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INVESTIGATION OF SURFACE ROUGHNESS GENERATED BY END MILLING OF TOOLOX 44®

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Abstract. *Toolox 44® is a highly engineered quench and tempered pre-hardened tool steel that presents high toughness, high yield strength at elevated temperature, and very low residual stress when compared to other similar tool steels. Due to its characteristics, this material is suitable for situations where high hardness, high impact resistance, and excellent dimensional stability are essential such as die-casting, bending, and sheet forming tools. Despite its good mechanical properties, it is reported to present good machinability. In this work, the machined surface finish is evaluated after dry and flood lubrication-assisted end milling of Toolox 44® with different cutting conditions. An experimental approach was carried out using 3-factor Box-Behnken design of experiments (BBD) to evaluate the influence of each controllable factor (cutting speed, axial depth of cut, feed per tooth) and its combinations on the surface finish, here evaluated through the arithmetic mean deviation (R_a) and the mean value of maximum heights (R_z) for both lubricooling conditions. ANOVA and BBD showed that linear and quadratic effect of a_p and linear effect of f_z presented significant influence over R_a and R_z for dry cutting. For the flood lubrication-assisted cutting, the significant factors are a_p and the interactions $v_c \times a_p$ and $a_p \times f_z$. Multivariate regression analysis indicates that, for the studied domain, the best surface finish in dry cutting is obtained with v_c = 76.6 m/min, f_z = 0.05 mm/tooth, and a_p = 0.56 mm. On the other hand, the best results are reached for flood lubrication-assisted cutting with v_c = 60 m/min, f_z = 0.05 mm/tooth, and a_p = 0.4 mm. The results indicate that, despite resulting in a more pronounced waviness on the machined surface, dry cutting allows smaller surface roughness in the end milling of Toolox44®.*

Keywords: *Toolox 44®, Box Behnken Design, end milling, surface roughness.*

1 INTRODUCTION

The constant scientific and technological advances frequently present engineering practitioners with new technical challenges. To meet those increasingly complex and specific needs, it is often necessary to develop new materials and alloys. Thus, steels with different compositions and properties, such as AHSS (Advanced High Strength Steels), are constantly evolving to ensure high performance in service. The Toolox 44® is an AHSS produced by SSAB and consists of pre-hardened tool steel with high cleanliness. This material also presents a high resistance to cracks and extended fatigue life, high tenacity, and high mechanical resistance at elevated temperatures (SSAB, 2021).

According to Hansson (2009), Toolox 44® is delivered as quenched and tempered to 450 HBW, thus dispensing further heat treatments as reformation or cementation. This material has good dimensional stability, is weldable, and suitable for chemical engraving and polishing processes. It may also be subjected to nitriding processes and receive PVD coating (Lugand, 2021), provided that temperatures never surpass 590°C. Toolox 44® is used to manufacture plastic injection molds, forging dies, pressure casting, and plate forming tools. However, it is also suitable for machine components, wear-related parts, rail guides, and applications at high temperatures. According to the manufacturer, this steel has good machinability and high impact resistance. Due to low internal stress levels, large sections can be machined with no need to stress relief procedures (SSAB, 2021). However, the cutting parameters should be reduced due to the dynamic instability during the machining of Toolox 44® caused by its high hardness (SSAB, 2014). Thus, in order to obtain a good compromise between cost, productivity, and quality, it is essential to develop efficient machining strategies, which requires effective control of the machining process by acting directly on the input variables (independent) and measuring their effect on the output variables (dependent) (Kalpakjian and Schmid, 2010).

Some input variables (controllable factors) in end milling are the part material, tool geometry, the machine tool characteristics, the cutting parameters – cutting speed (v_c), axial depth of cut (a_p), and feed per tooth (f_z) – and the lubricooling condition. Both cutting parameters and the lubricooling condition may be easily varied and influence output variables such as chip formation, tool wear, force components, and the surface finish.

The surface finish is a characteristic usually specified in machined parts. According to Astakhov (2011), besides an important design requirement, surface finishing can be considered an indicator of machining quality, and the numerical evaluation of the surface roughness is a way to quantify it. According to Garcia *et al*. (2019), the roughness parameters R_a (arithmetic mean deviation) and R_z (mean value of maximum heights) are, in many cases, valid criteria for determining the quality of the machined surface. Policena *et al*. (2018) explain that due to the limitations of the R_a in representing the roughness profile in which different surface profiles may present the same roughness values, with R_z being beneficial to determine whether the results mask irregularities of the analyzed profiles. According to Benardos and Vosniakos (2003), different deviations of order overlap and form the roughness profile of the machined surface. The waviness corresponds to the deviations of the nominal surface of first- and second-order (greater amplitude), while roughness (lower amplitude) is associated with third- and fourth-order deviations. R_z considers the average distribution of vertical surfaces, and it is more sensitive to variations than R_a because only the maximum heights of the profiles, not their means, are compared and analyzed. Consequently, R_z can be used to detect this waviness (Klocke, 2011).

