Experimental Numerical Model of Roughness in Finishing Face Milling of AISI 4140 Hardened Steel

Marco Stipkovic Filho, Marco Antônio Stipkovic, Éd Cláudio Bordinassi, Sérgio Delijaicov and Sérgio Luis Rabelo de Almeida

Abstract This work is based on the roughness analysis of a hardened steel, AISI 4140 quenched and tempered with 58HRC, during an end milling process executed with a CBN (cubic boron nitride) tool, obtained by varying three basic cutting parameters (cutting speed, feed and cutting depth). It was decided for the experimental planning, to use a central composite design, widely applied in research related to machining experiments. The results were statistically processed by the software "Statistica", enabling the generation of a mathematical equation to predicted the surface roughness value due to the optimization of the three cutting parameters adopted. The surface roughness results are in the range of 0.16–0.4 R_a. Two numerical models were created using the NLREG software confirming the interaction of the cutting parameters with the roughness. The cutting parameter with the most influence on the surface integrity during the end milling process was the feed per tooth.

M.S. Filho (✉) · S.L.R. de Almeida
Escola de Engenharia, Universidade Presbiteriana Mackenzie, Rua Da Consolação, 930, 01302-090 São Paulo, SP, Brasil
e-mail: mstip@uol.com.br

S.L.R. de Almeida
e-mail: slrabelo@terra.com.br

M.A. Stipkovic · É.C. Bordinassi · S.L.R. de Almeida
Instituto Maua de Tecnologia, Centro Universitário, 01–09580.900 São Caetano Do Sul, SP, Brasil
e-mail: marco.stipkovic@schuler.com

É.C. Bordinassi
e-mail: ecb@maua.br

M.A. Stipkovic · É.C. Bordinassi · S. Delijaicov
Faculdade de Engenharia Industrial, Centro Universitário, 3972–09850.901 São Bernardo Do Campo, SP, Brasil
e-mail: sergiode@fei.edu.br

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1 Introduction

Development of a numerical model able to predict the value of roughness in machining AISI 4140 hardened steel according to the main cutting parameters and thus help to assist the machinist in the correct selection of these parameters.

Given the constant search to reduce manufacturing costs of mechanical components in the segment of machinery and equipment, there is a growing tendency to replace the grinding process hardened steel (in the range 45–65 HRC), by turning and milling processes and with cubic boron nitride CBN tools.

2 Materials and Methods

The material used was a wrought AISI 4140 steel.

It was quenched and tempered with a hardness of 58 ± 2 HRC and a depth of 3 ± 1 mm with the following chemical composition attested by trial: C-0.413; Mn-0.842; Si-0.241; P-0.013; S-0.012; Cr-0.904; Ni-0.045; Mo-0.181; Al-0.030; Cu-0.063; Ti-0.002; V-0.004.

The specimens were of prismatic format with 140 × 110 × 20 mm previously roughed, according to Fig. 1.

The tool used was a face milling head with ϕ63 mm provided with 5 cutting edges in a straight path through the center of the part and the whole diameter in touch and no refrigerant. The insert code CBN used was R245 12T3 E CB50. Figure 2 shows one specimen during the end milling process.

The milling machine employed was manufactured by Sanches Blanes, model FU-1, ISO cone 40, with a maximum rotation of 6000 rpm and V_{fmax} = 1500 mm/min with good rigidity.

The cutting parameters were chosen with the intent to explore the limits of the CBN tool, representing a wide variation of 400% per cutting parameter.

The statistical analysis was performed based on a composed central design. It fits very well to machining tests, due to the good repeatability in relation to the cutting parameters and concentrates the necessity of some replicas only in the central points to assure the stability of the process.

