

EFFECT OF ABANDONMENT OF COOLING AND LUBRICATION ON SURFACE ROUGHNESS AND CYLINDRICITY IN TURNING OF STEEL

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Abstract

One of the defining global issues today is to reduce the load on the environment. Thus, in this paper, the effect, and consequences of the abandonment of cooling and lubrication were investigated when turning of non-alloyed steel. The 2D and 3D surface roughness parameters, cylindricity deviations and circularity errors were examined at different feeds and cutting speeds. The experiments were performed, using the full factorial experimental design method. It was found that with dry machining, the average roughness is slightly higher with increasing productivity, however, at lower feed and cutting speeds, the surface has better wear resistance and lubricant retention, and cylindricity deviation can be minimized.

Keywords: turning, surface roughness, cylindricity deviation, environmentally friendly machining

1. Introduction

The use of coolants-lubricants (CL) in machining improves the quality and accuracy of manufactured parts, increases productivity, and helps remove chips from the cutting region. At the same time, their use pollutes the environment (Dudás et al., 2010; Kundrák et al., 2018), and in addition to its high cost, they can also cause skin and breathing problems for machine operators (Saliminia and Abootorabi, 2019). Therefore, the environmental protection (which is becoming increasingly important worldwide) aims in machining to the minimization or abandonment of CLs. It is further exacerbated by the fact that their use is particularly high worldwide. There are several possibilities associated with this (Kundrák et al., 2018): the use of naturally occurring and degradable oils (Bonfá et al., 2019; Derani and Ratnam, 2021; Gariani et al., 2021), the reduction of the amount used (e.g., Minimum Quantity Lubrication, MQL) (Bonfá et al., 2019; Gupta et al., 2020; Niknam and Jalali, 2020; Zaman and Dhar, 2019), the change of composition, or the omission of cooling-lubrication (Gupta et al., 2019; Leppert, 2011). The latter was pointed out by Kundrák et al. (Kundrák et al., 2018) in the study of the machining of case-hardened steel gear hole. Three strategies were compared in terms of productivity and the amount of CL fluid used; hard turning, conventional traverse bore grinding and combined machining (turning and grinding). It was found that in contrast to grinding, the combined process requires less cutting fluid in a shorter machining time, but more importantly, the CBN insert used in hard turning allows dry machining with high productivity, making the latter the most environmentally friendly choice.

In the field of cooling-lubrication and environmental protection, MQL and MQCL (Minimum Quantity Cooling and Lubrication) have been central issues in the last decade, the application of which shows promising results (Gupta et al., 2019; Leppert, 2011; Joshi et al., 2018; Varga and Kundrák, 2013). In addition

to reduce the cost of excipients and the environmental impact, the cutting temperature is lower (Gupta et al., 2020), which makes the chip morphology smoother and more discontinuous, and has a direct effect on reducing surface roughness and tool wear. Also, the range of cutting speeds characteristic of built-up edge formation is shifted, and the tool life is expected to increase (Gupta et al., 2019) as opposed to both dry and conventional cooling and lubrication. When turning an aluminum alloy (Niknam and Jalali, 2020), it was found that the chip thickness was not affected by the CL fluid type and flow rate. The best surface quality improving effect was achieved with a higher viscosity, biodegradable cutting fluid. During hard turning of a hardened steel, the resulted R_a , R_q and cutting temperature decreased by 23-24% compared to dry cutting (Gupta et al., 2020). Zaman et al. studied [9] the MQL method with embedded double jet nozzle in which greater reductions in cutting temperature, roughness (-15%), cutting force, and tool wear (+37% tool life) were measured compared to MQCL method with single nozzle. In the same procedure, Bonfá et al. (Bonfá et al., 2019) found that using the MQL technique, cooling and lubrication significantly reduced tool flank wear, but had a small reducing effect on surface roughness compared to dry machining. Leppert (Leppert, 2011) observed lower values of average roughness R_a in most cases of the settings with MQL and found the largest decrease at lower feed rate and lower cutting speed. Gupta et al. (Gupta et al., 2019) observed that in addition to the different nano-cutting fluids used, the cutting force, tool wear and surface roughness also showed similar characteristics, the examined cutting parameters significantly influenced them. Joshi et al. (Joshi et al., 2018) experienced less flank wear and better surface quality under MQL conditions during turning of Incoloy-800 steel. Varga et al. (Varga and Kunderák, 2013) evaluated the effect of MQL in dry helical turning using 3D roughness parameters. They found that the roughness S_a of dry milled surfaces was larger in all cases, but the effect of changing the feed and cutting speed became smaller.

The MQL technique is also applied and studied using nano-cutting fluids. In doing so, certain liquid properties (thermal conductivity, viscosity, surface tension, contact angle) are changed by dispersing nanoparticles in deionized water (Das et al., 2021). An investigation (Das et al., 2021) reported in hard turning of steel that the effect of different oxide nanoparticles was significant in cutting force (maximum 44% deviation), workpiece residual stress and was minor in flank wear and average roughness. In turning of a nickel-based superalloy, their change showed a similar nature of the output characteristics (force, roughness), though the effect of the changes of the examined cutting parameters was more significant (Gupta et al., 2019).

