consumption, but at the same time can place greater mechanical stress on the tool and degrade surface quality (Figure 3). As for the depth of cut (ap), it directly influences the mechanical load of the process, causing an almost linear increase in energy consumption as its value increases.

The standard model for turning can be written as follows:

$$P_e = \frac{k_c \cdot a_p \cdot f \cdot v_{as}}{6000 \cdot \eta} \qquad (1)$$

where:

- P_e = estimated electrical power [kW];
- K_c = specific cutting force [N/mm²];
- a_p = cutting depth [mm];
- f = feed rate [mm/rev];
- $v_{aș}$ = cutting speed [m/min];

- η = overall machine efficiency:

For energy consumption per piece, if a constant volume of material is being processed, the following equation can be used:

$$E = (P_o + P_e) \cdot t \qquad (2)$$

where:

- E = energy consumed per part;
- P0 = auxiliary power of the machine;
- t = processing time;

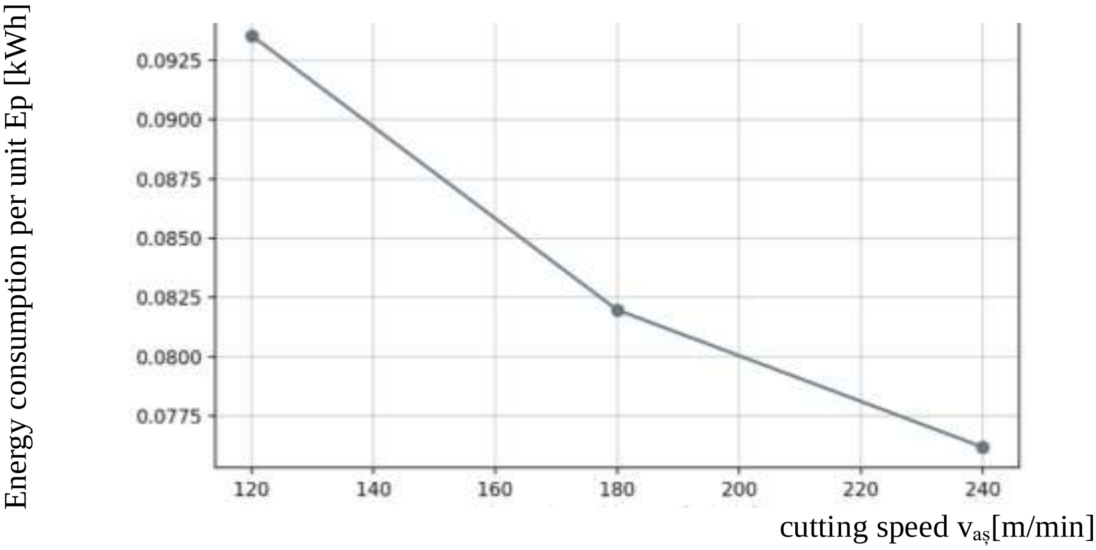

Figure. 2. The relationship between energy consumption and cutting speed (f=0,20 mm/rot, a_p=1,0 mm. V=100 cm^3)

