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TAGUCHI BASED OPTIMIZATION OF POLYETHILENE MILLING PARAMETERS BASED ON CUTTING TEMPERATURE AND SURFACE ROUGHNESS CRITERIA

Research paper

Dušan Jovanić[1], Spasoje Erić[2], Miodrag Kovačević[3]
[1,2,3]Technical College of Applied Sciences, Zrenjanin, Serbia

Abstract: This paper presents the optimization of face milling parameters for polyethylene (PE) using an end mill on an Emco 55 Mill CNC machine by applying the Taguchi method. The aim was to investigate the influence of machining parameters on cutting temperature, cooling rate, and the surface roughness of the machined surface in both the feed direction and the direction perpendicular to the feed.
During the experiment, the machining parameters: spindle speed, feed rate, and depth of cut, were varied at three levels. A thermographic camera was used to measure the characteristic temperatures at a point immediately behind the face milling cutter and after a specified time interval. Based on these measurements, the cooling rate was determined, as it influences the surface roughness of the machined surface.
The surface roughness of the polyethylene specimens was evaluated using a surface roughness tester. The measured output geometric parameters included the Arithmetic Mean Roughness (Ra), Root Mean Square Roughness (Rq), Maximum Profile Height (Rz), and Total Profile Height (Rt). In addition, the surface profile geometry, i.e., the roughness profiles, was presented both in the feed direction and perpendicular to it, in accordance with the EN ISO 4287 standard.
Key words: Optimization, Roughness, CNC milling, Polyethylene, Thermography, Cutting temperature.

INTRODUCTION

During machining by cutting, stresses are generated within the material due to plastic deformation occurring in the initial stage of chip formation, as well as due to the heat produced during the cutting process. As a result of the interaction between the cutting tool and the workpiece, in addition to thermal energy, a machined surface is created with a series of peaks and valleys, referred to as the surface roughness. In milling operations, the surface roughness is directly proportional to the square of the feed rate and inversely proportional to the cutter diameter.
The aim of this study is to investigate the influence of polyethylene milling parameters, namely spindle speed, feed rate, and depth of cut, on cutting temperature and the surface roughness of the machined surface.
Previous studies have addressed this issue to some extent. For example, one study evaluated the influence of cutting parameters, specifically cutting speed, feed per tooth, and depth of cut, on surface quality, represented by the arithmetic mean roughness (Ra) and the total profile height (Rt), as well as on productivity expressed by the material removal rate (MRR), during face milling of polyoxymethylene (POM). The results showed that feed per tooth had the greatest influence on the arithmetic mean surface roughness-Ra (Tibakh et al., 2025).
In another study, the optimal cutting conditions were determined using the desirability function approach. The results indicated that feed rate was the dominant factor contributing to the minimization of the surface roughness of high-density polyethylene (HDPE). Conversely, the cutting temperature was found to be mainly affected by cutting speed, depth of cut, and three interaction effects: cutting speed and feed rate, cutting speed and depth of cut, and feed rate and depth of cut. Finally, the optimized cutting temperatures were discussed for three target conditions: the minimum value, a target temperature of 30 °C, and the maximum allowable temperature of 32 °C (Hamlaoui et al., 2017).

[1] Corresponding author, dusan.jovanic@vts-zr.edu.rs, ORCID: 0009-0001-6058-4074
[2] spasoje.eric@vts-zr.edu.rs, ORCID: 0009-0006-0705-0635
[3] miodrag.kovacevic@vts-zr.edu.rs, ORCID:0000-0002-1803-6816

Another study applied the surface topography method to characterize four different surface roughness levels of a polyethylene liner (Pe-Lite liner) manufactured by Biomill. Three surface roughness parameters were selected for evaluation: the arithmetic mean roughness (Ra), the root mean square roughness (Rq), and the ten-point height of irregularities (Rz). The results showed that the Ra value of the conventionally manufactured liner was between the Ra values of the standard and the fast-finished surfaces (Hamzah et al., 2022).

