25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COBEM-2019-0588
OPTIMIZATION OF CUTTING PARAMETERS CONSIDERING SURFACE ROUGHNESS WHEN MILLING AISI 304 STEEL USING COATED WC-CO AND TIALN / WC-CO COATED

Lopes, Murilo Pereira
Carneiro, José Rubens Gonçalves
Mechanical Engineering Department, Pontifícia Universidade Católica de Minas Gerais – PUC Minas, Belo Horizonte, MG, Brazil. Avenue Dom josé Gaspar, 500 – Campus COREU – Coração Eucarístico – zip code. 30545-901 - Graduate program in mechanical engineering – Tel +55 31 33194179.
murilo.start360@gmail.com; joserub@pucminas.br.

Silva, Gilmar Cordeiro da
Mechanical Engineering Department, Pontifícia Universidade Católica de Minas Gerais – PUC Minas, Belo Horizonte, MG, Brazil. Avenue Dom josé Gaspar, 500 – Campus COREU – Coração Eucarístico – zip code. 30545-901 - Graduate program in mechanical engineering – Tel +55 31 33194179.
gilmarcord@gmail.com.

Santos, Carlos Eduardo dos
Materials Engineering Department, Centro Federal de Educação Tecnológica de Minas Gerais – CEFETMG, Belo Horizonte, MG, Brazil. 5253 Amazonas Ave. – Nova Suíssa — zip code. 30421-169. Tel +55 31 988632774.
carloseduardo@cefetmg.br.

Santos, Ítalo Bruno dos
Mechanical Engineering Department, Pontifícia Universidade Católica de Minas Gerais – PUC Minas, Belo Horizonte, MG, Brazil. Avenue Dom josé Gaspar, 500 – Campus COREU – Coração Eucarístico – zip code. 30545-901 - Graduate program in mechanical engineering – Tel +55 31 33194179.
italobsantos@gmail.com.

Abstract. *This paper presents an investigation on the behavior of the roughness response Ra and Rz on the surface of AISI 304 steel submitted to the process of top milling by dry milling, using different cutting tools and varying the cutting parameters. The study was based on experimental planning techniques through RSM response surface methodology. The parameters used in the experiments were cutting speed Vc, m / min, feed per tooth fz, mm/tooth and depth of cut ap, mm. To compare the results, WC-Co cemented carbide cutting tools with and without TiAlN coating were used. The results showed that, for uncoated cutting tools, the parameter fz, quadratic, 30.03% and linear, 28.47%, caused the greatest effects on the roughness response Ra and Rz respectively. For the tools with TiAlN coating, the interaction between the parameters Vc and fz, caused a greater influence on the roughness response Ra, 20.92% and Rz 35.40%. The second-order polynomial regression model and ANOVA were efficient for the investigation. The use of TiAlN coated tools, compared to the uncoated specification used in the experiment, pointed to low roughness indexes. A mathematical model capable of describing the roughness behavior as a function of the investigated cutting parameters was developed.*

Keywords: *Milling, Stainless steel, Roughness, Optimization, Analysis of variance.*

1. INTRODUCTION

Stainless steels are Fe-C-Cr alloys with a chromium content greater than 10%. In this family, austenitic alloys are the most used in industries because of their mechanical properties and resistance to corrosion (Berkani et al., 2015a). The AISI 304 alloy generally contains 18% Cr and 8% nickel by weight and is known as 18-8 stainless steel, the most commonly used in general use (Askeland and Wright, 2014). These steels are widely used in the chemical industry, health, food production, pharmaceuticals, textiles, nuclear, biomedical, etc. They exhibit high hardness and resistance to deformation, as well as excellent ductility and toughness over a wide range of temperatures and have excellent corrosion and oxidation resistance (Asilturk and Neseli, 2012).

Machining is a mechanical manufacturing process characterized by the removal of the splinter. It is usually performed in a machine tool that, through the increment of movements associated with the attack of a cutting tool, processes the material (Ferraresi, 2011). In machining processes, the key point to ensure the quality of the manufactured product is the appropriate selection of cutting parameters (Do and Hsu, 2016). The study and previous definition of factors such as cutting speed, cutting depth and feed are fundamental for the good performance of a machining operation (Arbizu and Pérez, 2003). The integrity of the surface of ductile materials can be compromised when subjected to certain machining conditions (Rodrigues et al., 2010). The feed rate and cutting speed of the machining tool are factors that influence more significantly the surface roughness of the AISI 304 steel as a function of its high ductility (Berkani et al., 2015b).

