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OPTIMIZATION OF A HARD TURNING PROCESS USING WIPER GEOMETRY TOOL BY NORMAL BOUNDARY INTERSECTION

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ABSTRACT

Conventional factors influence analysis, in a machining process, is usually done studying the effect of each one separately. In this context, arises the Normal Boundary Intersection (NBI), which is a statistical technique that allows the simultaneous analysis of several influence factors in a process. This statistical approach consists of planning experiments, which are able to generate appropriate data for effective analysis, resulting in valid and objective conclusions. This paper specifically addresses the modeling of the surface roughness parameters (Ra) and the tool life (T) in the AISI H13 (54 HRC) hardened steel turning process, by using a ceramic tool coated with titanium nitride. The models were obtained by the Design of Experiments methodology, using the following parameters: cutting speed, feed rate and depth of cut, as the influence variables. Thus, a brief analysis of the process quality and productivity were done by NBI method.

Keywords: hard turning, cutting tools, Normal Boundary Intersection (NBI).

INTRODUCTION

The increase demand of machining precision, accuracy and precision and the large variety of workpieces material available interfere on the competitiveness of the machining industry. An improvement can only be achieved if were a set of references for designing a machining process for a range of products [1, 2]. Thus, hard turning can be seen like a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surfaces [1]. Machining processes, such as hard turning, have multiple responses with conflicting objectives. This fact characterizes hard turning like a multiobjective optimization problem (MOP) [4]. The purpose is to find a combination of the responses that satisfies, at the same time, the objective functions and the constraints and provides an acceptable value for each response [5]. MOP´s can be solved by applying techniques like the Normal Boundary Intersection (NBI) method. The NBI method is an optimization routine developed to find a uniformly spread Pareto-optimal solutions for linear and nonlinear MOP´s [4, 5].

TEORETHICAL FUNDAMENTALS

The Normal Boundary Intersection method was developed by Das and Dennis (1998) for finding a uniformly spread Pareto-optimal solutions for a general nonlinear multi-objective optimization problem.

The establishment of payoff matrix $\overline{\mathbf{\Phi}}$ is the first step in the NBI method given by the calculation of the minimum $f_i^*(x_i^*)$ and maximum $f_i\ (x_i^*)$ values of the i-th objective function $f_i\ (x)$. The payoff matrix $\overline{\mathbf{\Phi}}$ can be written as:

$$\Phi = \begin{bmatrix} f_1^*(x_1^*) & \cdots & f_1\ (x_i^*) & \cdots & f_1\ (x_m^*) \\ \vdots & \ddots & & & \vdots \\ f_i\ (x_1^*) & \cdots & f_i^*(x_i^*) & \cdots & f_i\ (x_m^*) \\ \vdots & & & \ddots & \vdots \\ f_m(x_1^*) & \cdots & f_m(x_i^*) & \cdots & f_m^*(x_m^*) \end{bmatrix} \tag{1}$$

The objective functions can be normalized by using $f_i^*(x_i^*)$ and $f_i\ (x_i^*)$ values, mostly when different scales or units are used to define them. A vector with the set of individual minimum can be written such as $f^U = \left[f_1^*(x_1^*)\ \ \ldots,\ \ f_i^*(x_i^*)\ \ \ldots,\ \ f_m^*(x_m^*)\right]^T$, to obtain the Utopia point $f_i^*(x_i^*)$. This specific point is generally outside of the feasible region that corresponds to all objectives simultaneously being at their best possible values. The Nadir point $f_i\ (x_i^*)$, likewise, is obtained by joining the maximum values of each objective function $f^N = \left[f_1^N\ \ \ldots,\ \ f_i^N\ \ \ldots,\ \ f_m^N\right]^T$. It is the design space where all objectives are simultaneously at their worst values. When the i-th objective is minimized independently the two anchor points are obtained, and the Utopia line is the one that connects them.

The normalization of the objective functions can be obtained using these two sets, as in:

$$\bar{f}(x) = \frac{f_i(x) - f_i^U}{f_i^N - f_i^U}, i = 1, \ldots, m \tag{2}$$

This normalization leads to scalarization of the payoff matrix $\overline{\mathbf{\Phi}}$ and the vector $\overline{\mathbf{F}}(\mathbf{x})$. Associated to vector of weights $\boldsymbol{\beta}$ and an unitary normal vector $\hat{\mathbf{n}}$, the classical NBI formulation can be described as:

$$\begin{aligned} &\underset{(\mathbf{x},t)}{Max}\ D \\ &S.t:\ \overline{\mathbf{\Phi}}\boldsymbol{\beta} + D\hat{\mathbf{n}} = \overline{\mathbf{F}}(\mathbf{x}) \\ &\qquad \mathbf{x} \in \Omega \\ &\qquad g_j(x) \le 0 \\ &\qquad h_j(x) \le 0 \end{aligned}$$

This optimization problem must be solved for different values of w, which will lead to the construction of the Pareto frontier.