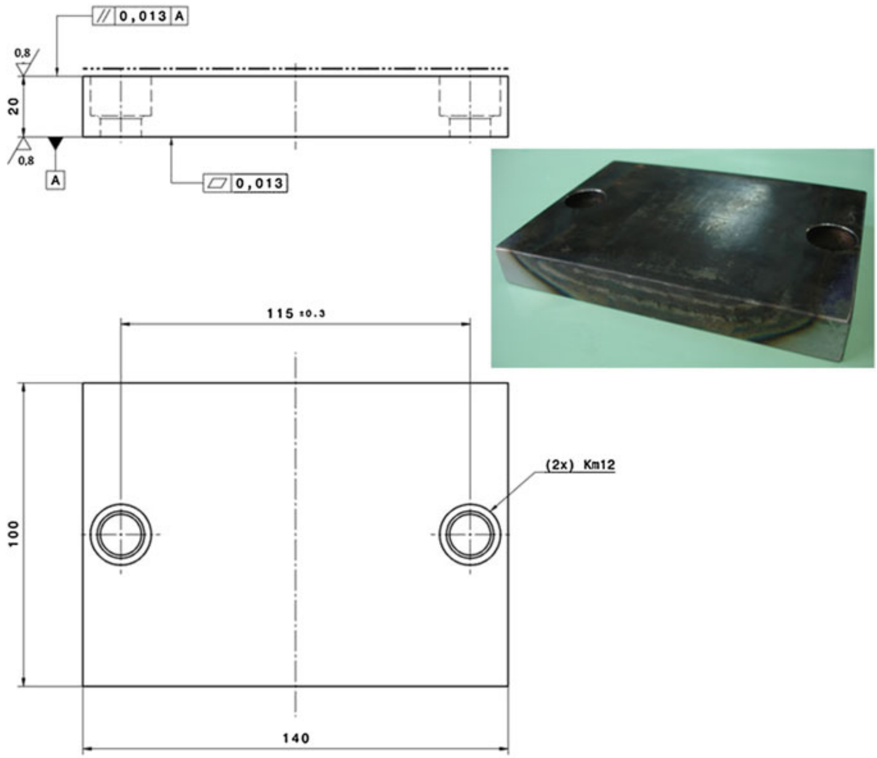

Fig. 1 Specimen's drawing and photo of wrought AISI 4140

Table 1 gives a clear vision of the cutting parameters variation and the defined central point at the cutting speed $\boldsymbol{V_c}$ of 225 m/min, feed per tooth $\boldsymbol{f_z}$ of 0.1 mm/rev and depth penetration $\boldsymbol{a_p}$ of 0.15 mm to confirm process repeatability.

Specimens' roughnesses were measured with a portable Mitutoyo rugosimeter model SJ-301, adjusted to a cut off length of 0.8 mm. Roughness measures were displaced in the feeding direction. For each point, the roughness adopted was an arithmetic mean of three consecutive measures. Figure 3 illustrates the equipment measuring one specimen.

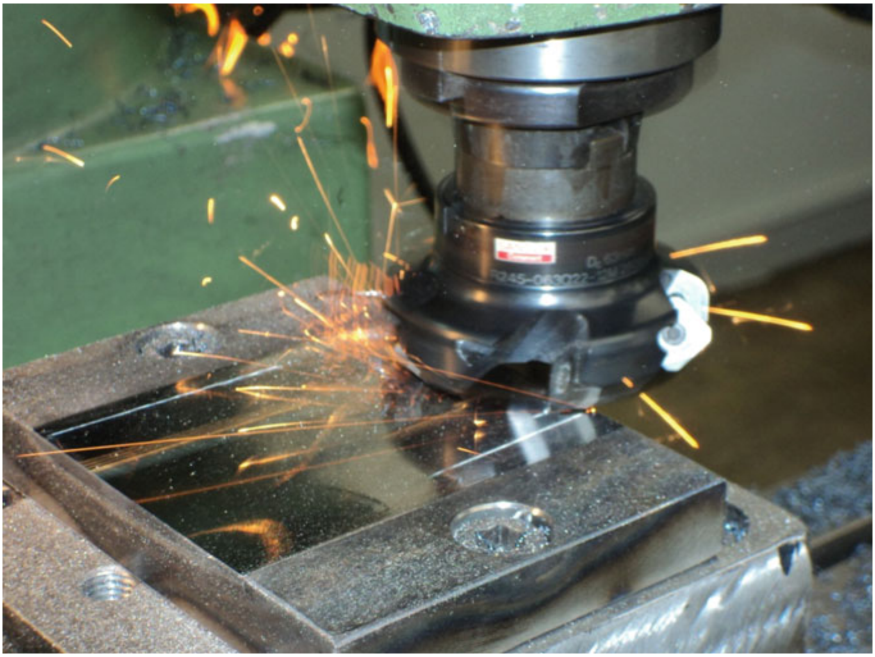

Fig. 2 Specimen during end milling machining

Table 1 Defined cutting parameters by the use of an experimental composed central design (CCD)