This work evaluates each machining parameter's influence, and their combination affects the surface roughness in the end milling of Toolox 44®. The effect of the lubricooling condition is also evaluated for dry and flood lubrication-assisted cutting.

2 MATERIALS AND METHODS

Table 1 presents the chemical composition of the Toolox 44® steel samples used in this work according to the inspection certificate provided by the manufacturer.

Table 1. Chemical composition of Toolox 44® (%wt.)

C	Cr	Mo	Mn	**Si**	**V**	**Ni**	P	S
0.32	1.35	0.80	0.80	0.60-1.10	0.14	< 1.00	< 0.01	< 0.002

The tests were performed in a 53 x 195 x 115 mm workpiece fixed on the machine table by four Allen screws. Before the machining of each run, the cutter was always positioned at a distance of 3 mm from the workpiece. Thus, 15 runs were performed on each face, all with a length of 34 mm. Each run comprised a specific combination of cutting parameters. The measurement of the surface roughness was performed, in each sample, in a 14 x 20 mm stable region that discarded both the beginning (tool entrance) and the end of the run. Figure 1 illustrates one of the faces of the Toolox 44® workpiece used in this study and depicts both the execution planning and the stable regions for the evaluation of the surface roughness.

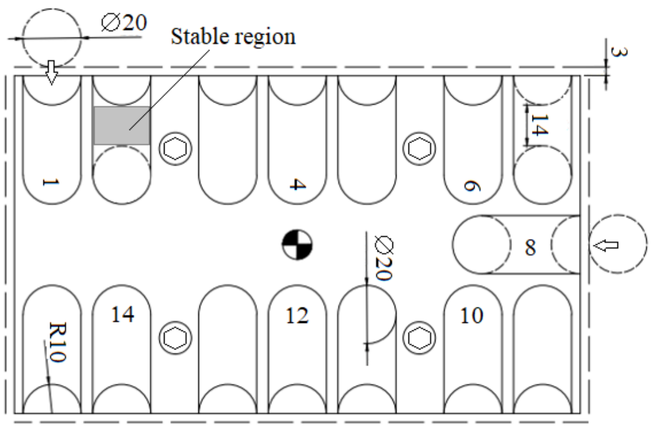


Figure 1. Process planning for end milling of Toolox 44®

End milling tests were performed with Walter Tools ADMT10T308R-F56 WKK25S PVD/TiAlN+Al_2O_3 coated carbide inserts. The carbide inserts have a tool radius of 0.8 mm, rake angle of 15°, and 15° clearance angles (both primary and secondary), and where used with a Walter Tools Xtra-tec F4042R. W20.02 milling head (D=20 mm, K_r = 90°). Since negligible tool wear was expected, one set of cutting edges was used for each lubrication condition. The tool condition was monitored after each run with a Dino-Lite AM-413ZT USB digital microscope. The negligible tool wear expected, confirmed by the tool monitoring, was also described by Chandrasekaran *et al*. (2006), who concluded that the lower carbide content in pre-hardened tool steels reduces abrasive wear. Similar conclusions were reached by Binali *et al*. (2018) in the machining of Toolox 44.

The experiments were performed with a ROMI Discovery 308 machining center, with a maximum spindle speed of 4000 rpm and a power output of 5.5 kW. During the tool's assembly, the run-out was verified with a Digimess dial gauge with a 0.01 mm resolution.

Dry cutting and flood-lubricated cutting were performed in opposite faces of the workpiece. The cutting fluid used was the fluid B90 oil-free bio-lubricant supplied by Bondmann Química.

The surface roughness of the machined samples were analyzed using a Mitutoyo SJ-201P rugosimeter with a 5 µm probe tip and a resolution of 0.01 µm. The assessment of the surface roughness followed the procedures and parameters defined by EN ISO 4288, including an evaluation length of 4 mm split into five sampling lengths (cut-offs) of 0.8 mm. The roughness measurement procedure is illustrated in Figure 2. A 2CR75 filter was used by the rugosimeter.

Figure 2. Surface roughness measurement performed on the workpiece

The experiments were performed according to the Box-Behnken Design (BBD). BBD is a statistical optimization technique based on the Response Surface Methodology (RSM) that seeks to determine the best levels within a set of controllable factors (e.g., cutting parameters), including the interactions between them, which exert a certain degree of influence on the response variables of a process (e.g., R_a and R_z roughness values). Its application in machining processes is well documented (Garcia *et al*., 2019; Niharika *et al*., 2016, Policena *et al*., 2018). One advantage over complete factorial design projects of 3-factor 3-level is the possibility of performing a smaller experiment, going from 27 to only 15 runs for a 3-factor analysis. In addition, the factors are never simultaneously at their high and low levels, thus avoiding experiments under extreme conditions. The BBD supports the numerical calculation of the importance attributed to each of the parameters and the importance of the effects of the interactions between them and determines the point where the most satisfactory response possible is reached (Ferreira *et al*., 2007).