Another method of reducing the environmental impact is the use of biodegradable cutting fluids of plant origin. The efficiency of their applicability is evaluated according to several aspects (Derani and Ratnam, 2021), these are typically flank wear, cutting force, roughness, temperature, vibration, chip formation, etc. When turning titanium alloy (Gariani et al., 2021), it was found that while the feed and tool type had a strong effect on roughness and flank wear, the cutting fluid concentration had a slight reducing impact, the best results (for roughness and flank wear) were obtained at 5% oil concentration.

Cryogenic machining is one of the emerging manufacturing techniques in the machining industry regarding the use and disposal of chemically contaminated conventional coolants due to new strict environmental regulations (Sivaiah and Chakradhar, 2020). Temperature control during machining makes it possible to comply with the shape, size and design specified for the components (Araújo et al., 2019). In doing so, liquid nitrogen (LN_2) is used for cooling (Bogajo et al., 2020), about which we briefly summarize some research results. Saliminia et al. (Saliminia and Abootorabi, 2019) investigated the effect of this on surface roughness and chip ratio in stainless steel turning. Compared to dry machining, the chip ratio increased by an average of 32% and chip breaking improved during cryogenic machining. Also, the cutting force and tool vibration were reduced, thus reducing the surface roughness (by 13% on average). Kim et al. (Kim et al., 2018) observed that in hard turning, the cryogenic coolant increased the cutting force as well as the segment angle due to the increase in the thermal gradient during chip formation. Flank wear

was observed under both wet and dry conditions, with liquid nitrogen the amount of flank wear was reduced by 12–27%. Araújo et al. (Araújo et al., 2019) presented a steam compression cooling system for cooling cutting fluid. By keeping the temperature of the fluid low, it contributes to increase the life of the fluid while preserving its properties for a longer period. Also, it reduces the growth of fungi and bacteria, thereby lowering the time frequency of fluid replacement, which is beneficial for the environment. The values of the average roughness were very close to each other, in the cooled and non-cooled cases, the tendency of the lower average roughness was observed with CL fluid having low temperature. In addition, an advantage of the system is its acquisition cost; it is 1.5% of the cost of a high-pressure jet engine system, 3% of the cost of a cryogenic cooling system, and 30-60% of a compressed air-cooled vortex.

There are research works in other fields related to environmentally friendly machining as well. One example for that is a study (Gajrani et al., 2018) in which a special cutting equipment was presented which contained molybdenum-disulfide (MoS_2) solid lubricant in a mechanically developed texture to form a self-lubricating tool, thus the traditional CL fluid was omitted, much less lubricant was used, and lubrication was also much more effective in terms of tool wear, cutting force and surface roughness.

Surface quality is an important property of the surfaces of a component in terms of operation, fit, surface treatment, appearance, etc. so that a machining process can be well characterized by it, because of the machining. This includes surface roughness and shape errors and among them, cylindricity deviations. Therefore, not only the effect of cutting data (Kundrak and Felho, 2016; Felho and Kundrak, 2012; Masoudi et al., 2019) but the effect of cooling-lubrication (Masoudi et al., 2019) can be evaluated on such bases as well.

In this paper, the effect of cooling and lubrication is investigated on 2D profile and 3D roughness parameters and cylindrical characteristics on turned surfaces. Experiments were performed with different feed rates and cutting speed values and the measurement results were used in a full factorial experimental design. The study is conducted by comparing the results thus obtained. The aim is to determine what roughness and cylindricity can be achieved in the case of dry, environmentally friendly machining in addition to the examined technological parameters. This study can be useful in the field of turning experimental examination on AISI 1040 grade steel workpiece cut with a coated carbide tool and cooled-lubricated with a 4% emulsion.

2. Experimental conditions

The conditions of the experiments performed for the study and the equipment used are listed in Table 1. The set cutting data and fluid consumption are summarized in Table 2.

