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A Pre-Study of the Relationship Between Machining Technology Parameters and Surface Roughness in the Scope of the Optimal Cost Efficiency of Machining †

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Abstract: This research investigates the relationship between machining technology parameters and surface roughness to optimize the cost efficiency of machining processes. In modern manufacturing, particularly in the automotive sector, achieving the desired surface quality while minimizing costs is critical. By evaluating tools from various manufacturers under different combinations of cutting parameters—such as cutting speed, feed, and depth—this study focuses on determining the most effective settings for producing an optimal surface roughness. The experiments highlight that selecting appropriate technological parameters impacts the machining process's surface finish and economic efficiency. This study provides insights into balancing surface quality requirements with cost constraints, contributing to more efficient and sustainable manufacturing practices.

Keywords: surface roughness; machining optimization; cutting conditions

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1. Introduction

In the turning process, surface roughness [1–3] plays a significant role in the quality of the final product, especially in the automotive industry, where stringent surface specifications are required [4]. Surface roughness directly impacts the functionality and durability of a product. Cost-effective and efficient manufacturing processes are needed, which can be obtained by applying optimal cutting parameters (cost and energy efficiency are discussed in [5–8] in general and in detail; the optimization is discussed in [9,10]). This study contains preliminary experiments examining the relationship between machining technology parameters and surface roughness, using tools from different manufacturers and various combinations of technological parameters, focusing on surface roughness measurements.

Theoretical Background

According to machining theories [11,12], it is possible to predict the final surface roughness during the machining processes if the machined material, the tool used, and the machining parameters are exactly known. However, there is variability in each case in terms of material composition and structure consistency, tool quality, and machining process stability.

Various parameters are used to measure surface roughness, such as the arithmetic mean height (Ra in micron), the root mean square height (Rq in micron), and the maximum height of the profile (Rt in micron). For example, these parameters can be defined according to the ISO 1997 standard [13] and measured using different methods. Theoretical modeling methods can be classified into two main categories: theoretical and empirical solutions. Theoretical models are based on physical phenomena such as cutting-edge duplication

and material swelling, while empirical models rely on process parameters and surface roughness data.

It is evident that there is an optimal surface roughness, which is a variable factor, for every workpiece if there is a specific application for the workpiece depending, for example, on whether it is a moving part or a stationary one, so it is not necessary in every case to tend to the best quality. Surface roughness is considered optimal if it is under the allowed maximum roughness prescribed based on function, without economically overburdening the part manufacturer. It is also vital to count the change in the surface roughness during the lifetime of the workpiece [14–16].

2. Experimental Setup

In long-term experiments, different tools from various manufacturers and several combinations of technological parameters are investigated. The parameters include cutting speed, cutting depth, and feed. The following experiments aimed to determine the optimal parameters to find the predetermined optimal surface roughness with the most cost-effective machining method. During experiments such as these, it is necessary to count including the cycle time and other economic factors since the tools' price is only a small percentage of the production costs.

2.1. Tools and Materials

Tools from different manufacturers were applied with different surface treatment methods, coatings, chip breakers, and corner radii. The materials examined included steel DIN-C45 (Werkstoff-Nr. 1.0503) and DIN-C70 (Werkstoff-Nr. 1.1249) carbon steel and aluminum alloys DIN-AlMgSi1 (Werkstoff-Nr. 3.2315) and DIN-AlZn5.5MgCu (Werkstoff-Nr. 3.4365) with a diameter of 50 mm and a length of 400 mm, which are common in automotive applications. The turning machine for the experiments was a DMG Gildemeister CTX310 CNC lathe. The workpiece clamping was a hydraulic 3-jaw lathe chuck of a 200 mm size with hard jaws.

The tools used during the experiment are detailed in Table 1.

Table 1. Main properties of the cutting inserts.

Type of the Insert	Corner Radius [mm]	Coating Type	Substrate Type	Experiment	Producer
TNMG 160404E-SM:T7325	0.4	MT-CVD	FGM submicron sintered carbide	steel	Dormer Pramet
TNMG 160404ER-SI:T9325	0.8	MT-CVD	FGM sintered carbide	steel	Dormer Pramet
DCGT 11T304F-AL:T0315	0.4	PVD	Submicron carbide	aluminum	Dormer Pramet
DCGT11T308F-AL KX	0.8	none	Submicron carbide	aluminum	Seco

During the experiment, the toolholders used comprised a square cross-section (16 × 16 mm) of right-handed tools from the company Dormer Pramet:

PTGNR 1616 H 16 for steel turning
SDJCR 1616 H 11 for aluminum turning

2.2. Methods

Before the experiments, preliminary tests were performed on DIN-C45 carbon steel. A specimen with a 50 mm diameter and 400 mm long was machined on both ends with the first two inserts from Table 1, suited for steel machining with five different technologies. All the technology parameters were chosen from the middle of the producer-offered range, except for the feed during the test. As for the feed, the authors chose one from 0.02 mm/rev

below the optimal range and one from 0.02 mm/rev above the range. The rest of the selected feeds were from the application window's low, middle, and high parts for the selected tools after all the machining. The cutting parameters of the two different cutting inserts are summarized in Table 2.