The values of cutting speed (v_c) and feed per tooth (f_z) were defined based on the machining window recommended by Toolox 44® manufacturer (SSAB, 2014). The lowest values for both parameters were chosen slightly below the minimum, the highest slightly above the maximum, and the average values within the recommended range. The three levels of the axial depth of cut used were based on the tool nose radius (50, 100, and 150% of r_ε). The combinations between the input parameters (v_c, a_p, f_z) were randomly varied considering three significance levels (low, medium, high). Table 2 presents the values chosen for the input parameters at each significance level.

Table 2. Controllable factors and significance levels of BBD

Controllable Factors	Significance Levels		
	Low	Medium	High
v_c [m/min]	60	80	100
a_p [mm]	0.4	0.8	1.2
fz [mm/tooth]	0.05	0.075	0.1

The execution order of the experiments was fully randomized using Minitab® 19. Two sets of 15 runs were performed, one for dry cutting and the other for flood lubricated cutting. Each set included the combinations of the cutting parameters needed to perform the analysis of variance (ANOVA).

3 RESULTS AND DISCUSSIONS

Table 3 presents the average values of R_a and R_z roughness obtained after end milling of Toolox 44® with dry and flood lubricated cutting for each combination of cutting parameters. The run order corresponds to the execution order, determined through full randomization. Figure 3 presents the measured R_a values for both dry and flood milling of Toolox 44®. Since the tests a followed a Box-Behnken doe the results are presented according to the execution order, thus allowing the easy identification of conditions where the lubrication techniques used were more influent. The R_z values are plotted in Figure 4.

Table 3. Surface roughness results for the end milling of Toolox 44® in all tested conditions

Runs	Cutting parameter			Surface roughness			
				Dry		Flood	
	v_c (m/min)	a_p (mm)	f_z (mm/tooth)	*Ra* (µm)	*Rz* (µm)	*Ra* (µm)	*Rz* (µm)
1	80	0.4	0.1	0.237	1.547	0.387	2.603
2*	80	0.8	0.075	0.277	1.793	0.360	2.140
3	60	0.8	0.1	0.300	2.123	0.360	2.350
4*	80	0.8	0.075	0.200	1.473	0.343	2.490
5	60	1.2	0.075	0.640	3.827	0.677	4.337
6	100	0.8	0.1	0.317	1.883	0.343	2.077
7	80	1.2	0.05	0.420	2.663	0.663	3.937
8	100	0.4	0.075	0.240	1.457	0.217	1.423
9	100	0.8	0.05	0.193	1.210	0.240	1.627
10	60	0.4	0.075	0.233	1.463	0.213	1.617
11*	80	0.8	0.075	0.183	1.290	0.283	1.767
12	60	0.8	0.05	0.163	1.113	0.317	1.897
13	100	1.2	0.075	0.583	3.517	0.307	2.017
14	**80**	**0.4**	**0.05**	**0.137**	**0.853**	**0.177**	**1.237**
15	80	1.2	0.1	0.580	3.673	0.340	2.087

* Three runs at the medium significance level of the controllable input factors

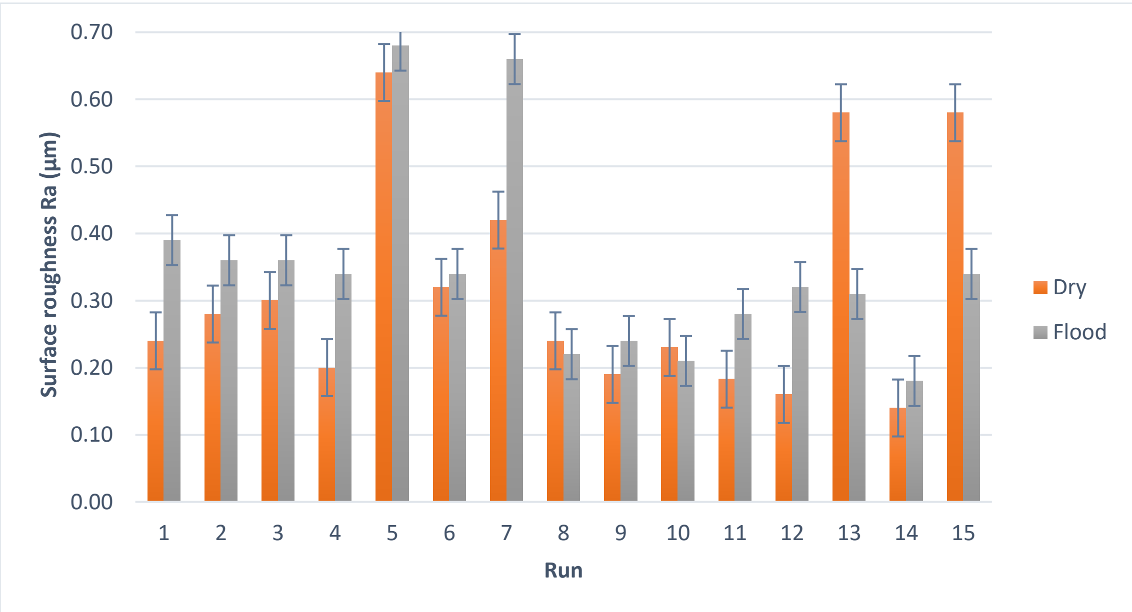


Figure 3. R_a values for dry and flood-lubricated milling of Toolox 44®

The results of tests performed with dry and flood lubricated cutting presented strong discrepancies. When $a_p \leq 0.8$ mm, smaller values were mainly obtained with dry cutting for both roughness parameters considered. However, smaller values were obtained with flood lubrication for most runs with $f_z \geq 0.075$ mm/tooth for the highest axial depth of cut tested (a_p = 1.2 mm).