THERMODYNAMICS OF CUTTING AND THERMOGRAPHY

Nearly all of the mechanical energy supplied during the cutting process is converted into thermal energy within the cutting zone through elastic and plastic deformation, friction at the tool–workpiece and tool–chip interfaces, and internal friction within the workpiece material. The generated heat significantly affects tool wear and tool life, machining productivity, surface roughness, and the overall quality of the machined surface [Milikić, 2003].
The temperatures generated during the cutting process include the temperature in the shear plane, which increases with increasing cutting speed; the temperature at the cutting edge and flank face of the tool, resulting from chip deformation; the temperature on the rake face, which reaches the highest value due to friction between the chip and the tool; and the temperature of the machined surface, caused by friction between the flank face of the tool and the workpiece surface.
Cutting temperature is influenced by numerous factors, the most important of which are the workpiece and tool materials, machining parameters, tool geometry, and the type of cooling and lubrication applied. The temperature of the cutting tool is generally higher than that of the chip and may reach up to twice the chip temperature [Stanković, 1967].
Infrared thermography (IRT), also referred to as thermovision, is widely used to identify and document irregularities for machine condition monitoring, quality control, and non-destructive testing, as well as for monitoring temperatures in various manufacturing processes, including the cutting zone. IRT has proven to be a highly effective method for temperature monitoring because it enables comprehensive thermal imaging of machines and their components through non-contact temperature measurement (ISO, 2008).

MACHINED SURFACE ROUGHNESS

Surface roughness is defined as the collection of surface irregularities that form the texture of a surface over a specified reference (sampling) length. The reference length is selected in accordance with the ISO 4287 standard to exclude larger waviness features and other macro-scale irregularities from the roughness evaluation.
The most commonly used surface roughness parameters are:
- Arithmetic Mean Roughness (Ra): The arithmetic mean of the absolute values of the profile deviations from the mean line over the evaluation length. It is the most widely used roughness parameter and provides an overall measure of average surface roughness.
- Root Mean Square Roughness (Rq): The root mean square (RMS) value of the profile deviations over the evaluation length. Compared with Ra, this parameter is more sensitive to pronounced surface peaks and valleys because larger deviations have a greater influence on its value.
- Maximum Height of the Profile (Rz): The arithmetic mean of the height differences between the five highest profile peaks and the five deepest profile valleys within the reference length.
- Total Profile Height (Rt): The total vertical distance between the highest profile peak and the deepest profile valley over the entire evaluation length.

In turning and planing operations, surface roughness is directly proportional to the square of the feed rate and inversely proportional to the tool nose radius. In milling, however, surface roughness is directly proportional to the square of the feed rate and inversely proportional to the cutter diameter.

POLYETHYLENE

Polyethylene is one of the most widely used thermoplastic materials in industry due to its excellent mechanical properties. In this study, polyethylene PE 500 was selected because of its good machinability, favorable mechanical properties, and excellent impact and wear resistance. However, its limitations include relatively low resistance to elevated temperatures and shear loading.The chemical formula of polyethylene-PE 500 is $(C_2H_4)_n$.

EXPERIMENTAL RESEARCH

A series of experiments was carried out on an EMCO Mill 55 CNC milling machine. Prismatic PEspecimens with dimensions of 70 × 60 × 25 mm were used as workpieces. The specimens were face milled using a high-speed steel (HSS) end mill, type B, conforming to DIN 327, with a shank diameter of 12 mm.The machining parameters, namely spindle speed (rpm), feed rate (mm/min), and depth of cut (mm), were then varied according to the experimental design, and a series of specimens was produced.Figure 1 shows the EMCO Mill 55 CNC milling machine, a simulation of the milling process, and the HSS end mill used in the experiments.