It is possible to analyze the behavior of cutting parameters in a machining process, applying the Design of Experiments (DOE) techniques. The experimental assays are designed using the multilevel factorial model - DOE, and their results are analyzed through Analysis of Variance - ANOVA (Razavykia et al., 2015a). The statistical ANOVA tools applied in the optimization of cutting parameters in milling are efficient in the study of roughing and finishing operations (Das et al., 2016a). Statistical models are developed to represent the relationship between machining parameters as independent variables, and surface roughness or cutting force as response variables (Razavykia et al., 2015b). Response Surface Analysis - RSM is a DOE technique that focuses on a new and renowned approach for the optimization of input process parameter models based on physical experiments, simulation experiments and experimental discoveries (Das et al., 2016b).

The tool-material interactions under machining conditions significantly modify the properties of the layers near the metal surface and consequently their behavior and durability. The nature and extent of modifications depend on the types of tool-part interactions (Moussa et al., 2012). Achieving the desired surface quality is fundamental to the functional performance of a component (Makadia and Nanavatiof, 2013), especially as to its useful life due to the fatigue of the material in service (Sarnobat and Raval, 2019). The dimensional accuracy and in-service performance of machined products are directly affected by surface roughness (Razavykia et al., 2015c). The roughness of the surface also influences the tribological characteristics, the fatigue resistance, the corrosion resistance and the aesthetic appearance of the machined parts (Tanikié and Marinković, 2012).

The cemented carbide cutting tools are widely used in the machining industry, the cemented carbide is the alloy of various metal carbides - tungsten (W), titanium (Ti) vanadium (V) bonded with an elastic binder (Kazlauskas et al., 2017a). Tungsten carbide is a composite material that consists mainly of two phases. The hard WC phase is responsible for good wear resistance and high abrasiveness, the Co phase, binder, is responsible for the strength of the material (Hintze et al., 2018). The cutting edges made of WC-Co are more wear-resistant compared to tools made of high-speed steel (Kazlauskas et al., 2017b).

In this context, this research presents an experimental analysis of the surface roughness behavior Ra and Rz along a series of frontal milling tests performed on the surface of AISI 304 austenitic stainless-steel using WC-Co tool and WC-Co coated with TiAlN.

2. MATERIALS AND METHODS

The milling experiments were performed on stainless steel AISI 304 specimens, whose initial dimensions were 35mm in height, 50mm in width and 100mm in length. Samples of the same material with 35x50x50mm were analyzed in an ARL 4460 optical emission spectrometer from Thermo Scientific. For the metallographic test the sample was cut in the direction perpendicular to the lamination, then milled and later prepared in sandpaper with 180, 220, 320, 400, 500, 600, 1000 and 1200 mesh granulometry. Afterward, a felt finishing polish impregnated with a diamond paste of 9, 3 and 1 mm size was made. For analysis of the microstructure of the AISI 304 steel was attacked with regal water (1 portion of concentrated nitric acid for 3 parts of concentrated hydrochloric acid), and then analyzed under a Zeiss optical microscope, with an image analyzer.

The machines used in the milling were a ROMI BRIDGEPORT - DISCOVERY 560 CNC machining center. Two different cutting inserts were used in the tooling during the experiments, the first of Tungsten and Cobalt Carbide, WC-Co of the KYOCERA brand with specification: 050405ER-SH PR1225, and the second of Tungsten Carbide and Cobalt, WC-Co with TiAlN PVD coating, specification: 050405ER-SH PR1025 from the same manufacturer. To guarantee reliability in the comparison of the results, samples of the inserts were fractured and observed in a scanning electron microscope. The top section was preferred to describe the morphology, while the thickness measurement was made in the cross-section. The dispersive energy spectrometer coupled to SEM was used for the qualitative evaluation of the chemical composition. To measure the roughness Ra and Rz, a rugosimeter of the brand TAYLOR HOBSON model SURTRONIC S-128 was used.

Table 1. Cutting parameters and their levels for milling.

Symbol	Control factor	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Vc	Cutting speed	m/min	120	140	160	180	200
fz	Feed per tooth	mm/tooth	0.10	0.125	0.15	0.175	0.20
ap	Depth of cut	mm	1.0	1.2	1.4	1.6	1.8

The process started with the definition of input variables and their respective levels, as shown in Tab. 1. For the cutting speed Vc, the five levels used in the DOE were: 120 m/min, 140 m/min, 160 m/min, 180 m/min and 200 m/min. The levels of the input variable fz, feed per tooth, were: 0.10 mm/tooth, 0.125 mm/tooth, 0.15 mm/tooth, 0.175 mm/tooth, and 0.20 mm/tooth; and the depth of cut ap, varied in the levels: 1.0 mm, 1.2 mm, 1.4 mm, 1.6 mm and 1.8 mm.

After the elaboration of the experimental design through the response surface methodology, the milling experiments were done in the laboratory, according to Tab. 2.

Table 2. Design of response surface experiment.