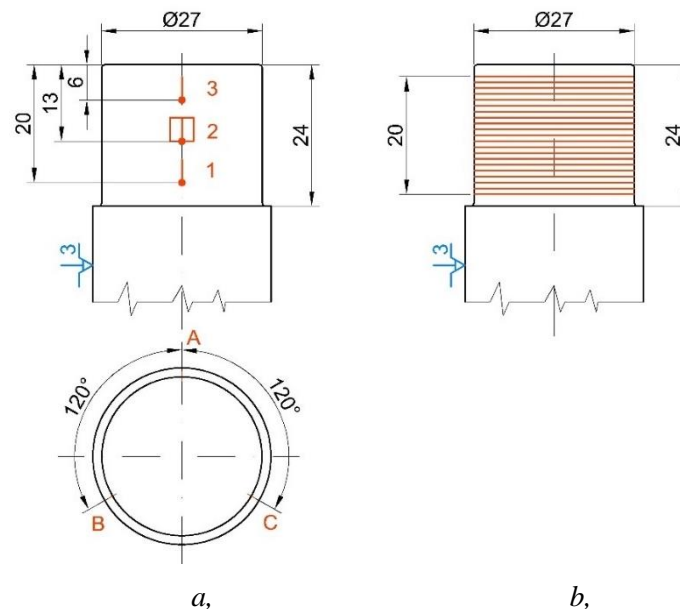
Table 1. Experimental conditions

Machine tool:	E400 universal lathe
Cutting tool:	Korloy DCMT 11T304-MP, grade: NC3225, $\alpha_o=7^\circ$, $r_\epsilon=0.4\text{mm}$
Toolholder:	Korloy SDACR1616-H11
Fixture:	Three-jaw self-centering chuck
Workpiece:	AISI 1040 unalloyed carbon steel, tensile strength: 770 MPa, yield strength: 430 MPa, elongation: 25%, cut dimensions: $\varnothing 27 \times 24\text{mm}$
Coolant-lubricant fluid:	4% emulsion of Rhenus FU71 T, flow rate: $V_p=150\text{ ml/min}$, oil viscosity: 160 mm^2/s

Table 2. Technological parameters and volumes of CL fluid

No.	f [mm/rev]	n [1/min]	v_c [m/min]	V_p [ml/min]	a_p [mm]
1	0.1	750	63.62	0	0.5
2	0.3				
3	0.1	1060	89.91		
4	0.3				
5	0.1	750	63.62	150	
6	0.3				
7	0.1	1060	89.91		
8	0.3				

After executing the experiments, the roughness measurement was performed on an AltiSurf 520 three-dimensional roughness measuring device with a CL2 confocal chromatic sensor having a vertical resolution of $0.012 \mu\text{m}$. On that device, 2D profile and 3D areal roughness measurements were executed for this study. The profile roughness is well-known, instantly comparable to other previous or newer measurements, based on records in many literatures. However, 3D surface roughness measurements have so far been analyzed by fewer authors. Its novelty lies in the fact that the more extensive surface that is examined gives more specific, more authentic information about the given surface. The 2D and 3D measurement locations on the surfaces are shown in Figure 1a, where the specimens were rotated by 120° (A-C) in the same positions (1-3), and then the results were averaged. The measured profiles were 4 mm long and were recorded in the same way regardless of the variable feeds, deviating from the standard, as this way the results can be authentically compared. The 3D areas covered $4 \times 4 \text{ mm}^2$ on the workpieces. In each case, a Gaussian filter with a wavelength of $\lambda_c = 0.8 \text{ mm}$ was used for the evaluation after subtracting the nominal shape.

**Figure 1.** Measurement plan: surface roughness (a), cylindricity (b)

Cylindricity was measured on a Taylor Hobson TalyRond 365 roundness-cylindricity measuring device with a 1 mm diameter ruby stylus. On the cylindrical surface 21 sections form the measured profile at a height of 20 mm. A measurement drawing of this is shown in Figure 1b. Here, Gaussian filtering was used too.

3. Results and Discussion

The surface roughness is evaluated based on the parameters defined in ISO 4287:2002 and ISO 25178:2012, those of which show some unique characteristics during the evaluation. These are the material ratio (R_{mr} and S_{mr}), the reduced valley depth (R_{vk} and S_{vk}), and the skewness (R_{sk} and S_{sk}) and Kurtosis (R_{ku} and S_{ku}) indices.

The first two represent complex tribological features (friction, wear, lubrication etc.), the valley depth can be used to determine the ability of the surface to retain lubricant (Sedlaček et al., 2012). Beside them, the commonly prescribed (Todhunter et al., 2017) average roughness parameters are also analyzed: R_a and S_a . To determine the material ratio values, $c = 3 \mu\text{m}$ height was set from the highest peak of the profile or topography. The definitions of these parameters are described in Table 3 (MSZ EN ISO 4287:2002; ISO 25178-2:2012). The results are summarized in Table 4.

In the case of cylindricity, the evaluation is performed based on three indices specified in ISO 12180-1:2011: the highest peak height CYL_p , the lowest valley depth CYL_v and the total height CYL_t . All the results are shown in Table 4.