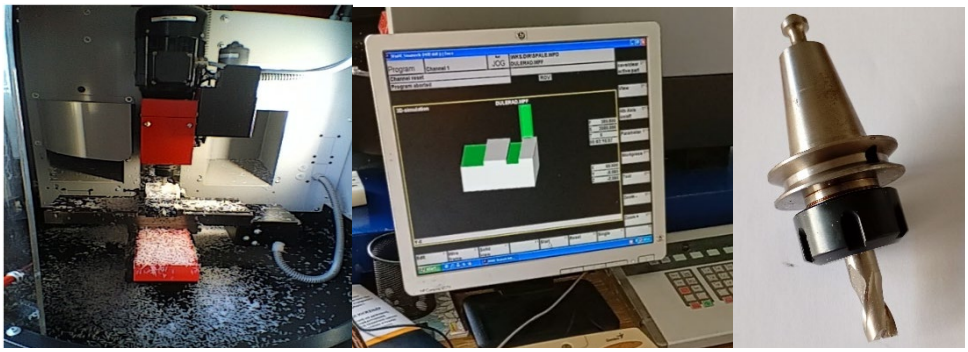


Fig. 1. *EMCO mill55 CNC milling machine, a simulation of the milling process, and the end mill*

Figure 2 also presents the cutting temperature (hot spot) measured during the face milling of PE 500 under the following machining conditions: a spindle speed of 2000 rpm, a feed rate of 200 mm/min, and a depth of cut of 4 mm. The measured cutting temperature was 35.5 °C (Testo SE & Co. KGaA, 2026).
During the face milling operation, the temperature in the cutting zone and the cooling rate were measured using a Testo 860i thermal imaging camera. The thermographic images shown in Figure 2 were captured from a distance of 50 cm, at an angle of 45° to the workpiece, with an emissivity value of 0.95.

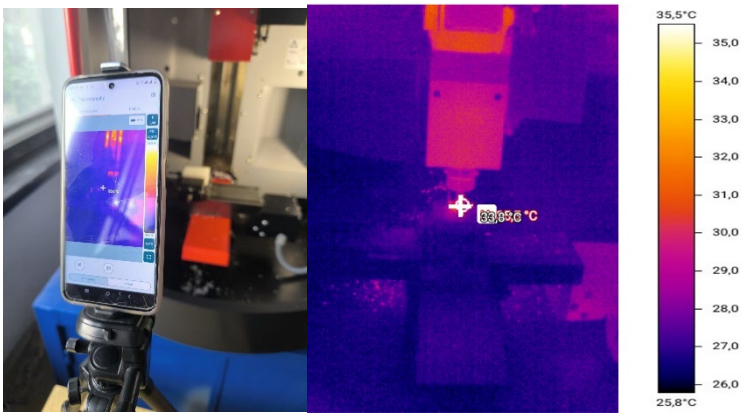


Fig. 2. *Thermography and Hot-Spot Cutting Temperature*

Figure 3 shows the maximum temperature measured immediately behind the end mill, as well as the temperature measured after a specified time interval, which were used to calculate the cooling rate.

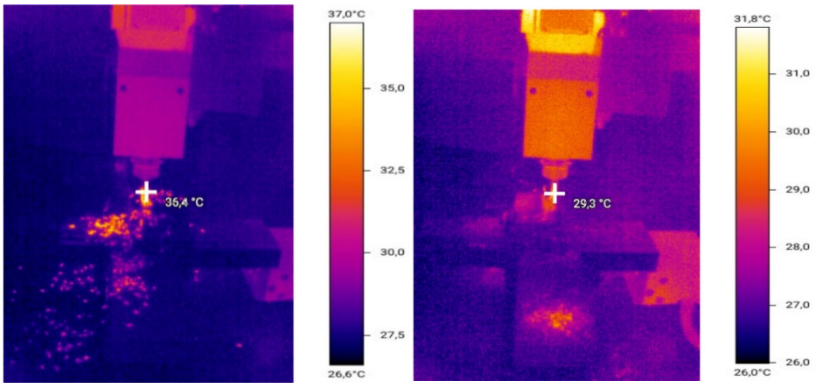


Fig. 3. *Thermograms of the temperature after the milling pass and a specified time interval*

Figure 4 shows the calibration and measurement procedure using the PCE RT 1200 surface roughness tester. In addition to the measured results, measurement units, and the Arithmetic Mean Roughness (Ra) parameter, the instrument allows the values of other surface roughness parameters to be displayed, including Root Mean Square Roughness (Rq), Maximum Height of the Profile (Rz), and Total Profile Height (Rt). The figure also shows the Gaussian filter, which is used to separate surface roughness from waviness, as well as the defined evaluation length of 2.5 mm, in accordance with EN ISO 4287 (ISO, 2025).
The instrument uses an inductive probe with a diamond stylus tip to trace the surface profile. The obtained profile data are then processed and the roughness parameters are calculated in accordance with the EN ISO 4287 standard.