EXPERIMENTAL PROCEDURE

The workpiece material was ABNT steel H13 with a hardness of approximately 54 HRC. The chemical composition of this steel includes the following: C (0.370-0.420%); Mn (0.200-0.500%); Si (0.080-0.120%); Cr (0.050-0.055%); V (0.080-0.012%) and Mo (0.012-0.017%).

The turning experiments were conducted on a turning center MHP Kingsbury, with 18 kW power and maximum rotation of 4500 rpm, and the tool used was a CC6050 Wiper.

A sequential set of 19 experimental runs was established using a central composite design (CCD) with three input parameters: cutting speed (v_c), feed rate (f) and depth of cut (a_p). Table 1 shows the experimental planning levels. The design of experiments is show in Table 2.

Table 1 - Cutting parameters and respective levels.

Cutting parameters	**Levels (Uncoded and Coded)**				
	-2	**-1**	**0**	**1**	**2**
Cutting speed (v_c, m/min)	57.39	100	162.5	225	267.61
Feed rate (f, mm/rev)	0.06	0.10	0.16	0.22	0.26
Axial depth of cut (a_p, mm)	0.09	0.15	0.24	0.33	0.39

Table 2 - Experimental design.

N° Exp.	**v_c**	**f**	**a_p**	**T**	**R_a**
1	100.00	0.10	0.15	62.0	0.13
2	225.00	0.10	0.15	33.0	0.11
3	100.00	0.22	0.15	52.0	0.41
4	225.00	0.22	0.15	30.5	0.72
5	100.00	0.10	0.33	63.0	0.34
6	225.00	0.10	0.33	30.0	0.09
7	100.00	0.22	0.33	52.0	0.08
8	225.00	0.22	0.33	28.5	0.42
9	57.39	0.16	0.24	59.0	0.22
10	267.61	0.16	0.24	24.5	0.29
11	162.50	0.06	0.24	39.0	0.13
12	162.50	0.26	0.24	40.3	0.49
13	162.50	0.16	0.09	51.0	0.22
14	162.50	0.16	0.39	47.5	0.12
15	162.50	0.16	0.24	43.5	0.47
16	162.50	0.16	0.24	43.0	0.49
17	162.50	0.16	0.24	44.5	0.49
18	162.50	0.16	0.24	44.0	0.48
19	162.50	0.16	0.24	45.0	0.47

RESULTS

Modeling of the dry end milling process

To analyze the influence of the turning input parameters on the measured responses, the second-order polynomial models were developed using RSM, the responses coefficients are presented in Table 3.

Table 3 - Quadratic models for responses and ANOVA.

Coeficient	T	Ra
Constant	43.986	0.478
v_c	-12.083	0.036
F	-1.677	0.115
a_p	-0.724	-0.045
v_c^2	-0.718	-0.067
f^2	-1.470	-0.048
a_p^2	1.933	-0.098
$v_c.f$	2.125	0.115
$v_c.a_p$	-0.750	-0.025
$f.a_p$	0.000	-0.103
Adj.R^2 (%)	93.170	92.240
Regression p-value	0.000	0.000
Normality (AD) test	0.225	0.748
Normality (AD) p-value	0.687	0.042

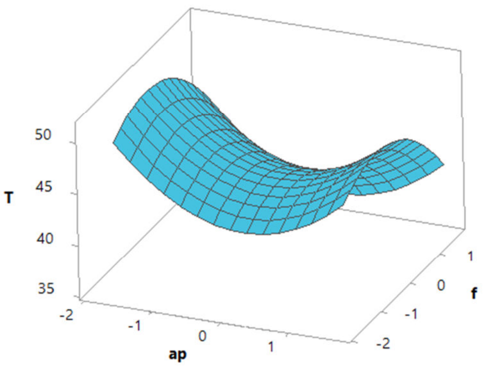
Table 3 also shows the ANOVA results for the responses. Both have p-values less than 5% of significance and an adjustment with adj. R^2 higher than 90% and no lack of fit. These results indicate that all expressions are adequate for full quadratic models.

The objective functions relating the input parameters with the responses, can be written as:

$$T = 43.990 - 12.083_{vc} - 1.677_{f} - 0{,}724_{ap} - 0.718_{vc^2} - 1.470_{f^2} + 1.933_{ap^2} + 2.130_{vc*f} - 0.750_{vc*ap} + 0.000_{f*ap} \quad (1)$$

$$Ra = 0.477 + 0.036_{vc} + 0.114_{f} - 0{,}044_{ap} - 0.067_{vc^2} - 0.048_{f^2} - 0.097_{ap^2} + 0.115_{vc*f} - 0.250_{vc*ap} - 0.102_{f*ap} \quad (2)$$

Figure 1 shows the response surface graphics for analyzed characteristics.