The highest *Ra* and *Rz* roughness values for both dry machining and flood lubrication were generated in run 5, which corresponds to the situation with the lowest cutting speed (v_c = 60 m/min), highest axial depth of cut (a_p = 1.2 mm), and the intermediate feed per tooth tested (f_z = 0.075 mm/tooth). The roughness profiles from run 5 are presented in Fig. 5a (dry cutting) and Fig. 5b (flood lubricated cutting).

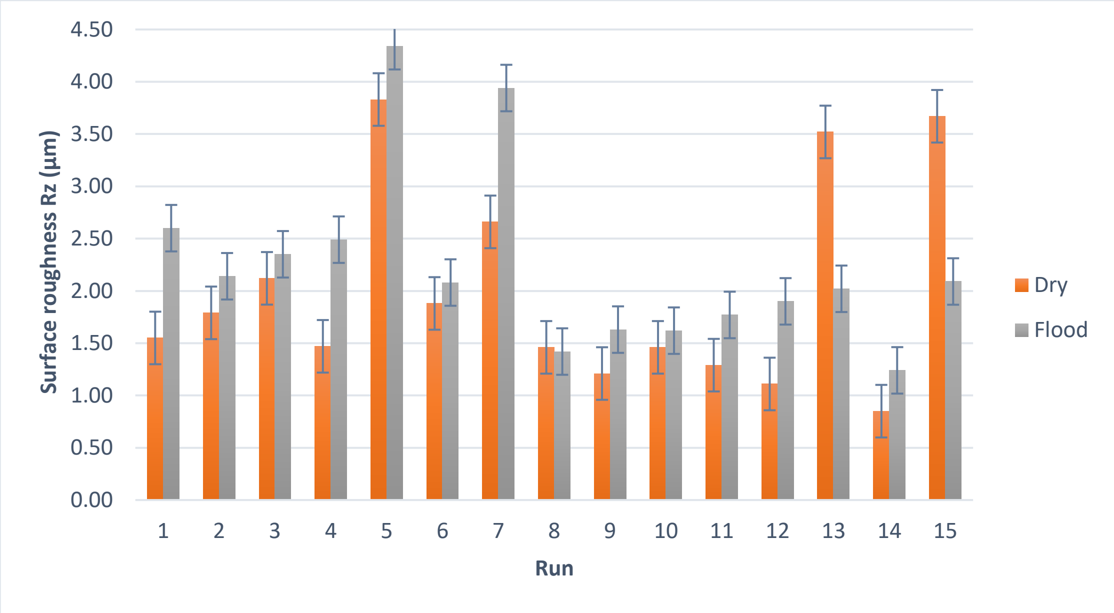
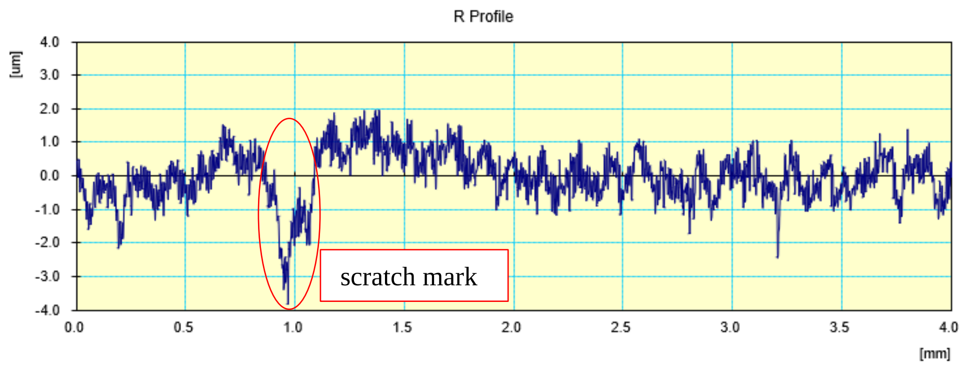


Figure 4. R_z values for dry and flood-lubricated milling of Toolox 44®

(a)



(b)