Nº Test	Process parameter settings			Experimental procedure of milling for each machining tool			
				Tool WC - Co		Tool PVD TiAlN	
	Vc (m/min)	fz (mm/tooth)	ap (mm)	Ra (µm)	Rz (µm)	Ra (µm)	Rz (µm)
1	200	0.100	1.0	1.69	7.61	1.13	4.82
2	160	0.150	1.6	1.58	10.10	1.55	8.85
3	160	0.125	1.4	2.42	10.80	1.97	9.03
4	200	0.100	1.8	1.72	7.90	0.86	5.07
5	180	0.150	1.4	1.80	11.30	1.42	8.58
6	160	0.150	1.4	1.58	10.80	2.09	9.36
7	120	0.200	1.0	2.23	11.70	0.97	4.89
8	120	0.200	1.8	1.40	6.79	1.08	6.41
9	120	0.100	1.0	1.10	5.91	1.25	5.90
10	160	0.150	1.4	1.66	9.60	1.60	8.74
11	160	0.150	1.4	1.82	8.58	1.89	9.55
12	160	0.150	1.2	2.20	9.91	1.57	9.58
13	160	0.175	1.4	2.72	15.70	2.25	11.40
14	200	0.200	1.0	2.77	17.50	1.49	9.90
15	120	0.100	1.8	1.63	7.82	1.26	8.15
16	160	0.150	1.4	1.87	11.50	1.56	9.83
17	160	0.150	1.4	2.03	12.30	1.77	9.21
18	140	0.150	1.4	1.09	7.20	1.90	9.17
19	160	0.150	1.4	1.74	12.50	1.960	10.20
20	200	0.200	1.8	2.42	10.40	2.540	13.80

After data tabulation, the results were analyzed by means of statistical ANOVA techniques, the second order polynomial regression equations that described the roughness behavior Ra and Rz for each situation were developed. The significance index adopted in the study was $\alpha=0.05$.

The response surface methodology was used for modeling and analysis of the machining parameters during the milling process, the observed response was to the surface roughness in its Ra and Rz parameters. The RSM method is a sequential and exploratory approach that seeks to establish the relationship between more than one variable and a given response (Ghevariya et al., 2011). The response surface can present approximation functions or effects called the polynomial regression model, these models are of 1st order, which represents the linear effect of the 2nd order model, which represents the curvature effect through a combination of the linear effect, quadratic and interaction.

In addition, the statistical model of second-order effects is given by Eq. (1):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{1}$$

Where:

$\sum_{i=1}^{k} \beta_i x_i$: are the terms of linear effects.

$\sum_{i=1}^{k} \beta_{ii} x_i^2$: are the quadratic terms.

$\sum_{i<j}\sum \beta_{ij} x_i x_j + \varepsilon$: are the terms of the interactions.

The RSM project adopted in this research was the Central Composite Design (CCD), recommended when the plan requires sequential experiments. The central composite experiment is used to obtain data for the creation of a second-order model surface, which includes factorial or cubic points, axial or star points and central points. The second-order polynomial regression model represents the curvature effect through a combination of linear, quadratic and interaction effects (Montgomery and Runger, 2007a).

3. RESULTS AND DISCUSSION

The chemical composition of the steel in percentage by weight occurred, as shown in Tab. 3.

Table 3. Chemical composition of AISI 304 steel in percentage by weight.

C	Mn	Si	Cr	Ni	Mo	Others
0.05	1.22	0.48	17.66	8.00	0.05	72.49

The microstructure of the AISI 304 steel evidenced the presence of austenite with equiaxial crystals and the presence of annealing twinning Fig. 1.