Test	V_c (m/min)	f_z (mm/rev)	a_p (mm)
1	150	0.05	0.1
2	150	0.05	0.2
3	150	0.15	0.1
4	150	0.15	0.2
5	300	0.05	0.1
6	300	0.05	0.2
7	300	0.15	0.1
8	300	0.15	0.2
9	98.9	0.1	0.15
10	351.1	0.1	0.15
11	225	0.016	0.15
12	225	0.187	0.15
13	225	0.1	0.07
14	225	0.1	0.23
15	225	0.1	0.15
16	225	0.1	0.15
17	225	0.1	0.15
18	225	0.1	0.15
19	225	0.1	0.15
20	225	0.1	0.15

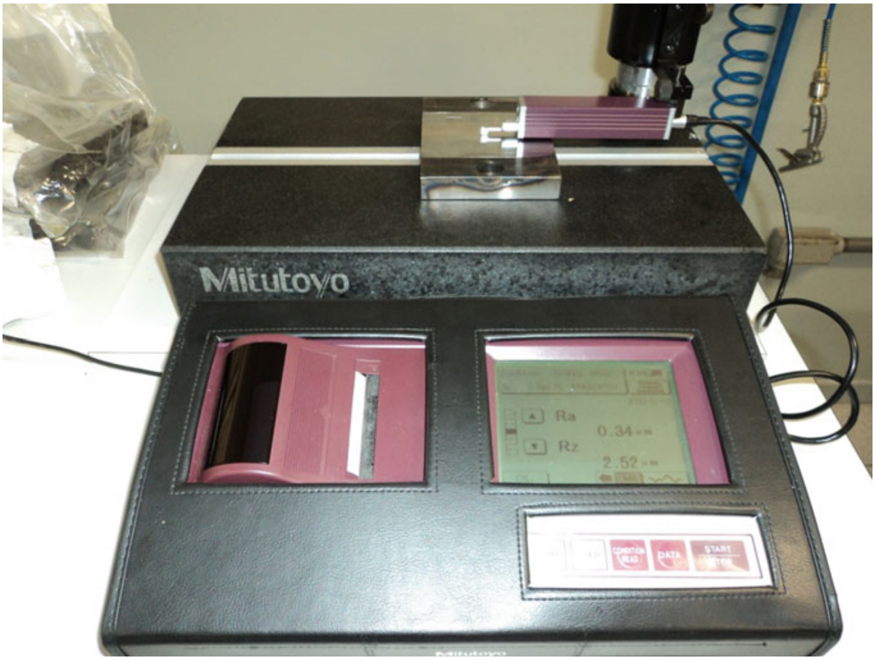

Fig. 3 Roughness tester Mitutoyo SJ-301 used to measure specimens roughness

3 Results

The roughness values obtained for the various tests revealed an appropriate roughness for finish machining processes, with an R_a ranging from 0.16 to 0.41 μm illustrated in Table 2.

The data was analyzed using the STATISTICA statistics software with a 95% confidence level. The roughness R^2 correlation factor was 0.81 and 0.64 R^2_{aj}.

The roughness was influenced by two of the three studied cutting parameters, the feed per tooth $\boldsymbol{f_z}$ (most representative) and the depth $\boldsymbol{a}_p$. Figure 4 shows the relevance of the feed per tooth in comparison with others cutting parameters and their interactions.

The influence of feed in the surface roughness was evident through the graphics showed in Fig. 5, indicating the behavior of the feed as a function of cutting speed ($\boldsymbol{f_z}$ **x** $\boldsymbol{V_c}$), and the feed as the function of depth of cut ($\boldsymbol{f_z}$ x $\boldsymbol{a_p}$).

Numerical Model 1

A non-linear regression was performed using the NLREG software, with the equation of form (Fig. 6):

Table 2 Roughness measurements with different cutting parameters

Cutting parameters—End milling (AISI 4140, Hardened)				
	Cutting speed	Feed per tooth	Depth penetration	Roughness
Exp.	V_c (m/min)	f_z (mm/rev)	a_p (mm)	R_a (μm)
1	150	0.05	0.1	0.18
2	150	0.05	0.2	0.19
3	150	0.15	0.1	0.22
4	150	0.15	0.2	0.41
5	300	0.05	0.1	0.19
6	300	0.05	0.2	0.25
7	300	0.15	0.1	0.25
8	300	0.15	0.2	0.29
9	98.9	0.1	0.15	0.3
10	351.1	0.1	0.15	0.19
11	225	0.016	0.15	0.16
12	225	0.187	0.15	0.3
13	225	0.1	0.07	0.2
14	225	0.1	0.23	0.25
15	225	0.1	0.15	0.21
16	225	0.1	0.15	0.24
17	225	0.1	0.15	0.25
18	225	0.1	0.15	0.23
19	225	0.1	0.15	0.22
20	225	0.1	0.15	0.23