Fig. 4. *Calibration and measurement procedure using the PCE RT 1200 surface roughness tester*

RESULTS AND DISCUSSION

In the experiment, the most important milling parameters were varied, namely spindle speed, feed rate, and depth of cut. The values corresponding to the upper, middle, and lower levels of the selected machining parameters for polyethylene are presented in Table 1.

Tabela 1.*Upper, middle, and lower levels of the milling parameters*

The parameters	Values		
	Level 1	Level 2	Level 3
Spindle speed (rpm)	1000	2000	3000
Feed (mm/min)	100	200	300
Depth of cut (mm)	2	3	4

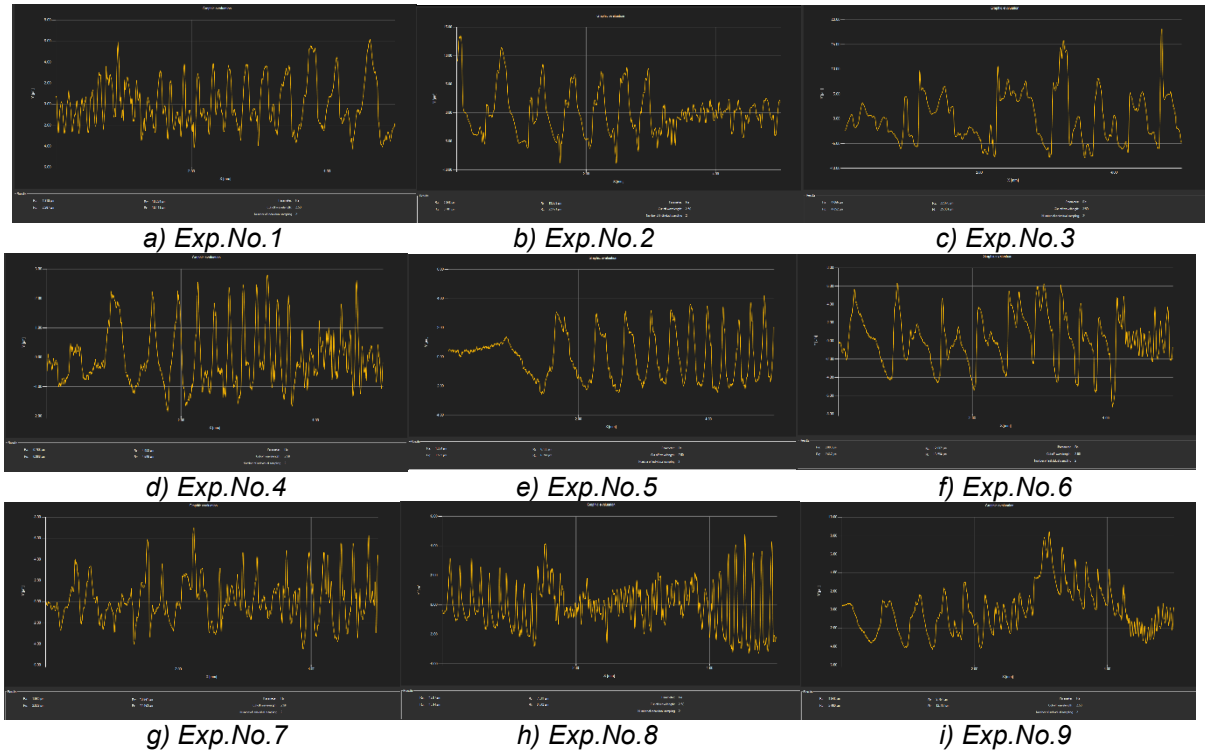
The Taguchi L9 orthogonal array was used for the experimental design. Design of Experiments(DOE) is a systematic approach used to evaluate how input process parameters affect one or more output responses. By systematically varying the input factors, DOE