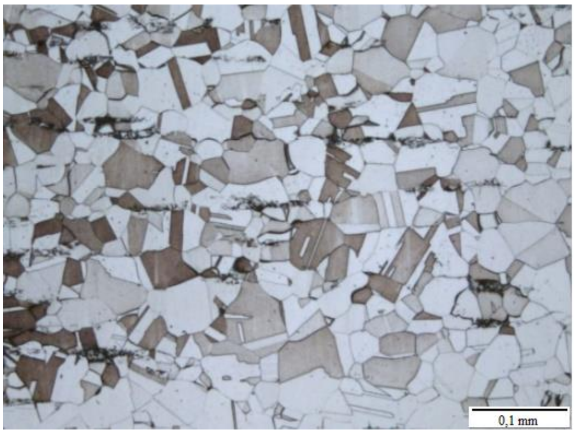
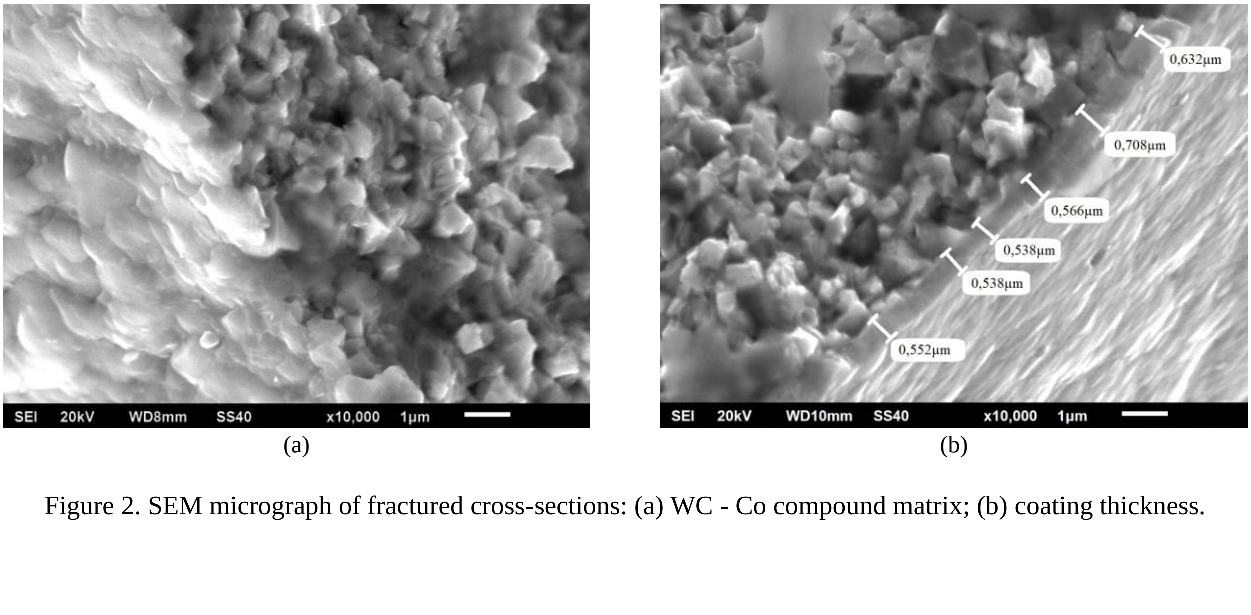


Figure 1. Microstructure of the AISI 304 steel showing crystals of austenite and annealing twinning.

Figure 2 (a) shows the microstructures of the cemented carbide insert, specified by 050405ER-SH PR1225, made of tungsten carbide in the Cobalt matrix, WC-Co and the coated insert Fig. 2 (b) specification indicated by the manufacturer is 050405ER- SH PR1025.



(a) (b)

Figure 2. SEM micrograph of fractured cross-sections: (a) WC - Co compound matrix; (b) coating thickness.

It is observed that the thickness of the coating was close to 1µm with the presence of Ti, Al and N (TiAlN) obtained by EDS.

3.1 Analyze of variance

The inferential relationship between the cutting parameters, Vc, fz, ap, and the investigated response variable, roughness Ra and Rz, were expressed based on the adequacy of the models through the coefficient of determination R^2, corresponding to the amount of variability considered by the regression model. The higher the R^2 value, the better the model fits the data (Montgomery and Runger, 2007b).

In the case of the experiments performed, the value of R^2 was 86.17% in the Ra roughness evaluation using the WC - Co cemented carbide tool, and 87.42% in the Rz roughness evaluation, for the cemented carbide tool with PVD TiAlN coverage the values of R^2 were 83.44% in the Ra roughness and 92.62% Rz.

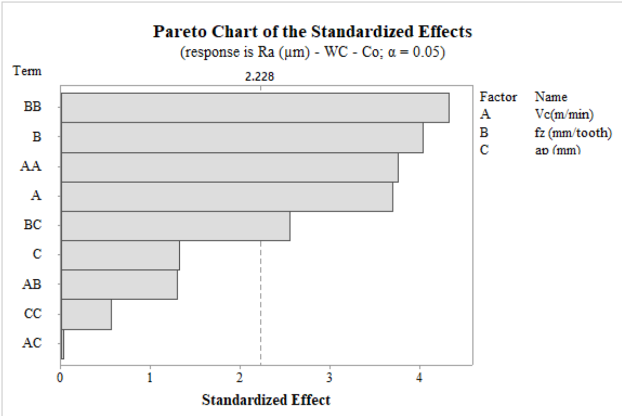
Table 4 and Figure 3 (a-d) provide results of the analysis of variance for surface roughness Ra and Rz based on the tests performed with the two specifications of the cutting tools. The table indicates the results of the P-Value, which is a statistical index used in the analysis of variance, if P-value $\leq \alpha$ the association is statistically significant, if P-value> α the association is not statistically significant (Montgomery and Runger, 2007c). The table also shows the index of contribution of each factor, in a linear, quadratic and interaction form. It is important to relate these responses in ANOVA to understand better the results.

Table 4. Results of ANOVA.