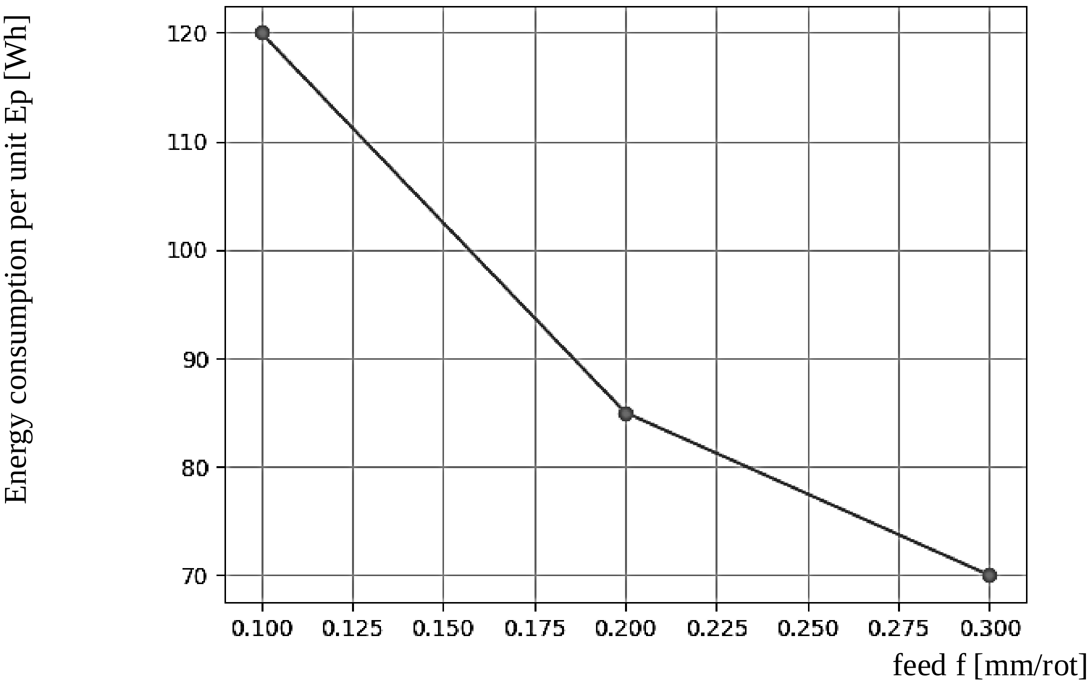

Figure. 3 Energy consumption per feed rate (f=0,20 mm/rot, a_p=1,0 mm. V=100 cm^3)

Surface Quality and Roughness

Surface roughness, expressed by the Ra parameter, was analyzed in relation to the cutting parameters. The results indicate that feed rate is the dominant factor in determining surface quality. Higher feed rates lead to a significant increase in roughness due to the formation of more pronounced chip marks. In contrast, cutting speed has a positive effect on surface quality up to a certain limit, by reducing adhesion phenomena and the formation of built-up edge.

At very high cutting speeds, a deterioration in surface quality was observed, a phenomenon explained by the occurrence of vibrations and dynamic instabilities in the machining system. Cutting depth has a lesser influence on surface roughness, but high values can contribute to the amplification of local plastic deformations and the occurrence of surface defects.

The graphs below show the variation in surface roughness (Ra) as a function of cutting parameters: cutting speed (Figure 4), feed rate (Figure 5), and cutting depth (Figure 6).

It can be observed that surface roughness decreases as the cutting speed increases, increases significantly with feed rate, and increases moderately with cutting depth.