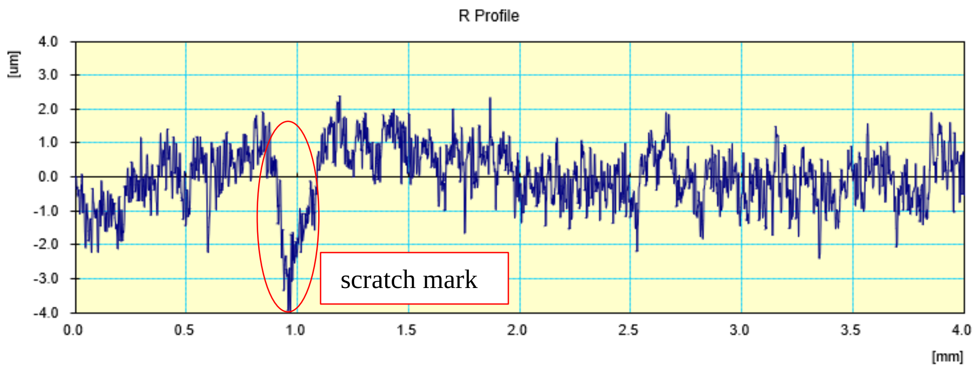
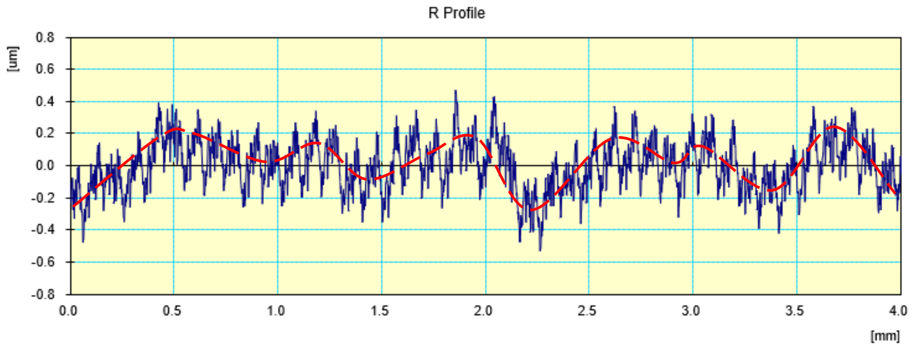


Figure 5. Roughness profiles for run 5: (a) dry cutting; (b) flood cutting

Both roughness profiles from Fig. 5 present large valleys in the vicinities of the 1.0 mm mark. These valleys corresponded to scratch marks on the workpiece surfaces, and were possibly originated from the release of an adhered chip. On the other hand, the lowest roughness values for both lubricooling conditions were obtained in run 14, which corresponds to the situation with the medium level of cutting speed (v_c = 80 m/min) and low levels of axial depth of cut (a_p = 0.4 mm) and feed per tooth (f_z = 0.05 mm/tooth). Fig. 6a presents the roughness profile for dry cutting (run 14), and

Fig. 6b for flood-lubricated milling. Both lubricooling conditions resulted in roughness values between 0.1 and 0.2 μm R_a for the combination of parameters of run 14. A direct comparison between the roughness values for dry and flood lubricated cutting shows that lower roughness was obtained after dry machining. However, the analysis of the roughness profiles allows the identification of some waviness after dry cutting (dotted red line), that is much less pronounced in the sample machined with flood lubrication. Machado *et al.* (2015) explain that the cutting fluid reduces friction in the tool/workpiece and tool/chip interfaces, contributing to improving the surface finish. Thus, the more efficient the penetration of the cutting fluid in the interfaces the greater its the lubricating effect, leading to the reduction of force components associated with vibrations, frequently reflecting favorably on the quality of the machined surface. Despite the waviness observed after dry machining of run 14 being more pronounced than the observed for the flood lubrication-assisted machining, it is important to consider that the scale used in Fig. 6 is considerably smaller than the scale of Fig 5.

(a)



(b)

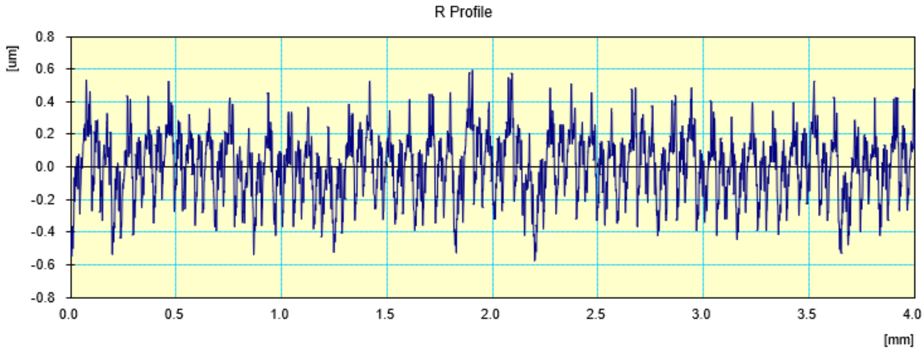


Figure 6. Roughness profiles for run 14: (a) dry cutting; (b) flood-lubricated milling

Table 4 presents the ANOVA results for R_a and R_z values in both lubricooling conditions. A 95% confidence interval was used, i.e., for values of $\alpha < 0.05$, it is assumed that the control variable has a significant influence on the result (values in bold). The lower the p-value, the greater the influence of the parameter on the response variable. The partially significant values (in gray) are presented for the confidence interval between 90 and 95%.