enables the determination of optimal process parameters and the identification of the most influential factors and their optimal levels for achieving the desired performance targets.
The Taguchi method uses the signal-to-noise (S/N) ratio to evaluate and optimize process performance. In the present study, the S/N ratio was applied for multi-response process optimization using the Smaller-the-Better criterion to minimize surface roughness.
The measured surface roughness values, based on three measurements taken in both the longitudinal (feed) and transverse (perpendicular to the feed) directions, as well as the cooling rate as a function of spindle speed, feed rate, and depth of cut, are presented in Table 2. It can be observed that the surface roughness measured in the feed direction is higher than that measured perpendicular to the feed direction.

Table 2. *Arithmetic Mean Roughness (Ra)values and cooling rates for different milling parameters*

Exp No.	Spindle speed (rpm)	Feed (mm/ min)	Depth of cut (mm)	Cooling rate (°C/s)	Ra transverse (μm)	Ra longitud. (μm)	S/N transverse (dB)	S/N longitud. (dB)
1	1000	100	2	0,1330	2.236	2.628	-6.99	-8.39
2	1000	200	3	0,0848	3.405	3.737	-10.64	-11.45
3	1000	300	4	0,0408	3.736	4.051	-11.45	-12.15
4	2000	100	3	0,1183	1.779	0.990	-5.00	0.09
5	2000	200	4	0,0741	1.920	2.746	-5.67	-8.77
6	2000	300	2	0,0286	2.436	2.807	-7.73	-8.97
7	3000	100	4	0,1280	1.110	0.565	-0.91	4.96
8	3000	200	2	0,0667	1.804	2.889	-5.12	-9.21
9	3000	300	3	0,0283	1.739	1.822	-4.81	-5.21

The arithmetic mean roughness (Ra) profiles measured perpendicular to the feed direction, arranged according to the experimental sequence, are presented in Figure 5. In addition to the effective profile surface, the figure presents the values of the roughness parameters Ra, Rq, Rz, and Rt, as well as the cut-off wavelength, which is 2.5 mm, and the number of individual sampling lengths.