Table 3. Definitions of roughness parameters (MSZ EN ISO 4287:2002; ISO 25178-2:2012)

Parameter	Profile (2D)	Areal (3D)
Average (a)	$R_a = \frac{1}{l} \int_l z(x) dx$	$S_a = \frac{1}{A} \iint_A z(x, y) dx dy$
Skewness (sk)	$R_{sk} = \frac{1}{R_q^3} \left[\frac{1}{l} \int_l z^3(x) dx \right]$	$S_{sk} = \frac{1}{S_q^3} \left[\frac{1}{A} \iint_A z^3(x, y) dx dy \right]$
Kurtosis (ku)	$R_{ku} = \frac{1}{R_q^4} \left[\frac{1}{l} \int_l z^4(x) dx \right]$	$S_{sk} = \frac{1}{S_q^4} \left[\frac{1}{A} \iint_A z^4(x, y) dx dy \right]$
Material ratio (mr)	Ratio of the area of the material at a specified height c to the evaluation area	
Red. Valley depth (vk)	Average height of the protruding dales below the core surface	

Table 4. Values of roughness and cylindricity parameters

No.	R_a [μm]	R_{mr} [%]	R_{vk} [μm]	S_a [μm]	S_{mr} [%]	S_{vk} [μm]	CYL_p [μm]	CYL_v [μm]	CYL_t [μm]
1	1.10	21.81	0.65	1.11	1.32	0.74	16.36	14.50	30.86
2	6.75	2.61	0.20	6.67	0.15	0.62	33.18	16.44	49.62
3	1.13	17.73	0.69	1.13	7.97	0.66	21.46	14.44	35.90
4	6.63	2.23	0.28	6.41	0.20	0.65	18.33	16.93	35.27
5	1.32	17.61	0.81	1.33	1.18	0.77	21.61	14.34	35.95
6	6.57	2.12	0.17	6.16	0.19	0.36	21.50	18.60	40.10
7	1.46	18.16	0.76	1.45	3.93	0.84	17.41	13.63	31.04
8	6.51	2.23	0.37	6.26	0.14	0.69	20.83	15.72	36.55

A full factorial experimental design was used to evaluate the results and to estimate them for various cutting settings. Empirical formulas (1-9) were determined using the MathCAD software, the calculation results of which are illustrated in axonometric diagrams (Figures 2, 3, 5, and 7).

$$R_a = -1.9795 + 30.029 \cdot f + 0.00379 \cdot v_c + 7.63 \cdot 10^{-4} \cdot V_p - 0.027 \cdot f \cdot v_c - 0.01 \cdot f \cdot V_p + 3.12 \cdot 10^{-5} \cdot v_c \cdot V_p - 5.02 \cdot 10^{-5} \cdot f \cdot v_c \cdot V_p \quad (1)$$

$$S_a = -2.07 + 31.214 \cdot f + 0.00604 \cdot v_c + 0.00446 \cdot V_p - 0.052 \cdot f \cdot v_c - 0.045 \cdot f \cdot V_p - 7.951 \cdot 10^{-6} \cdot v_c \cdot V_p + 3.193 \cdot 10^{-4} \cdot f \cdot v_c \cdot V_p \quad (2)$$

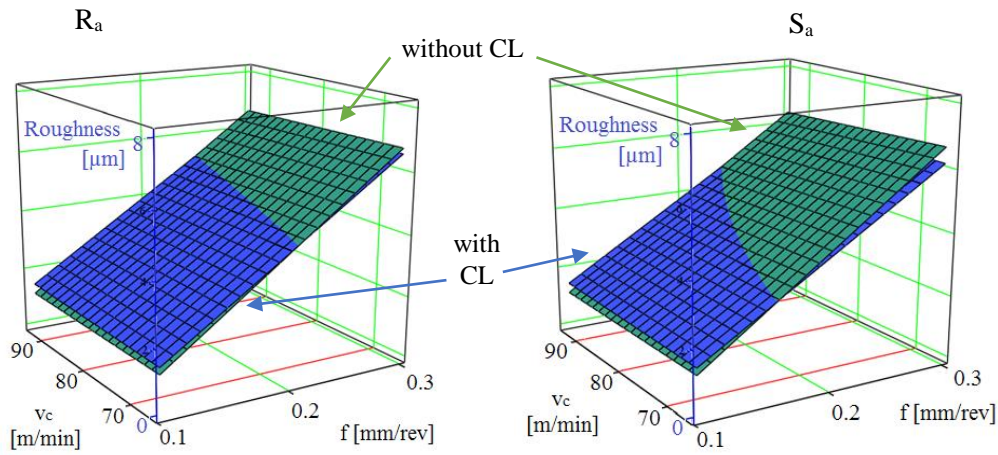


Figure 2. Changes in the values of R_a and S_a

$$R_{mr} = 45.7594 - 140.805 \cdot f - 0.218 \cdot v_c - 0.149 \cdot V_p + 0.68 \cdot f \cdot v_c + 0.458 \cdot f \cdot V_p + 0.00164 \cdot v_c \cdot V_p - 0.00507 \cdot f \cdot v_c \cdot V_p \quad (3)$$

$$S_{mr} = -22.1763 + 74.031 \cdot f + 0.365 \cdot v_c + 0.092 \cdot V_p - 1.211 \cdot f \cdot v_c - 0.301 \cdot f \cdot V_p - 0.00142 \cdot v_c \cdot V_p + 0.00466 \cdot f \cdot v_c \cdot V_p \quad (4)$$

Using the values in Table 3, the Equations (1-6) and Figures 2, 3, 5 may help analyze the effect of cooling and lubrication on the surface roughness. The values of the average roughness parameters are almost identical in pairs (Figure 2). Here it can be found that by reducing the feed, better surface roughness was obtained with dry machining, at higher feed rates the values increase towards the values of wet cutting. The cutting speed shows the exact opposite, where the increase of it leads to a decrease in R_a and S_a values on both cooling conditions. Although the average roughness of the dry turned surface have higher average values with the increase of productivity (f , n or v_c), the difference in terms of environmental load and cost reduction is negligible.