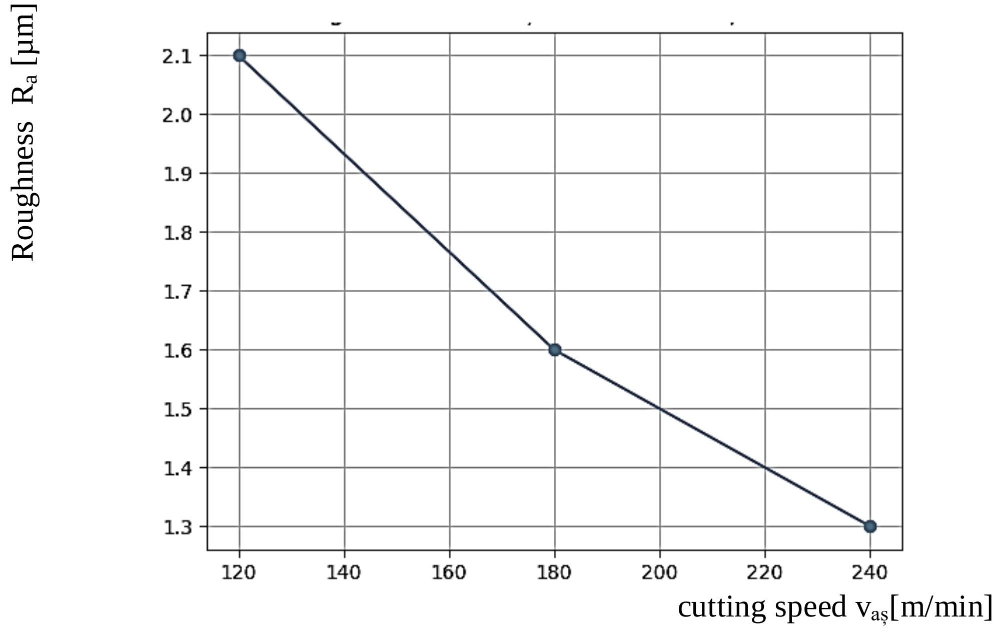

Figure. 4. Surface roughness as a function of cutting speed

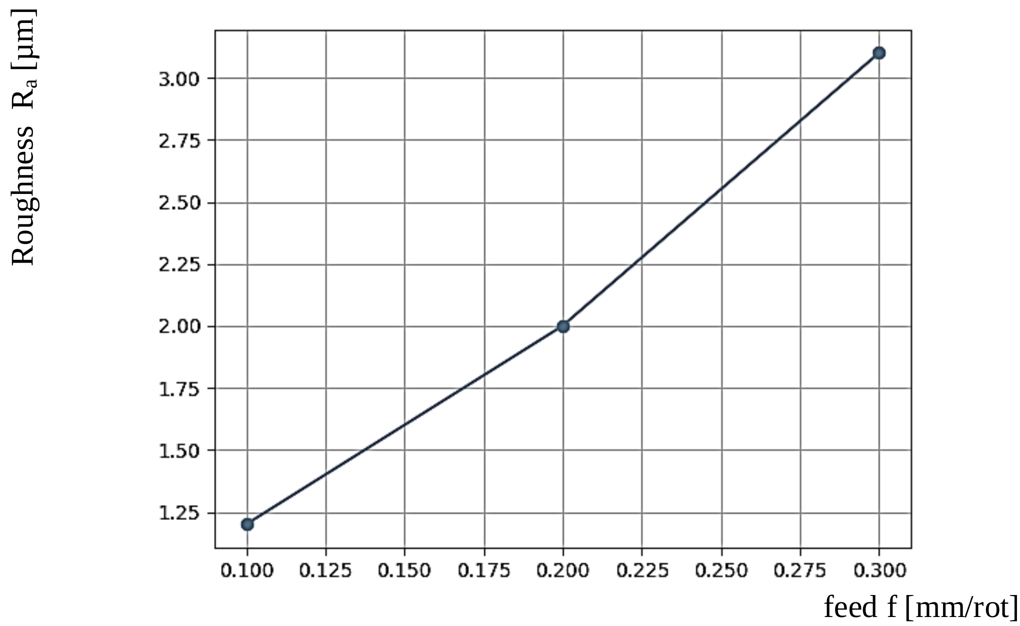

Figure. 5. Roughness as a function of feed rate

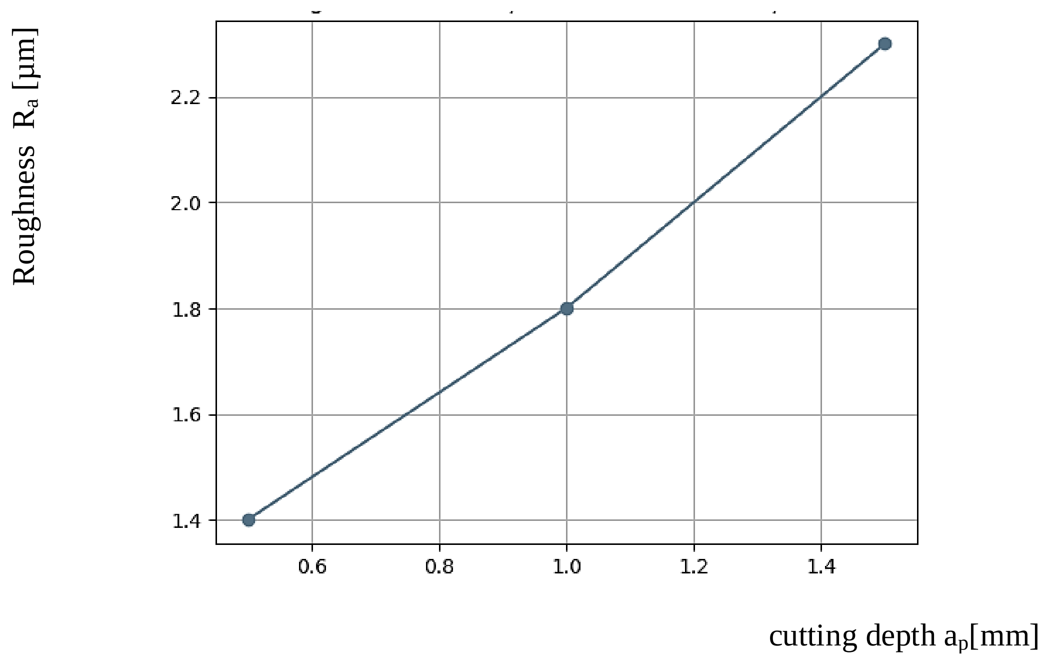

Figure. 6. Surface roughness as a function of cutting depth

Multi-objective process optimization

By applying multi-objective optimization methods, an optimal set of process parameters can be determined that strikes a balance between energy consumption and surface quality. The results show that the optimal solutions do not lie at the extremes of the parameter ranges, but are located in intermediate regions [6,7].