Table 4. ANOVA for R_a and R_z after dry and flood end milling of Toolox 44

factor	Dry				Flood			
	Ra		*Rz*		*Ra*		*Rz*	
	P-Value	Contrib. (%)	P-Value	Contrib. (%)	P-Value	Contrib. (%)	P-Value	Contrib. (%)
v_c	1.000	0.00	0.419	0.19	**0.057**	9.06	**0.074**	11.28
a_p	**0.000**	61.85	**0.000**	65.86	**0.003**	41.96	**0.010**	36.57
f_z	**0.003**	10.53	**0.001**	10.83	0.879	0.04	0.775	0.20
v_c^2	0.092	0.93	**0.063**	0.88	0.507	1.10	0.624	0.86
a_p^2	**0.001**	23.32	**0.000**	19.71	0.185	3.43	0.223	4.34
f_z^2	0.357	0.38	0.148	0.72	0.723	0.21	0.961	0.01
v_c x a_p	0.409	0.30	0.430	0.18	**0.035**	12.36	**0.078**	10.83
v_c x f_z	0.903	0.01	0.390	0.22	0.669	0.31	1.000	0
a_p x f_z	0.183	0.87	0.430	0.18	**0.010**	24.05	**0.020**	24.83
R^2	98.18%		98.77%		92.52%		88.91%	

For the dry condition, the linear effect of the depth of cut, feed per tooth and the quadratic effect of the depth of cut (a_p^2) were the only significant factors for R_a and R_z considering $\alpha < 0.05$. Multivariate regression for dry cutting showed that both the increase of a_p and f_z result in higher R_a and R_z. This result may be associated with vibrations caused by the force growth resulted from the increase of the cutting section. Thus, considering the range of values adopted at work, lower roughness values are obtained in dry cutting for a_p = 0.4 mm.

For flood lubrication-assisted milling, the linear effect *of* a_p and its interaction effect with the feed per tooth presented significant influence over both response variables for the 95% confidence interval. The linear effect of the cutting speed was found to have a partially significant influence for R_a and R_z, and the influence of the interaction between v_c x a_p was significant for R_a (96.5% confidence interval) and partially significant for R_z (92.2% confidence interval). Multivariate regression for cutting with flood lubrication showed that the increase of a_p and f_z and the decrease of v_c promote a simultaneous increase of R_a and R_z. This increase may be associated with the vibrations generated with the growth forces resulted from the increase of the cutting section, and the higher cutting speed may stimulate the capacity of the cutting fluid to contribute to a good surface finish.

Gopalsamy *et al.* (2009) studied the optimization of the process parameteres for end milling of hardened steel. The authors analyzed surface roughness and tool life using Taguchi and ANOVA, and concluded that cutting speed was the most influencing parameter on both surface roughness and tool life. In this work, cutting speed showed weak influence over both surface roughness parameters for flood-lubricated milling, and no statistically signifficant influence over dry cutting.

Figure 7 presents the contour surface plots (f_z x v_c) for dry cutting with a_p = 0.4 mm (the minimum value used in the experiments performed). According to the plots, one can deduce which combination will be the most suitable for dry cutting. Both contour plots present peaks on higher corners, corresponding to combinations of f_z and v_c that result in higher roughness values according to the model. Also, despite the model indicate that the smallest roughness is obtained with the lowest levels of both parameters, the best roughness (*Ra* and *Rz*) for this a_p for dry cutting was observed after the end milling with f_z = 0.05 mm/tooth and v_c between 70-80 m/min. This is easily explained since the BBD does not allow all factors to be in their highest or lowest levels simultaneously. Thus, according to the model, an eventual combination of all factors in their lower levels would probably result in better surface finishes than those observed experimentally.