The material ratio values (Figure 3) are favorable for low feed rate, between 17.5-22% for R_{mr} and 1.1-8% for S_{mr} can be expected. On the other hand, an opposite characteristic is found among the 2D and 3D measurement results, based on the cutting speed, so this parameter shows significant differences, an exceptional case. The reduction of the speed for the case of profile examination, and the increase for the case of areal measurement results a higher material ratio. Further investigations are needed to explain this contradiction.

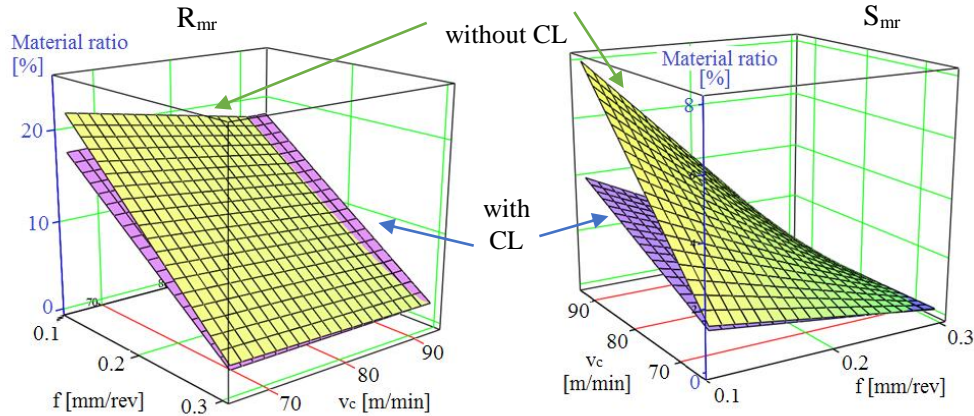


Figure 3. Changes in the values of R_{mr} and S_{mr}

For 2D measurement, the material ratio values (Figure 3) increase with decreasing feed and cutting speed in both cases, where the increase in dry machining is greater. Accordingly, the largest difference is at the minimum feed rate and speed set which is $\Delta R_{mr}=4.2\%$. In the examined range, the material ratio of dry machined workpieces in most cases exceeds the wet machining values, which means that at lower feed rates and cutting speeds, dry turned surfaces can be expected to have better wear resistance and dimensional stability. The values of the 3D parameter show a different character from the previous ones, where an increase in the material ratio can be achieved in the same way by reducing the feed rate, but also with the increase of the cutting speed. This difference and the significant deviations between the results measured on the individual test pieces between the R_{mr} and S_{mr} value pairs are yet unknown, thus further investigations are needed to find out the cause.

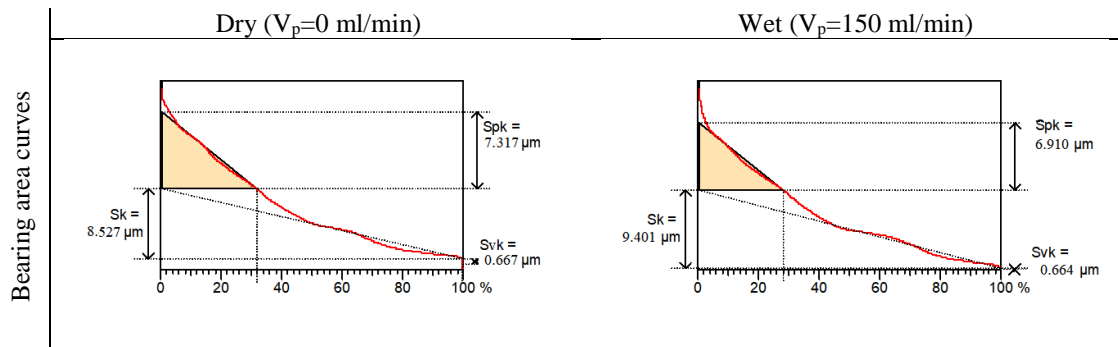


Figure 4. 3D functional parameters on Abbott-Firestone curves

Figure 4 shows the Abbott-Firestone curves where the average values of the functional areal parameters (S_{pk} , S_k , S_{vk}) between dry and wet machining can be observed. The curves are different from the ideal, so further studies may be needed. This also supports the general theory that during dry machining, the quickly wear surface layer height (S_{pk}) become larger and the core height (S_k) is smaller which is characteristic to the lifetime of the part. The differences are slightly significant: $\Delta S_{pk} = 0.407\ \mu\text{m}$ and $\Delta S_k = -0.874\ \mu\text{m}$, respectively. Both are disadvantageous in point of view of functionality and lifetime. Also, the S_{vk} parameter remained on low value regardless of the cooling, which means that turned surfaces do not have good ability for retaining lubricant.