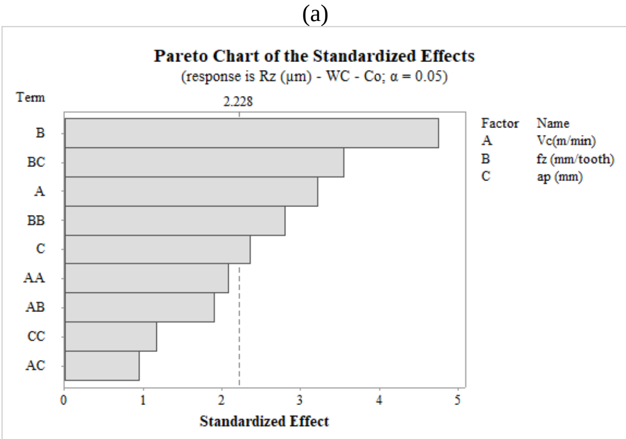
Source	Tool WC – Co				Tool PVD TiAlN			
	Ra, (µm)		Rz, (µm)		Ra, (µm)		Rz, (µm)	
	P-Value	Cont.%	P-Value	Cont.%	P-Value	Cont.%	P-Value	Cont.%
Vc	0.0041	18.99	0.0093	12.99	0.1237	4.68	0.0080	7.67
fz	0.0024	22.58	0.0008	28.47	0.0393	9.30	0.0005	18.22
ap	0.2137	2.44	0.0401	6.99	0.2482	2.49	0.0105	6.93
Vc^2	0.0037	0.31	0.0635	7.36	0.2994	29.67	0.1520	22.47
fz^2	0.0015	30.03	0.0187	8.27	0.0699	2.88	0.2387	0.66
ap^2	0.5872	0.44	0.2716	1.70	0.1039	5.30	0.4208	0.50
Vc*fz	0.2243	2.32	0.0635	4.58	0.0052	20.92	0.0001	35.40
Vc*ap	0.9771	0.00	0.0187	1.14	0.3720	1.45	0.8740	0.02
fz*ap	0.0283	9.07	0.2716	15.90	0.0710	6.76	0.2397	1.10

It was verified that for the WC-Co tool the factor that most affected the roughness response Ra was the feed per tooth fz, both linearly, 22.58%, and quadratic, 30.03%. It is noted that in both results the P-Value was lower than the significance level of $\alpha = 0.05$, so as the quadratic interaction was more significant, the relationship between the factor and the response will indicate a curve. In Fig. 3(a), through the Pareto graph, it is possible to compare the relative magnitude and the statistical significance of the input parameters in the roughness response Ra for the WC-Co tool.

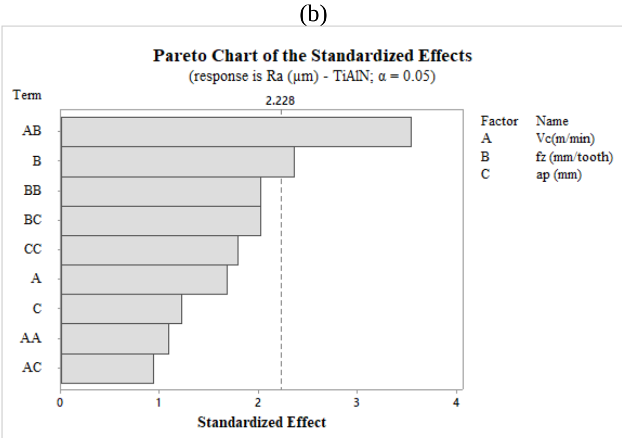
The graph of Fig. 3(b) shows the proportions of the influencing parameters in the 2nd order polynomial regression performed for Rz roughness using WC-Co tool. Relating the data of Tab. 4 to the graph shows a significant linear contribution of the parameter fz in the response, 28.47%, with P-Value = 0.0008.



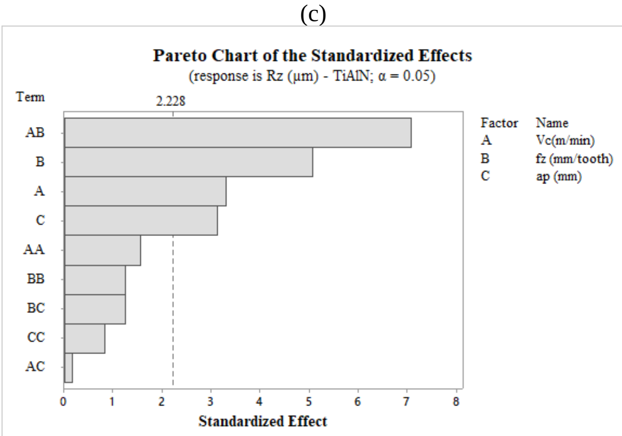
(a)



(b)



(c)



(d)

Figure 3. (a) Pareto WC - Co graph for roughness Ra. (b) Pareto Chart WC - Co for roughness Rz. (c) Pareto graph PVD TiAlN for roughness Ra. (d) Pareto graph PVD TiAlN for roughness Rz.