Table 2. Cutting parameters of the two different cutting inserts.

Type of Cutting Insert	Cutting Speed [m/min]	Depth of Cut [mm]	Feed [mm/rev]
TNMG 160404E-SM:T7325	160	2	0.16 0.18 0.19 0.20 0.22
TNMG 160408ER-SI:T9325	160	2	0.18 0.20 0.30 0.40 0.42

After all the machining in the preliminary tests, the surface roughness was measured according to the ISO 1997 standard [13], with the Mitutoyo measuring equipment and process.

During these further machining experiments on a defined length, every tool was used with the same technology and material as the first experiment. As a second step, the authors used the parameters offered by the producers for a specific application. After the statistical evaluation of the two experiments, the tool life of each tool was examined to allow for economic calculations. The tool life test was run for every case until obtaining the 0.1 mm flank wear of the working area. According to the producers, this is usually achieved after 20 min of the tool's cutting time.

During the tool life test, surface roughness was measured after every pass with the tool.

Surface roughness was measured using a profilometer, which allowed for the determination of the 2D profile of the surface. The results were analyzed using statistical methods to determine the effect of each parameter on surface roughness [16].

The parameters of the surface roughness measuring device are outlined below:

type	Mitutoyo SJ-301
detector	standard detector 5 μm radius
measuring force	4 mN
measuring standard	ISO 1997 [13]
profile parameters	R-profile, λc 0.8, and N5
value	Ra and Rz

3. Results of the Preliminary Experiment

After the machining process in the preliminary tests was executed, the difference in the surfaces was immediately visible (see Figure 1).

The increase in the feed decreased the smoothness of the surface according to the visual inspection; however, the exact measuring showed something different. The feed value below the producer's proposed range showed a significant decrease in surface quality. Looking at the results obtained during the measuring process (see Table 3), it became clear that this decrease in the surface quality did not precisely correspond to the roughening of the surface, but there was a significant wave on the surface, and the length of this wave showed that there was a kind of vibration [13].

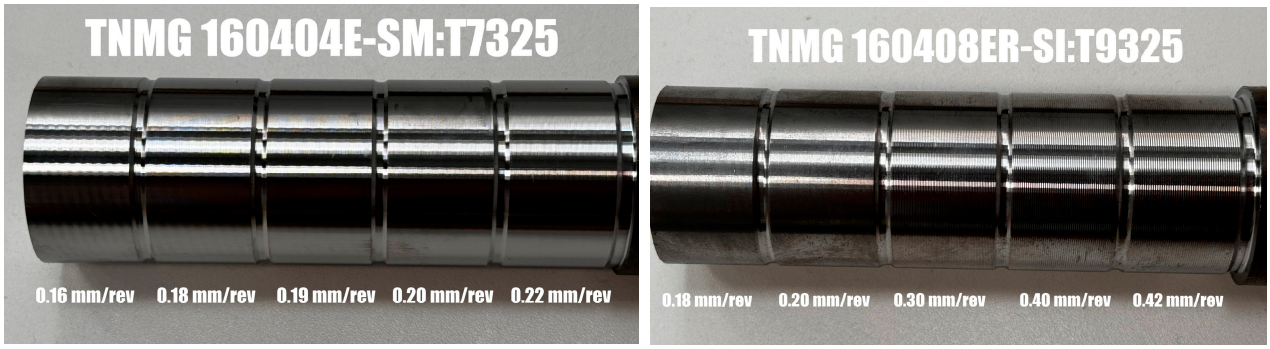


Figure 1. Surface roughness after only changing the feed.

Table 3. Surface roughness results according to ISO 1997 on the machined specimen.