$$R_{vk} = 0.7906 - 2.559 \cdot f + 0.00117 \cdot v_c + 0.00506 \cdot V_p + 0.00514 \cdot f \cdot v_c - 0.025 \cdot f \cdot V_p - 5.052 \cdot 10^{-5} \cdot v_c \cdot V_p + 2.752 \cdot 10^{-4} \cdot f \cdot v_c \cdot V_p \quad (5)$$

$$S_{vk} = 1.1387 - 1.973 \cdot f - 0.00505 \cdot v_c - 3.947 \cdot 10^{-4} \cdot V_p + 0.02 \cdot f \cdot v_c - 0.02 \cdot f \cdot V_p + 2.226 \cdot 10^{-5} \cdot v_c \cdot V_p + 1.639 \cdot 10^{-4} \cdot f \cdot v_c \cdot V_p \quad (6)$$

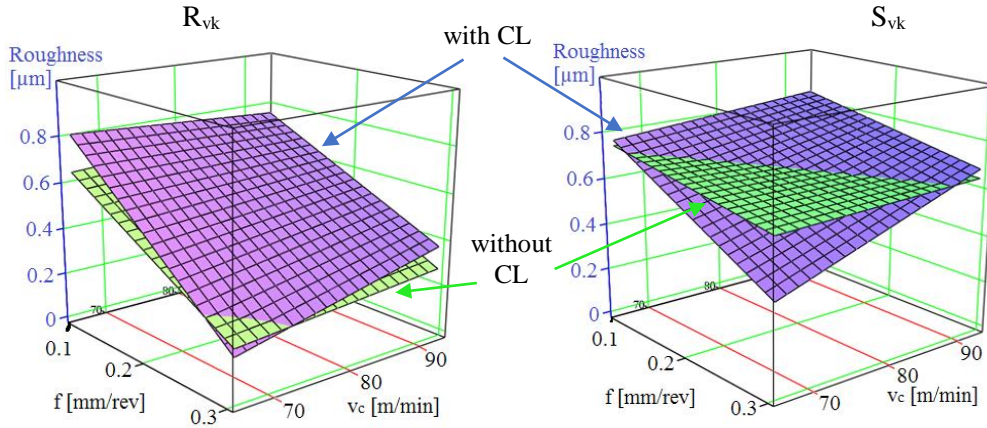


Figure 5. Changes in the values of R_{vk} and S_{vk}

The values of the reduced valley depth parameter (Figure 5) show maximum differences of $\Delta R_{vk}^{\max} = 0.64 \mu\text{m}$ and $\Delta S_{vk}^{\max} = 0.48 \mu\text{m}$. An increase can be observed with decreasing feed and increasing cutting speed, however, in the case of dry machined surfaces this change is smaller (the extent of difference for dry machining is 72% for R_{vk} and 51% for S_{vk} , compared to wet cases) in the examined range. A higher measured value indicates better lubricant retention, so in this respect in dry machining we recommend the use of lower feed and cutting speed values, though the 2D and 3D values remain lower at these settings, but the differences are very little: $\Delta R_{vk} = 0.16 \mu\text{m}$ and $\Delta S_{vk} = 0.03 \mu\text{m}$.

For all examined parameters, the effect of feed is dominant, followed by the cutting speed and then the cooling-lubrication. The combined effect of the setting data depends on the characteristics of the former ones, so that the feed and the cutting speed together are relatively decisive, the others are smaller and mostly negligible. So, it means that cooling-lubrication, at the amount used in the present study, has little effect on the reduced valley parameters. Although the omission of the fluid leads to a deterioration of roughness, its magnitude is not significant, in the examined range.

The skewness and kurtosis of the profile curves and topographies were also evaluated during the roughness measurement. The values obtained are summarized in Table 5, organized according to the measured specimen and the measurement location (Figure 1a). The values of these parameters are distributed between 0.33-0.83 and 2.36-2.95, for skewness and kurtosis, respectively. Increasing the feed also increases the skewness and reduces the kurtosis, the cutting speed basically does not / only slightly change both. The effect of cooling and lubrication is not noticeable.

A positive value of skewness means from a tribological point of view (Whitehouse, 2002) that there is a relatively larger part of the material below the center line, i.e., at the bottom of the profile, and there are narrow peaks between them. From the aspect of wear, the latter are the initially load-bearing and wear layer, so the turned surface cannot be characterized by good wear resistance and dimensional

stability. This is consistent with the reduced peak height (R_{pk} , S_{pk}) parameters' values and their associated findings.