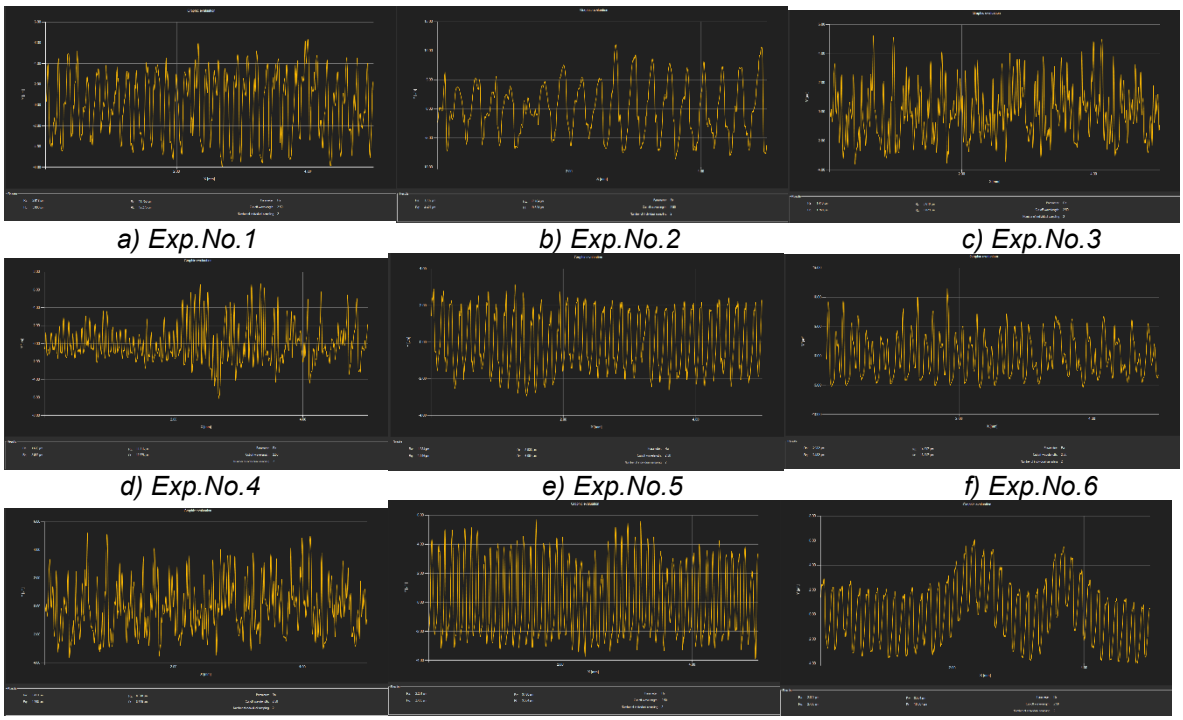
a) Exp.No.1 *b) Exp.No.2* *c) Exp.No.3*

d) Exp.No.4 *e) Exp.No.5* *f) Exp.No.6*

g) Exp.No.7 *h) Exp.No.8* *i) Exp.No.9*

Fig. 5*. The arithmetic mean roughness (Ra) profiles perpendicular to the feed direction in the experimental sequence*

Figure 6 presents the arithmetic mean roughness (Ra) profiles measured in the feed direction, arranged according to the experimental sequence.



a) Exp.No.1 *b) Exp.No.2* *c) Exp.No.3*

d) Exp.No.4 *e) Exp.No.5* *f) Exp.No.6*

g) Exp.No.7 *h) Exp.No.8* *i) Exp.No.9*

***Fig. 6**. The arithmetic mean roughness (Ra) profiles in the feed direction in the experimental sequence*

The mean Ra surface roughness values, measured both perpendicular to the feed direction and in the feed direction, together with the corresponding S/N ratios, for each machining parameter separately, are presented in Table 3.

***Table 3.** Mean Ra surface roughness values and S/N ratios for each machining parameter*

The parameters		Values			
		Ra transverse (μm)	S/N transverse Ratio	Ra longitudinal (μm)	S/N longitudinal Ratio
Spindle speed (rpm)	1000	3.126	-9.69	3.472	-10.66
	2000	2.045	-6.13	2.181	-5.88
	3000	1.551	-3.61	1.759	-3.15
Feed (mm/min)	100	1.708	-4.30	1.394	-1.11
	200	2.376	-7.14	3.124	-9.81
	300	2.637	-8.00	2.893	-8.78
Depth of cut (mm)	2	2.159	-6.61	2.775	-8.86
	3	2.308	-6.82	2.183	-5.52
	4	2.255	-6.01	2.454	-5.32

Based on the S/N ratios presented in Table 3, the optimal machining parameters for achieving minimum surface roughness in both measurement directions are a spindle speed of 3000 rpm, a feed rate of 100 mm/min, and a depth of cut of 4 mm, corresponding to Experiment No. 7**.**
This machining condition also provides the maximum cooling rate of 0.1280 °C/s, thereby reducing the risk of polyethylene melting and the formation of micro-ridges on the machined surface.

The influence ranking is determined based on the Delta value, which represents the difference between the maximum and minimum mean values for the observed factor. A larger Delta value indicates a greater influence of the corresponding factor on the final response. The influence rankings for transverse Ra,longitudinal Ra, and process stability are presented in Table 4 and Table 5.

Table 4. *Influence ranking for transverse Ra surface roughness and process stability*

The parameters	Δvalue Ra transverse	Rang Ra transverse	Δ value S/N transverse	Rang S/N transverse
Spindle speed (rpm)	1.575	1	6.08	1
Feed (mm/min)	0.929	2	3.70	2
Depth of cut (mm)	0.149	3	0.81	3

Table 5. *Influence ranking for longitudinal Ra surface roughness and process stability*

The parameters	Δ value Ra longitudinal	Rang Ra longitudinal	Δ value S/N longitudinal	Rang S/N longitudinal
Spindle speed (rpm)	1.713	2	7.51	2
Feed (mm/min)	1.730	1	8.70	1
Depth of cut (mm)	0.592	3	3.54	3

The results of the Taguchi analysis show that the lowest surface roughness during polyethylene milling is achieved at a low feed rate of 100 mm/min and a high spindle speed of 3000 rpm**.**

For surface roughness measured perpendicular to the feed direction, spindle speed has the greatest influence (Δ= 1.575 μm), followed by feed rate (Δ = 0.929 μm), while the depth of cut has a very small influence (Δ = 0.149 μm).