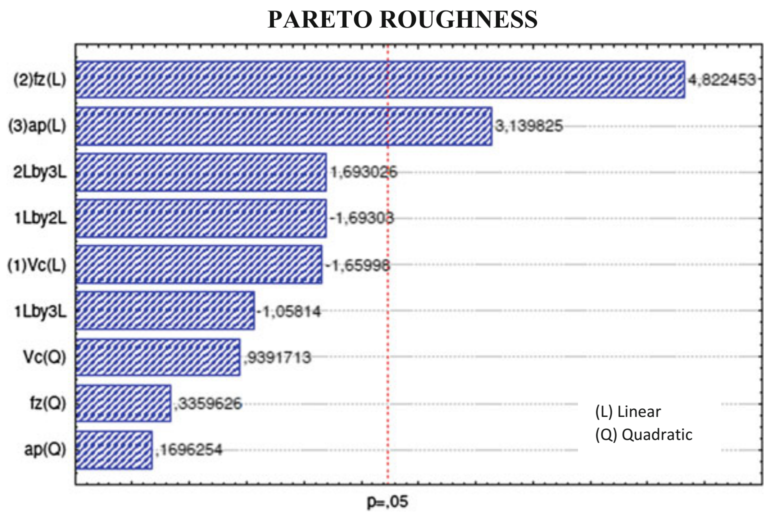

Fig. 4 Pareto diagram of cutting parameters influence on surface roughness

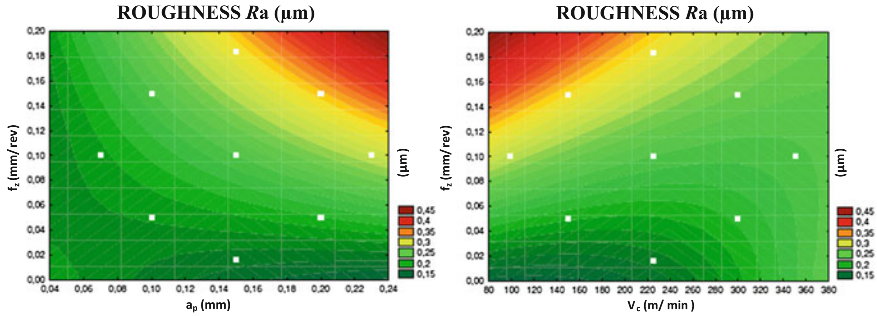

Fig. 5 Roughness graphics ($\boldsymbol{a_p}$ x $\boldsymbol{f_z}$) with $\boldsymbol{V_c}$ = 225 m/min and ($\boldsymbol{f_z}$ x $\boldsymbol{V_c}$) with a_p = 0.15 mm

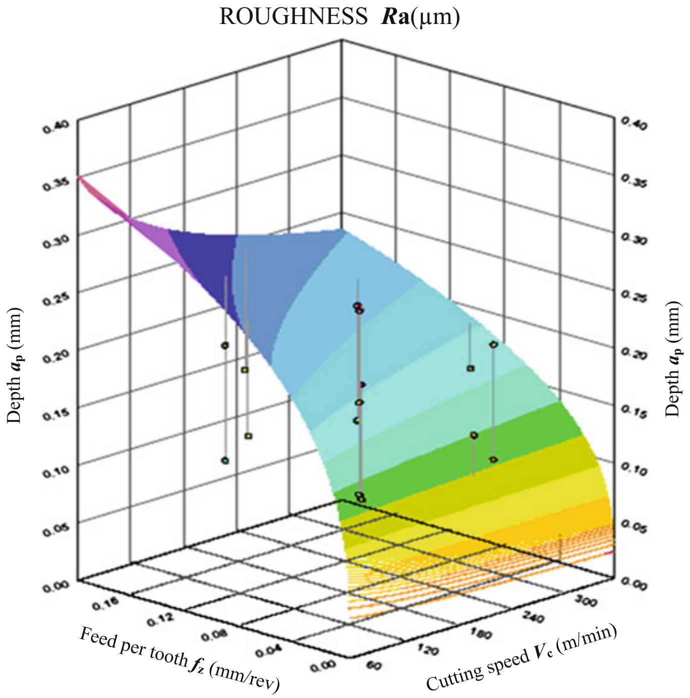

Fig. 6 Model 1, NLREG graphic, non linear regression of roughness based on cutting parameters $\boldsymbol{a_p}$, $\boldsymbol{f_z}$ e $\boldsymbol{V_c}$