Table 5. Skewness-kurtosis values of profile and areal roughness

No.	Place	2D		3D		No.	Place	2D		3D	
		R_{sk} [-]	R_{ku} [-]	S_{sk} [-]	S_{ku} [-]			R_{sk} [-]	R_{ku} [-]	S_{sk} [-]	S_{ku} [-]
1	A	0.48	2.56	0.46	2.71	5	A	0.35	2.52	0.33	2.59
	B	0.39	2.57	0.35	2.81		B	0.43	2.44	0.50	2.53
	C	0.56	2.84	0.47	2.77		C	0.47	2.59	0.54	2.76
2	A	0.73	2.36	0.77	2.48	6	A	0.78	2.55	0.83	2.73
	B	0.71	2.36	0.76	2.44		B	0.75	2.45	0.77	2.58
	C	0.77	2.50	0.78	2.48		C	0.77	2.53	0.81	2.63
3	A	0.66	2.95	0.57	2.71	7	A	0.40	2.44	0.38	2.50
	B	0.55	2.74	0.50	2.70		B	0.48	2.46	0.50	2.55
	C	0.55	2.73	0.50	2.70		C	0.34	2.37	0.33	2.45
4	A	0.76	2.52	0.75	2.51	8	A	0.74	2.49	0.77	2.56
	B	0.76	2.50	0.83	2.70		B	0.78	2.56	0.76	2.60
	C	0.75	2.47	0.81	2.62		C	0.78	2.58	0.80	2.69

Kurtosis is scattered between the values indicated above, which are values below 3, but not far from it. That is, the profiles and topographies are slightly rounder than the normally distributed Gaussian surfaces. Turning, on the other hand, is characterized by rounded valleys (cut by the edge radius) with pointed peaks. The values also reflect this, so these experimental surfaces are not wear-resistant and are only slightly able to keep the lubrication condition. The same were found based on the values of the functional parameters measured from the Abbott-Firestone curves (Figure 4).

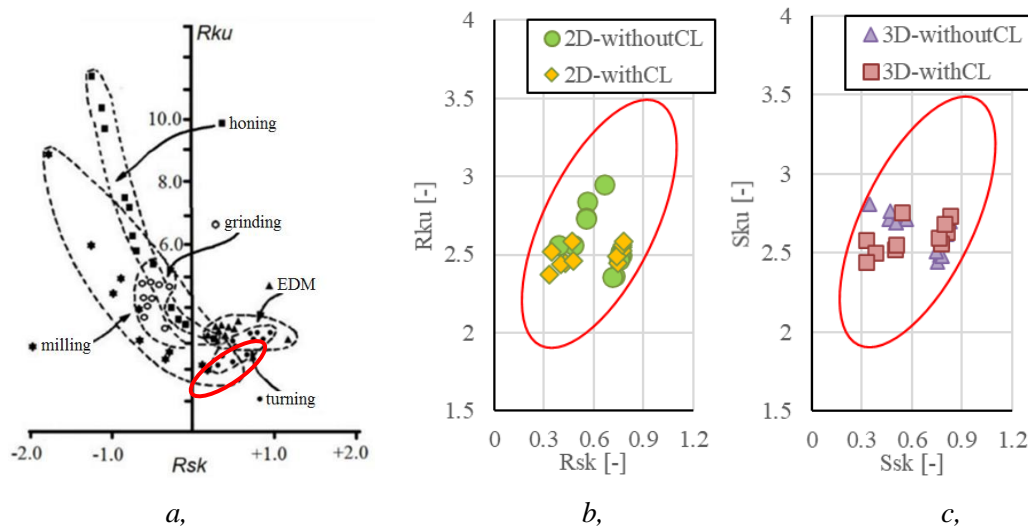


Figure 6. Tribological topographic map based on literature (Whitehouse, 1994) (a) and on experimental results (b, c)

The skewness-kurtosis value pairs in Table 5 are plotted separately for 2D (Figure 6b) and 3D (Figure 6c) parameters and the results are evaluated and compared with data from a tribological topographic

map (Figure 6a) taken from the literature (Whitehouse, 1994). All diagrams show the range of value pairs characteristic to the turned surface, marked with a red ellipse. It can be clearly seen that each value pair is in the marked range, in this respect the surfaces of the test pieces are regular, showing the expected results. This also means that the 2D and 3D parameter pairs have very similar characteristics. The set of points is concentrated within two smaller areas within the turning zone, which are independent of the method of measurement and the application of cooling-lubrication.