The composite objective function allowed the identification of cutting regimes characterized by moderate values of speed and feed, which lead to a favorable balance between productivity and sustainability. These results highlight the importance of a systemic approach to the turning process, in which the optimization of a single indicator can lead to the degradation of others.

Implications for the Circular Economy

A central aspect of this study is the evaluation of the process from the perspective of the circular economy. Reducing energy consumption and optimizing tool lifespan directly contribute to mitigating environmental impact. Furthermore, optimizing process parameters leads to a reduction in the amount of waste generated and to better management of the resulting chips. The analysis highlighted that, under optimal machining conditions, the chips obtained have a shape and size conducive to recycling, which facilitates their reintegration into the material cycle. Furthermore, reduced tool wear results in lower material consumption for tool manufacturing and a decrease in the frequency of tool replacement [8,9].

4. CONCLUSIONS

This paper highlights the fact that the turning process can be successfully adapted to the requirements of the circular economy through appropriate modeling and optimization. The main conclusions are:

- Optimizing cutting parameters contributes to reducing energy consumption;
- Mathematical modeling allows for the identification of optimal operating conditions.
- The reuse and recycling of chips is an essential component of the circular economy.
- Integrating circular principles into machining processes leads to significant economic and environmental benefits.

A key finding of the study is the confirmation that the turning process cannot be effectively optimized by analyzing a single parameter or performance indicator in isolation. The interdependencies between cutting speed, feed rate, and cutting depth, on the one hand, and energy consumption and surface quality on the other, require a systemic approach based on trade-offs and balance. Thus, multi-objective optimization has proven essential for identifying technological regimes that simultaneously meet the requirements of productivity, quality, and sustainability.

An important finding of the study relates to specific energy consumption, which is a key indicator in assessing the sustainability of manufacturing processes. The results showed that there are optimal operating ranges in which energy consumption is minimized without compromising part quality. This finding has direct implications for reducing production costs and mitigating environmental impact, contributing to the alignment of industrial processes with the requirements of the circular economy.

From the perspective of the circular economy, the results highlight the potential of the turning process to be adapted and optimized to reduce waste and increase the reuse of materials. The chips produced by the process, under optimal machining conditions, exhibit characteristics favorable to recycling, which facilitates their reintegration into the production chain. Furthermore, reducing material losses and optimizing the use of semi-finished products contribute to increasing the overall efficiency of the process [10, 11, 12].

Another novel aspect of this study is the integration of sustainability and circular economy concepts into the analysis of machining processes. Traditionally, the optimization of these processes has focused on productivity and quality criteria, without taking into account their environmental impact. By including indicators such as energy consumption and waste generation, the study proposes an expanded evaluation framework, adapted to the current requirements of modern industry.

However, it should be noted that the study has certain limitations, stemming from the controlled experimental conditions and the use of a single type of material and tool. Extending the research to other materials, tool geometries, and machining conditions could lead to the generalization of the results and increase their applicability in various industrial fields. Furthermore, the integration of advanced methods, such as artificial intelligence or machine learning, could significantly improve the ability to optimize and adapt processes.

Looking ahead, the development of smart manufacturing systems, based on concepts such as the digital twin and Industry 4.0, offers significant opportunities for implementing the results obtained. Continuous monitoring of process parameters, combined with predictive models and optimization algorithms, can lead to the creation of autonomous processes capable of adapting in real time to working conditions and maximizing efficiency and sustainability [13, 14].

In conclusion, this paper demonstrates that the modeling and optimization of the turning process, achieved through an integrated and sustainability-oriented approach, can significantly contribute to improving technological performance and reducing environmental impact. The results obtained confirm the relevance of adopting circular economy principles in the mechanical processing industry and highlight the need to develop innovative solutions for the transition to sustainable production systems.

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