In the case of TiAlN PVD-coated cutting tools, ANOVA presented slightly different results, the factor that contributed most to the roughness response Ra was Vc^2, but with P-Value = 0.2994, higher than the significance index α = 0.05, Tab 4. Thus, by analyzing the Pareto graph of Fig. 3 (c), it is understood that the interaction Vc*fz was shown to have a higher magnitude as a function of P-Value = 0.0052, lower than the index of significance. The interaction term Vc*fz was more significant, so strong interdependence between them was found.

Figure 3 (d) shows the behavior trend of the roughness response for the cutting tool coated of TiAlN PVD , the Rz response was strongly influenced by the interaction of the factors Vc*fz, even a phenomenon occurred in the Ra roughness response. In this case, the contribution index of Vc*fz was 35.40% and the P-Value = 0.0001, Tab. 4. The figure also represents the magnitude of the other linear, quadratic and interaction factors.

The Equations (2-5) represents the factorial regressions of the behavior of the roughness response Ra and Rz for the two cutting tools used in the experiment.

$$Ra\ (\mu m)_{WC-Co} = -16.58 + 0.418Vc - 275.9\,fz + 6.84\,ap - 0.001307Vc*Vc + 963\,fz*fz - 1.95\,ap*ap + 0.0550Vc*fz - 0.00016Vc*ap - 10.88\,fz*ap \quad (2)$$

$$Rz\ (\mu m)_{WC-Co} = -85.4 + 1.374Vc - 1007\,fz + 81.8\,ap - 0.00427Vc*Vc + 3669\,fz*fz - 23.8\,ap*ap + 0.477Vc*fz - 0.0298Vc*ap - 88.8\,fz*ap \quad (3)$$

$$Ra\ (\mu m)_{TiAlN} = -5.16 + 0.099Vc - 173.7\,fz + 16.1\,ap - 0.000394Vc*Vc + 468\,fz*fz - 6.44\,ap*ap + 0.1564Vc*fz + 0.00514Vc*ap + 8.89\,fz*ap \quad (4)$$

$$Rz\ (\mu m)_{TiAlN} = -17.8 + 0.457Vc - 450\,fz + 27.1\,ap - 0.00185Vc*Vc + 958\,fz*fz - 10.0\,ap*ap + 1.035Vc*fz + 0.0030Vc*ap + 18.2\,fz*ap \quad (5)$$

3.2 Multiple responses optimization

To minimize the roughness response Ra and Rz with the use of each tool tested in the experiment, the numerical optimization of the response surface model was applied. The optimal parameters for each RSM condition are described in Tab. 5 and shown in Fig. 4 (a-d). Response surface optimization is an ideal technique for determining the combination of cutting parameters (Berkani et al., 2015b).

Table 5. Optimization of cutting parameters to minimize roughness.

Tool	Parameters	Goal	Optimum condition			Lower	Upper	Pred. Resp.	Desirability
			Vc, (m/min)	fz, (mm/tooth)	ap, (mm)				
WC – Co	Ra, (μm)	Min.	120	0.10	1.00	1.09	2.77	1.09	0.99
	Rz, (μm)	Min.	200	0.16	1.00	5.91	17.5	5.91	1.00
PVD TiAlN	Ra, (μm)	Min.	200	0.10	1.80	0.86	2.54	0.86	0.99
	Rz, (μm)	Min.	200	0.12	1.00	4.82	13.8	3.94	1.00

For the WC - Co cemented carbide tool the input factors were set at: Vc = 120 m/min, fz = 0.10 mm/tooth and ap = 1.00 mm for an expected response of Ra = 1.09 μm; for Rz, the numerical optimization showed: Vc = 200m/min, fz = 0.16mm/tooth, ap = 1.00 mm and Rz = 5.91 μm. In the analysis of the data collected with the tool with WC - Co substrate and TiAlN coating the results were: Vc = 200m/min, fz = 0.10 mm/tooth, ap = 1.80 mm with roughness prediction Ra = 0.86 μm; and roughness Rz with the optimal parameters of Vc = 200 m/min, fz = 0.12 mm/tooth, ap = 1.00 mm for the prediction of Rz = 3.94 μm.