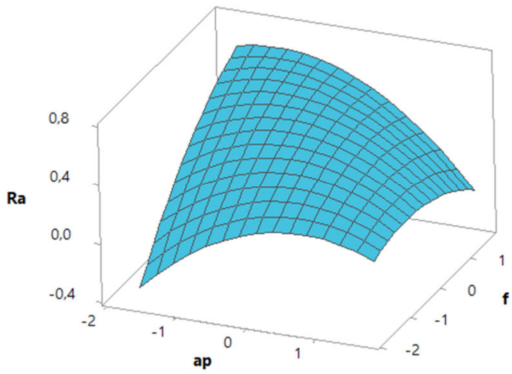


Fig. 1 - Response surfaces for T and Ra.

Optimization by NBI

The Payoff matrix $\overline{\mathbf{\Phi}}$ were established by Utopia and Nadir points for both responses, given by individual constraint maximization (for T) and individual constraint minimization (for Ra), and for this case it can be written as:

$$\Phi = \begin{bmatrix} 0.013 & 0.276 \\ 36.148 & 63.753 \end{bmatrix}$$

Table 4 presents the optimization results from NBI method.

Table 4 - Optimization results.

w	v_c	f	a_p	T	Ra
0.00	62.897	0.130	0.254	63.753	0.276
0.05	61.106	0.137	0.224	63.502	0.252
0.10	70.736	0.126	0.188	62.901	0.232
0.15	75.730	0.131	0.168	62.329	0.211
0.20	84.524	0.127	0.152	61.558	0.192
0.25	93.060	0.122	0.142	60.676	0.174
0.30	101.167	0.118	0.135	59.694	0.157
0.35	108.886	0.114	0.131	58.620	0.141
0.40	116.261	0.109	0.128	57.461	0.126
0.45	123.399	0.106	0.126	56.220	0.112
0.50	**130.350**	**0.102**	**0.125**	**54.898**	**0.098**
0.55	137.160	0.099	0.125	53.497	0.085
0.60	143.887	0.096	0.126	52.014	0.073
0.65	150.571	0.092	0.128	50.447	0.061
0.70	157.281	0.090	0.131	48.790	0.051
0.75	164.005	0.087	0.135	47.036	0.041
0.80	170.857	0.085	0.139	45.175	0.033
0.85	177.861	0.082	0.144	43.190	0.025
0.90	185.176	0.081	0.151	41.057	0.019
0.95	192.894	0.079	0.159	38.734	0.015
1.00	201.347	0.078	0.169	36.148	0.014

Note: The values in bold represent the optimal values obtained by global optimization.

The Pareto Frontier with 21 optimal responses are shown in Fig. 2. The optimal solution was calculated by Entropy/EPG criterion [7].

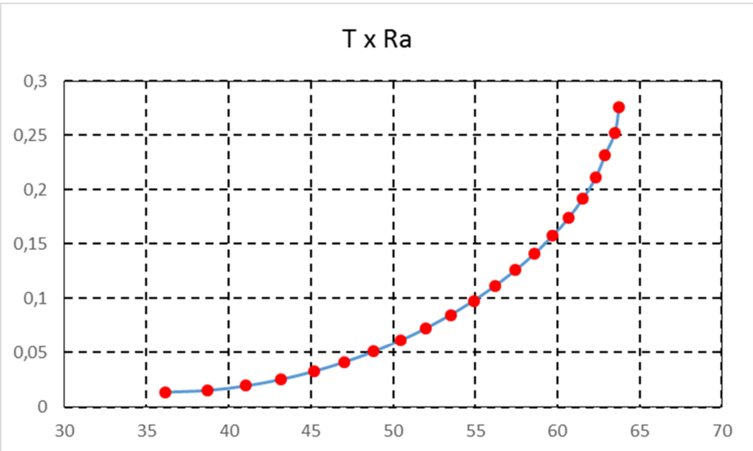


Fig. 2 - Pareto Frontier obtained for NBI method.

This result show that NBI method can find a combination of solutions for the problem. In this case, the best solution was when the entry parameters have the following values: cutting speed is 130 m/min, feed rate 0.102 mm/rev and depth of cut 0.125 mm, it leaves to a tool life 54.90 min and a Ra equal to 0.10 µm.

CONCLUSIONS

This work applies the NBI method to a turning process of H13 steel and is possible to reach some conclusions:

The numerical results indicate that the solution found by NBI method was characterized as appropriate optimal point.

Tool life is maximum and Ra is minimum, at v_c =130 m/min, f = 0.102 mm/rev and a_p = 0.125 mm.

This optimization shall provide a great assistance to engineers to identify a set of optimal solutions that matches the needs of the organization.

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