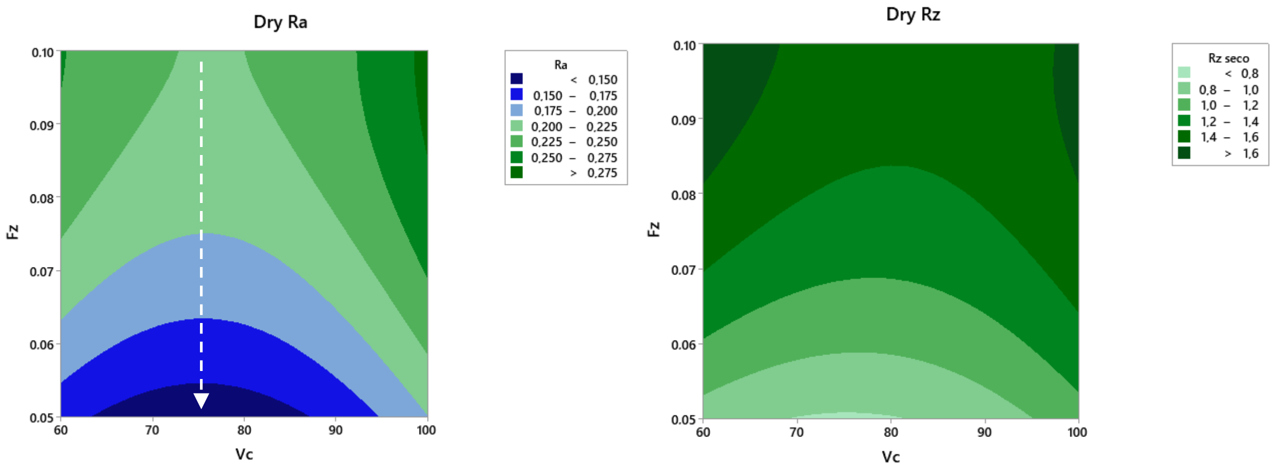


Figure 7. Contour surface plots (f_z x v_c) for dry cutting with a_p = 0.4 mm: (a) *Ra*, (b) *Rz*

The contour plots for flood lubrication-assisted milling are presented in Fig. 8. Since the best roughness values were obtained with the same axial depth of cut for both dry and flood cutting, the parameters and levels are the same as Fig. 7. An analogous procedure was performed with flood lubrication. For this purpose, the a_p value was also set at 0.4 mm (the level that produces the lowest R_a and R_z and the only significant main factor) and varied v_c and f_z. The contour plots of Fig. 8 allow the identification of regions associated with good and bad surface roughness for both the parameters evaluated in this study. The results differ significantly from those observed for dry milling. The plot suggests that an eventual peak might be outside the plot area; however, since this area is out of the domain of the response surface's function, one may not state this peak as a fact. Throughout this study, flood milling resulted in surfaces with higher roughness than those obtained by dry cutting. However, the width of the bands in Fig. 8 indicates that this condition is more stable than dry machining for surface finish.

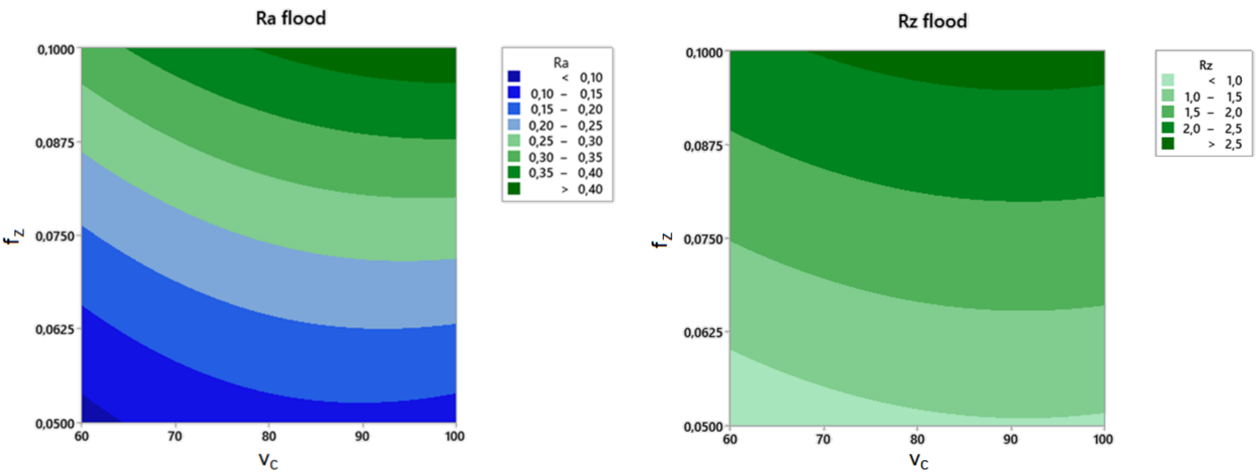


Figure 8. Contour plots for flood cutting

Multivariate regression analysis for dry cutting showed that both the increase of a_p and f_z result in higher R_a and R_z. This result may be associated with vibrations caused by the force growth resulted from the increase of the cutting section. Thus, considering the range of values adopted at work, lower roughness values are obtained in dry milling for v_c = 76,6 m/min, a_p = 0,56 mm, and f_z = 0,05 mm/tooth. For lubrication-assisted milling, the increase of a_p and f_z and the decrease of v_c promote a simultaneous increase of R_a and R_z. This increase may be associated with the vibrations generated with the growth forces resulted from the increase of the cutting section, and the higher cutting speed may stimulate the capacity of the cutting fluid to contribute to a good surface finish. Therefore, lower roughness values are obtained in flood milling with v_c = 60 m/min, a_p = 0.4 mm, and f_z = 0.05 mm/tooth.

Binali *et al.* (2018) studied the machining of Toolox 44, and concluded that the surface roughness increase with the cutting speed and feed rate. In this study, a_p and f presented stronger influence over the surface roughness.