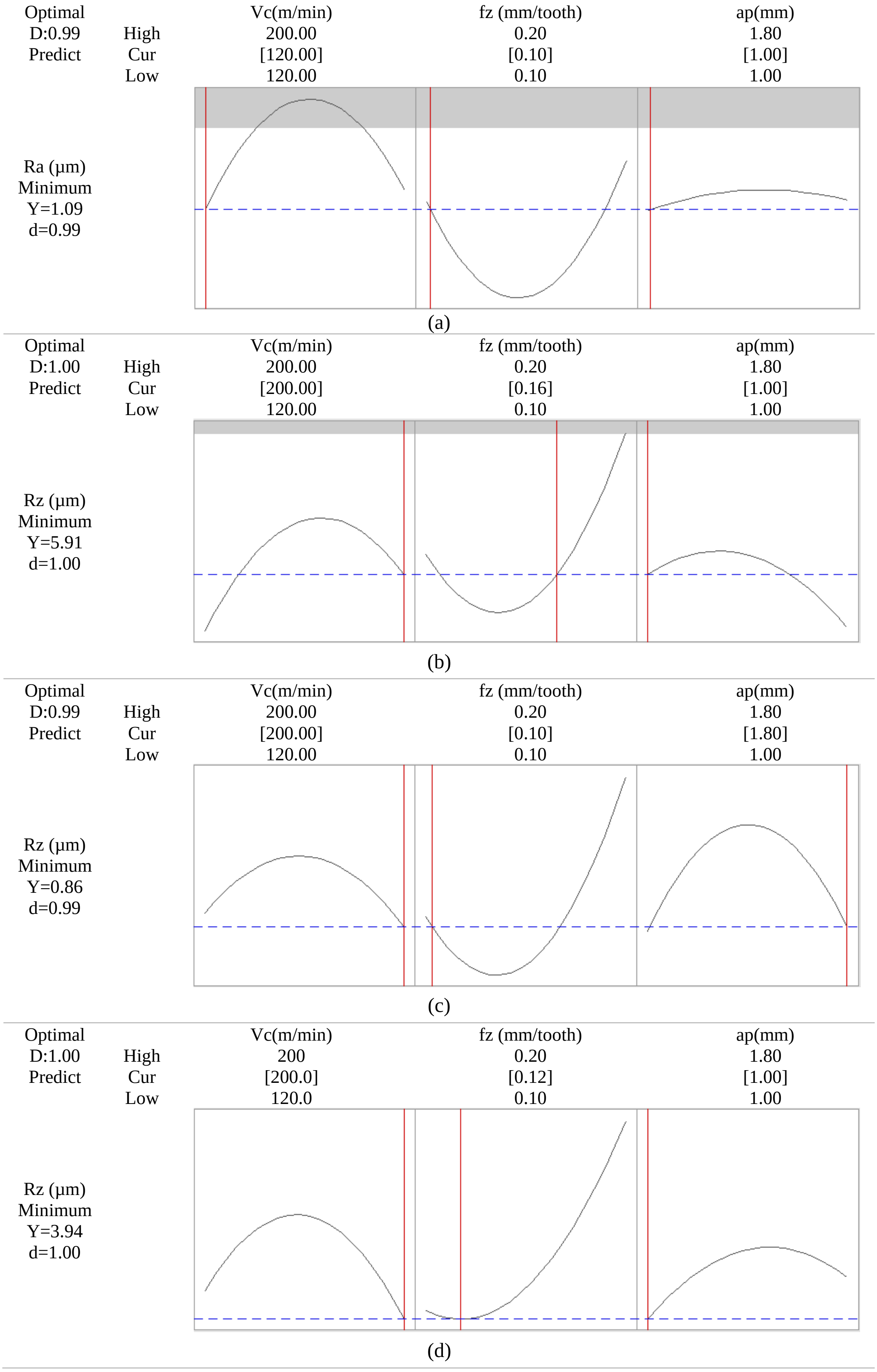


Figure 4. Graph of optimization of cutting parameters to minimize roughness.

To verify the numerical solution, a sequence of three experimental milling tests was performed for each analyzed response using the two cutting tools. The tests followed the guidelines of analytical optimization. Table 6 shows the comparison between the roughness responses predicted and the experimental results obtained, indicating the percentage error in each test.

Table 6. Confirmation tests.

Tool	Parameters	Predicted response (μm)	Experimental (μm)	Error %
WC - Co	Ra	1.09	1.16	6.42
			1.12	2.75
			1.11	1.83
	Rz	5.91	6.18	4.56
			5.78	2.19
			6.08	2.87
PVD TiAlN	Ra	0.86	0.87	1.16
			0.85	1.16
			0.88	2.32
	Rz	3.94	3.91	0.76
			4.02	2.03
			3.92	0.51

In the milling with the WC - Co tool, the answers found in the confirmation tests of the optimization of the minimum roughness presented a variation in Ra from 1.83% to 6.42%, between the predicted response and the value measured in the rugosimeter. In Rz, this percentage error ranged from 2.19% to 4.56%. For the tool coated with TiAlN PVD, the percent errors were 1.16% to 2.32% in Ra and 0.76% to 2.03% in Rz. The values found indicated that the adopted optimization model was acceptable, and correctly describes the machining process developed.

4. CONCLUSION

Statistical planning tools, Design of Experiments (DOE) and analysis of variance, ANOVA, were fundamental to obtain concrete and tangible results on the linear, quadratic and interaction effects of the cutting parameters on the roughness evolution Ra e Rz of the milled surface.