Cutting Speed [m/min]	Corner Radius [mm]	Feed [mm/rev]	Ra [µm]	Rz [µm]
160	0.4	0.16	1.88	8.81
		0.18	1.30	5.86
		0.19	2.56	10.83
		0.20	3.20	13.15
		0.22	4.23	16.74
160	0.8	0.16	1.72	7.76
		0.18	1.30	5.86
		0.19	2.91	13.09
		0.20	3.49	17.67
		0.22	3.77	18.75

4. Discussion

During the experiments, the increase in the cutting speed and the decrease in the feed were expected to result in a smoother surface finish, while the cutting depth was expected to not have a significant effect, especially in the case of aluminum, but it had a slight effect while machining steel. If the cutting depth were to increase while machining steel, the surface roughness would be increased over a specific value depending on the machined material and cutting tool parameters like material, chip breaker, coating, and corner radius.

In the case of a tool's life, when operating in the producer-recommended range, it is necessary to modify the cutting parameters in the opposite direction because the increased cutting speed shortens the tool life, and some have the same effect as that obtained from a decreased feed.

During the experiments, the authors wished to find the optimal point represented by the crossing of the two lines in Figure 2, containing the curves of the technological parameters.

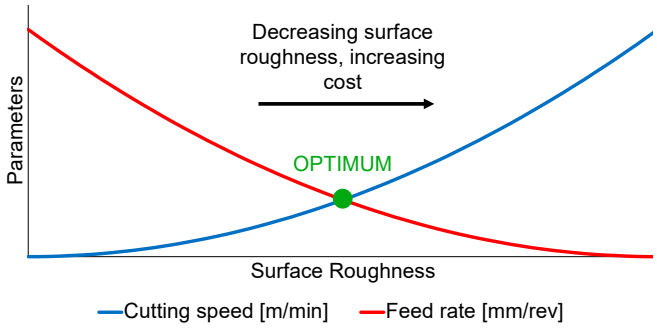


Figure 2. Visualization of the optimal point in the context of the cutting parameters, surface roughness, and tooling cost.

This method would make it possible to optimize the cutting method and include other economic factors like the hourly rate of the machining, the consumed power, or the cycle time of the workpieces. Considering all the economic factors mentioned, it would also be possible to optimize the machining process cost and carbon footprint [17] (see Figure 2).

4.1. Effect of Cutting Speed

The results showed that increasing the cutting speed generally reduces the surface roughness, as higher speeds facilitate material deformation, resulting in a smoother surface finish. However, if someone were to increase the cutting speed too much, this would result in a shorter tool life or even in the sudden wear of the cutting edge. The friction increase in the cutting area erodes the cutting edge, or in extreme cases, it can generate so much heat that the cutting edge's thermal stability cannot resist, causing said edge to deform or even melt down [18,19].

4.2. Effect of Feed

Increasing the feed increases the surface roughness, as higher rates leave deeper grooves on the surface due to the cutting edge. On the other hand, if the feed is decreased too much, chip forming will not be optimal. If the feed is lower than the edge preparation, there will be plastic forming on the machined surface in the cutting area, and the cutting forces and generated heat will increase, leading to a shorter tool life [14,19].

4.3. Effect of Cutting Depth

The effect of cutting depth was less significant, but higher cutting depths slightly increased the surface roughness, especially in the case of steel. It should be mentioned that having the minimal value configured adequately when it comes to the cutting depth is very important. There are two risks present when someone is machining with a cutting depth that is too low.

The first one is similar to the feed: if someone does not have a cut that is deeper than the edge that has been prepared, the same problem observed for the feed will arise.

The second problem caused by a cutting depth that is too low is that the forces which are necessary during cutting are not generated, and there can be a vibration in either the tool or the machined part, which will shorten the tool's life and/or increase the surface roughness. The overhang of the tool can also influence the vibration, the L/D rate of the machined part, and tool and workpiece fixing [14,17,19,20].

5. Conclusions

This study emphasizes optimizing machining parameters to achieve the desired surface quality while ensuring cost efficiency, especially in sectors like automotive manufacturing. Cutting speed and feed rate were found to impact surface roughness significantly. Higher cutting speeds resulted in smoother finishes but shortened the tool life due to increased wear, while higher feed rates produced rougher surfaces, and lower feeds led to inefficient chip formation and higher tool wear. Cutting depth had a more moderate influence, particularly when machining aluminum, though it still required careful adjustments to avoid tool vibrations.

The findings underscore the need for manufacturers to balance surface quality, tool life, cycle time, and energy consumption for cost-effective machining. Optimizing these parameters enhances productivity and reduces costs and environmental impact. Future research should investigate the interactions between machining variables and explore advanced technologies like predictive modeling to refine precision and efficiency further.

This study provides vital insights for manufacturers looking to improve surface quality and operational efficiency through smarter, more sustainable machining practices. Further research should aim to precisely define the optimal machining parameters for even more effective production methods.

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