For surface roughness measured in the feed direction, feed rate has the greatest influence (Δ = 1.730 μm), followed closely by spindle speed (Δ = 1.713 μm), while depth of cut again has the smallest influence (Δ= 0.592 μm).

Overall, feed rate and spindle speed are the dominant factors determining the quality of the machined surface, whereas the influence of depth of cut is considerably lower within the investigated range.

CONCLUSION

The optimization of the face milling parameters for polyethylene (PE) using an end mill on an EMCO Mill 55 CNC machine, based on the Taguchi method, enabled the determination of the optimal combination of spindle speed, feed rate, and depth of cut with respect to the surface roughness measured both in the feed direction and perpendicular to it.

It was confirmed that surface roughness in the feed direction depends primarily on the feed rate, followed by spindle speed, while the depth of cut has the least influence. It was also found that the surface roughness measured in the feed direction is higher than that measured perpendicular to the feed direction.

As the spindle speed increases, the surface roughness decreases significantly. In polyethylene machining, higher cutting speeds reduce the cutting force and enable cleaner material removal without excessive plastic deformation of the machined edges.

A reduction in feed rate results in lower surface roughness in all cases. Higher feed rates leave more pronounced tool marks on the machined surface.

The depth of cut has a statistically negligible effect on surface roughness within the investigated range. This indicates that the depth of cut can primarily be selected based on

productivity requirements, as it does not significantly impair the quality of the finished surface.
Polymers such as polyethylene have a relatively low melting point and low thermal conductivity. Therefore, effective thermal management is crucial during machining. The experimental data indicate a very strong correlation between feed rate and cooling rate. At a low feed rate, the cooling rate is highest. As the feed rate increases, the cooling rate decreases significantly.

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REFERENCES

EMCO GmbH. (n.d.). *Concept Mill 55*. https://www.emco-world.com/en/products/industrial-training/machines/milling/concept-mill/concept-mill-55.html

Hamlaoui, N., Azzouz, S., Chaoui, K., Mokhtar, B., &Azari, Z. (2017). Machining of tough polyethylene pipe material: Surface roughness and cutting temperature optimization. *The International Journal of Advanced Manufacturing Technology*, *92*(1), 517–527. doi.org

Hamzah, N. A., Razak, N. A. A., Karim, M. S. A., &Salleh, S. Z. (2022). Validation of a roughness parameters for defining surface roughness of prosthetic polyethylene Pe-Lite liner. *Scientific Reports*, *12*, Article 2636. doi.org

International Organization for Standardization. (2008). *Condition monitoring and diagnostics of machines — Thermography — Part 1: General procedures* (ISO Standard No. 18434-1:2008). iso.org

International Organization for Standardization. (2025). *Geometrical product specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters* (ISO Standard No. 4287:2025). iso.org

Milikić, D. (2003). *Tehnologijaobraderezanjem: Opštaiprimenjenateorija*. Fakultettehničkihnauka, Univerzitet u NovomSadu.

Stanković, P. (1967). *Mašinskaobrada: Obradametalarezanjem*. Građevinska knjiga; Mašinski fakultet, Univerzitet u Beogradu.

Testo SE & Co. KGaA. (2026). *Testo Smart App* (Version X.X) [Mobile app]. Google Play Store. google.com

Tibakh, I., Yallese, M. A., Belhadi, S., &Kaddeche, M. (2024). Multi-response optimisation during face milling of polyoxymethylene copolymer using grey relational analysis and data envelopment analysis based ranking coupled with the Taguchi approach. *Advances in Materials and Processing Technologies*, *11*(2), 681–706.
DOI:10.1080/2374068X.2024.2314838