For the uncoated cutting tools, the parameter fz^2 (quadratic, 30.03%) was the most influent in the roughness response Ra, and the parameter fz (linear, 28.47%) was the most significant for roughness Rz. For the tools with TiAlN coating, the interaction between the parameters Vc and fz, caused a greater influence on the roughness response Ra, 20.92% and Rz, 35.40%. The ap cutting depth variation moderately influenced the roughness responses during all the tests.

The use of TiAlN coated tools, compared to the uncoated specification used in the experiment, caused the lowest roughness indexes.

The mathematical model able to describe the behavior of the roughness according to the investigated parameters was developed. Numerical optimization has been proven through verification tests.

The study of roughness behavior in milling processes, applying the appropriate methodology, can contribute immensely to the increase of productivity in the companies and the quality of the products.

5. ACKNOWLEDGEMENTS

Carneiro, J.R.G., and the authors would like to thank the financial support of grant n° 2016/308964-0, Brazil Conselho Nacional de Pesquisa CNPq and CAPES.

6. REFERENCES

Arbizu, I. P., Pérez, C. J. L., 2003. “Surface roughness prediction by factorial design of experiments in turning processes”. *Journal of Materials Processing Technology*, Vol. 143-144, pp. 390-396.

Asilturk, I., Neseli, S., 2012. “Multi response optimization of CNC turning parameters via Taguchi method-based response surface analysis”. *Measurement*, Vol. 45, pp. 785-794.

Askeland, D., Wright, W. J., 2014. *Ciência e engenharia dos materiais*. Cengage Learning, São Paulo.

Berkani, S, Yallese, M. A., Boulanouar, L., Mabrouki, T., 2015. "Statistical analysis of AISI 304 austenitic stainless steel machining using Ti(C, N)/Al2O3/TiN CVD coated carbide tool". *International Journal of Industrial Engineering Computations*, Vol. 6, pp. 539-552.

Das, B., Roy, S., Rai, R. N., Saha, S. C., 2016. "Application of grey fuzzy logic for the optimization of CNC milling parameters for Al–4.5%Cu–TiC MMCs with multi-performance characteristics". *Engineering Science and Technology, an International Journal*, Vol. 19, No. 2, pp. 857-865.

Do, T. V., Hsu, Q. C., 2016. "Optimization of Minimum Quantity Lubricant Conditions and Cutting Parameters in Hard Milling of AISI H13 Steel". *Applied Sciences*. Vol 6, 83.

Ferraresi, D., 2011. *Usinagem dos Metais: fundamentos da usinagem dos metais*. Edgar Blucher, São Paulo.

Ghevariya, C.M., Bhatt J. K., Dave B.P., 2011 "Enhanced chrysene degradation by halotolerant Achromobacter xylosoxidans using Response Surface Methodology". *Bioresource Technology*, Vol. 102: 9668-9674.

Hintze, W., Steinbach, S., Susemihl, C., Kahler, F., 2018. "HPC-milling of WC-Co cemented carbides with PCD". *International Journal of Refractory Metals and Hard Materials*, Vol. 72, pp.126-134.

Kazlauskas, D., Jankauskas, V., Bendikiene, R., Keturakis, G., Macenaite, L., 2017. "Wear of cemented tungsten carbide (WC) router cutters during oak wood milling". *Mechanika*, Vol. 23, pp. 469-472.

Makadia, A. J., Nanavatiof, J. I., 2013. "Optimisation of machining parameters for turning operations based on response surface methodology". *Measurement*, Vol. 46, pp.1521-1529.

Montgomery, D. C., Runger, G.C., 2007. *Applied statistics and probability for engineers*. Hoboken, NJ, Wiley.

Moussa, N. B., Sidhom, H., Braham, C., 2012. "Numerical and experimental analysis of residual stress and plastic strain distributions in machined stainless steel". *International Journal of Mechanical Sciences*, Vol. 64, No 1, pp. 82-93.

Razavykia, A., Farahany, S., Yusof, N. M., 2015. "Evaluation of cutting force and surface roughness in the dry turning of Al-Mg2Si in-situ metal matrix composite inoculated with bismuth using DOE approach". *Measurement*, Vol. 76, pp. 170-182.

Rodrigues, A. R., Matsumoto, H., Yamakami, W. J., Paulo, R. G. da R., Assis, C. L. F., 2010. "Effects of milling condition on the surface integrity of hot forged steel". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 32, No.1, pp. 37-43.

Sarnobat, S. S., Raval, H. K., 2019. "Experimental investigation and analysis of the influence of tool edge geometry and work piece hardness on surface residual stresses, surface roughness and work-hardening in hard turning of AISI D2 steel". *Measurement*, Vol. 131, pp. 235-260.

Tanikić, D., & Marinković, V., 2012. "Modelling and optimization of the surface roughness in the dry turning of the cold rolled alloyed steel using regression analysis". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 34, No. 1, pp. 41-48.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.