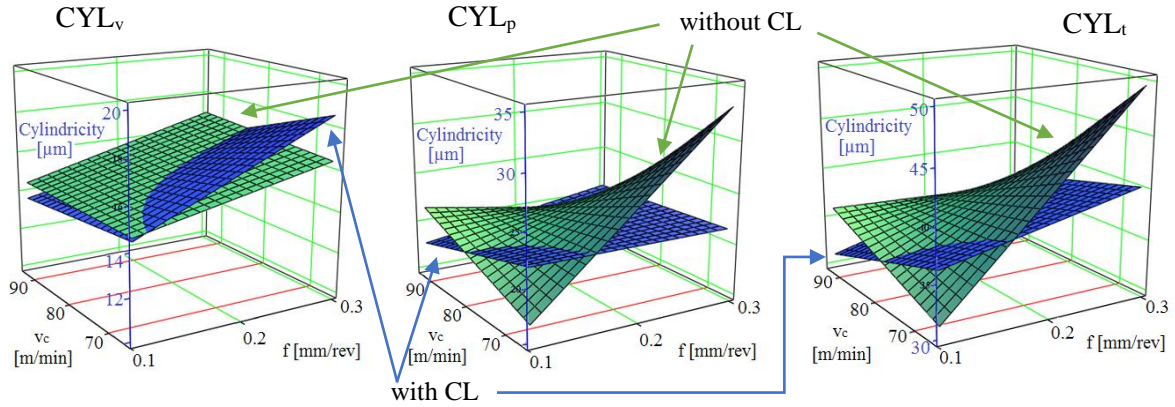


Figure 7. Changes in the values of cylindricity parameters (CYL_v , CYL_p , CYL_t)

$$CYL_v = 14.3406 + 3.046 \cdot f - 0.012 \cdot v_c - 0.02 \cdot V_p + 0.101 \cdot f \cdot v_c + 0.297 \cdot f \cdot V_p + 1.737 \cdot 10^{-4} \cdot v_c \cdot V_p - 0.00333 \cdot f \cdot v_c \cdot V_p \quad (7)$$

$$CYL_p = -28.5287 + 325.477 \cdot f + 0.553 \cdot v_c + 0.424 \cdot V_p - 3.661 \cdot f \cdot v_c - 2.434 \cdot f \cdot V_p - 0.00504 \cdot v_c \cdot V_p + 0.028 \cdot f \cdot v_c \cdot V_p \quad (8)$$

$$CYL_t = -14.176 + 328.401 \cdot f + 0.541 \cdot v_c + 0.411 \cdot V_p - 3.558 \cdot f \cdot v_c - 2.161 \cdot f \cdot V_p - 0.00497 \cdot v_c \cdot V_p + 0.025 \cdot f \cdot v_c \cdot V_p \quad (9)$$

Based on the values in Table 3, Equations (7-9) and the diagrams (Figure 7) are used to examine the cylindricity parameters. For all three indices, it can be found that the shape error is smaller at the maximum cutting speed and minimum feed rate with wet machining, in the test range. The CYL_v values increase with the increase of feed and the decrease of cutting speed. The degree of change is small in dry machining (max. 17%) and much more significant in wet machining (max. 36%). For this reason, the rate of profile valley error (CYL_v) is smaller in the environmentally friendly case when working with a lower cutting speed.

Basically, the CYL_v values do not show large differences between dry and wet conditions, the maximum deviation is $\Delta CYL_v = 2.16 \mu\text{m}$ (at max. feed and min. speed), so the characteristics of the maximum peak height CYL_p mainly determine the total height difference CYL_t . Thus, for these parameters, it can be said that increasing the feed increases them in most cases, except at the maximum speed it does not change them substantially. Increasing the cutting speed decreases them in the case of wet machining and increases them on dry turned surfaces, except for a greater decrease at the maximum feed compared to the wet case. Considering these, a smaller cylindricity error is expected at lower feed rates and lower speeds when turning steel, here the largest deviation is $\Delta CYL_t = 5.1 \mu\text{m}$, in the examined range.

4. Summary

In this paper, as the environmentally friendly machining is very important nowadays, non-alloy steel workpieces were turned on which the consequences of the abandonment of cooling and lubrication were investigated on surface roughness and cylindricity by setting different feed and cutting speeds. The experimental results were processed by a full factorial experimental design, based on which the evaluation was performed. The following statements were made:

- Feed rate had the greatest effect on average roughness, followed by the cutting speed and after them the volume of coolants and lubricants, which was negligible (max. deviation: 0.51 μm). In most cases the higher cutting speed resulted lower roughness on dry turned pieces. Thus, we recommend the use of higher cutting speeds and relatively lower feed rates.
- In terms of wear resistance and dimensional stability, the material ratio parameters showed a favorable case for dry machining with a lower feed value.
- The values of the reduced valley depth parameters were basically low, their increase can be achieved with decreasing values of the feed and cutting speed, where the lubricant retention ability is better. In overall, in dry machining, at the investigated conditions the best values ($R_{vk} = 0.65 \mu\text{m}$, $S_{vk} = 0.74 \mu\text{m}$) can be achieved with low feed rate ($f_{z1} = 0.1 \text{ mm/rev}$) and cutting speed ($v_{c1} = 70 \text{ m/min}$).
- Roughness skewness-kurtosis value pairs are in the range indicated in the tribological topographic map based on the literature (Whitehouse, 1994). Kurtosis values are scattered in a narrower range and the skewness values in a wider range. Kurtosis is scattered between the values indicated above, which are values below 3, but not far from it. That is, the profiles and topographies are slightly rounder than the normally distributed Gaussian surfaces.

Based on the analysis in this paper it is possible to analyze in the future on other materials, having different toughness and strengths, used in industry and with applying different coolants-lubricants.

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