$$Ra = k \cdot v_c^a \cdot f_z^b \cdot a_p^c \quad (1)$$

As a result, the following equations were obtained:

$$Ra = 3.48 \cdot V_c^{-0.228} \cdot F_z^{0.320} \cdot A_p^{0.373} \quad (2)$$

$$R^2 = 69.44\% \left(R_{aj}^2 = 63.7\%\right) \quad (3)$$

Numerical Model 2

A linear regression was performed, using the NLREG software, with an equation of the form (Fig. 7):behavior of the feed as a function

$$Ra = a \cdot V_c + b \cdot f_z + c \cdot a_p + k \quad (4)$$

As a result, the following equation was obtained:

$$Ra = -0.002 \cdot V_c + 0.872 \cdot f_z + 0.579 \cdot a_p + 0.1089 \quad (5)$$

$$R^2 \text{de } 66.8\% \left(R_{aj}^2 = 60.1\%\right) \quad (6)$$

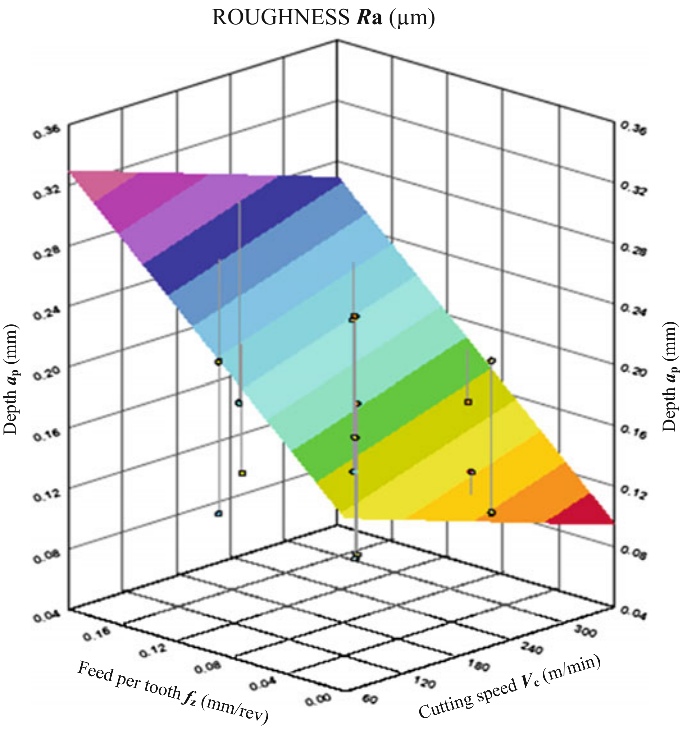

Fig. 7 Model 2, NLREG graphic, linear regression of roughness based on cutting parameters a_p, f_z e V_c

4 Conclusions

The roughness Ra values ranged from 0.16 to 0.41 μm.

The roughness interacted with the feed per tooth and the depth of penetration, so that greater feeds combined with greater depths of cut generated poorer surface finish.

Very low cutting speeds damaged the surface.

The milling machines used have demonstrated sufficient structural rigidity to not influence the roughness results within the range of the cutting parameters adopted.

It was possible to establish a numerical model relating, feed per tooth f_z, depth of cut $\boldsymbol{a}_{\mathbf{p}}$ and cutting speed $\boldsymbol{V}_{\mathbf{c}}$, with the roughness through a non-linear and linear regression.

Based on the results obtained, it can be said that the finishing milling of hardened steels with CBN tool without the presence of lubricant, generates a surface finish as good as those found by the grinding process, with the advantage of being faster and less aggressive to the environment by eliminating the refrigerant.

References

1. Souza MS, Lauro CH, Brandão LC (2010) Análise de rugosidade em função da velocidade de avanço em operações de torneamento, *VI CONEM*
2. Lahiff C, Gordon S, Phelan P (2007) PCBN tool wear modes and mechanisms in finish hard turning. Robot Comput-Integr Manuf 23:638–644
3. Gaurav B, Choudhury SK (2012) State of the art in hard turning. Int J Mach Tools Manuf 53:1–14
4. Diniz A, Marcondes FC, Coppini NL (2001) Tecnologia da usinagem dos materiais, 3rd edn. Artliber Editora, São Paulo
5. Batalha GF, Rossi GC, Kanenobu AA (2005) Relação entre os parâmetros de corte e a rugosidade da superfície usinada numa operação de fresamento de topo. 3° Congresso Brasileiro de Engenharia de Fabricação, vol 3. Joinville, pp 1–10