4 CONCLUSIONS

In this work, an experimental investigation was carried out to clarify the influence of the cutting parameters and lubricooling condition over the surface finish in the end milling of Toolox 44®. Considering the conditions tested, the main conclusions were:

- The analysis of the experimental data indicates that the only significant factor on the roughness generated in dry machining was the axial depth of cut a_p, which should be kept at a minimum level for obtaining better surface finishes.
- The significant factors indicated by ANOVA for flood end milling were a_p and its interactions with feed per tooth (a_p x f_z) and cutting speed (v_c x a_p). The combination of cutting parameters that produced the best surface finish in the experiments is v_c = 80 m/min, a_p = 0.4 mm, and f_z = 0.05 mm/tooth. However, according to the multivariate regression analysis, the best results for dry cutting will be obtained for v_c = 76.6 m/min, f_z = 0.05 mm/tooth, and a_p = 0.56 mm, while flood lubricated cutting will present its best surface finish with v_c = 60 m/min, f_z = 0.05 mm/tooth, and a_p = 0.4 mm.
- The lowest roughness values were obtained with dry cutting. However, less significant ripples were observed after flood lubrication-assisted milling. Also, the analysis of the contour plots indicates that the use of flood lubrication allows a more stable relationship between the machining parameters and the resulting surface roughness.

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REFERENCES

Astakhov, V.P.,2011. Modern Machining Technology – A Practical Guide. 1.ed. , Cambridge: Woodhead Publishing.

Benardos PG, Vosniakos G-C, 2003. "Predicting surface roughness in machining: a review". *International Journal of Machine Tools and Manufacture*, Vol. 43, pp. 833-844.

Binali, R., Ulaş, H.B. ve Demir, H., 2018. "TOOLOX 44 Malzemesinde Talaş Kaldırma Miktarının Yüzey Pürüzlülüğü ve Takım Aşınması Üzerindeki Etkilerinin İncelenmesi", *Technological Applied Sciences (NWSATAS)***,** 13(1):19-28, DOI:10.12739/NWSA.2018.13.1.2A0132.

Chandrasekaran H., M'Saoubi R., Karlsson O., Persson U., 2006. "Milling of prehardened mould steels – role of microstructure on machinability and tool wear". *Proceedings of 7th International Tooling Conference*, Vol. 1., pp. 623-630.

Ferreira, S.L.C.; Bruns R.E.; Silva E. G. P. da; Santos, W. N. L. dos; Quintella C.M.; David J.M.; Andrade, J.B. de; Breitkreitz M.C.; Garden I.C. S.F.; Neto B.B., 2007. "Statistical designs and response surface techniques for the optimization of chromatographic systems". *Journal of Chromatography A*, Vol. 1158, No. 1-2, pp. 2-14.

Garcia, R.F., Feix, E.C., Mendel, H.T., Gonzalez, A.R., Souza, A.J., 2019. "Optimization of cutting parameters for finishing turning of 6082-T6 aluminum alloy under dry and RQL conditions". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 41, A317.

Gopalswamy, B. M.; Mondal, B.; Gosh, S., 2009. "Taguchi method and ANOVA: An approach for process parameters of optimization of hard machining while machining hardened steel". *Journal of Scientific & Industrial Research*, Vol. 68, pp. 686-695.

Hansson, P., 2009. "TOOLOX – Pre-hardened Tool Steels Aimed for Die-casting Applications Enabling Faster Mould Manufacturing".*SAE International Journal of Materials and Manufacturing*,2(1), 121-127.

Hansson, P., 2009. "Modern Pre-hardened Tool Steels in Die-Casting Applications". Materials and Manufacturing Processes, Vol. 24, pp. 824–827.

Kalpakjian, S., Schmid, S., 2010. Manufacturing Engineering and Technology, 6ed, Hoboken: Pearson Prentice-Hall

Klocke F, 2011. Manufacturing Processes 1 – Cutting. RWTH edition. Berlin-Heidelberg: Springer.

Lugand, A., 2021, Catalog 2021 – V5. Available at http://lugand-aciers-online.com/Catalogue-lugand-aciers-pt.pdf

Machado, A. R., Mendes, A.M., Coelho, R. T., Silva, M.B., 2015. Theory of Materials Machining. 3. Ed., Sao Paulo, Blucher.

Niharika, B.P, Agrawal, I.A.K., Khan, Z.A., 2016. "Effects of cutting parameters on quality of surface produced by machining of titanium alloy and their optimization" Archive of Mechanical Engineering, Vol. 63, n. 4, p. 531-548.

Policena, M.R., Devitte, C., Fronza, G., Garcia, R.F., Souza, A.J., 2018. "Surface roughness analysis in finishing end-milling of duplex stainless steel UNS S32205" *The International Journal of Advanced Manufacturing Technology*, Vol. 98, pp. 1617-1625

SSAB, 2014. Toolox Machining Recommendations. Available at https://ssabwebsitecdn.azureedge.net/-/media/files/en/toolox/602_ssab_toolox_machining_rec_6.pdf?m=20200210092508.

SSAB, 2021. Toolox - Easy-to-machine steel. Available at https://www.ssab.com.br/products/brands/toolox/workshop-friendly.

RESPONSIBILITY

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