MODELING OF CUTTING FORCES IN BALL-END MILLING PROCESS OF HARD (HARDENED) STEEL BY USING RESPONSE SURFACE METHODOLOGY

Received: 06 September 2017 / Accepted: 02 November 2017

Abstract: The possibility of modeling the cutting forces provides an analytical basis for the planning of the machining process, for the construction of machine tool, the optimization of cutting tool geometry as well as on-line monitoring and process management. The planning and execution of the experiment was carried out on the basis of the rotatable central composite design-RCCD here for the input independent parameters the cutting speed was selected, i.e. the spindle speed (n), the feed per tooth (f_z), the axial (a_p) and radial (a_e) depth of cut. Cutting forces (F_x, F_y, F_z) and the resultant cutting force (F_R) for the responsive variables are selected. Using the RSM methodology, reliable mathematical models for cutting forces in the form of quadratic polynomials were obtained.

Key words: Modeling, Cutting Forces, Response Surface Methodology, Hard (Hardened) Steel, Ball-End Milling

Razvoj modela za sile rezanja korištenjem metodologije odzivne površine pri glodanju tvrdih čelika vretenastim loptastim glodalima. Mogućnost modelovanja sila rezanja daje analitičku osnovu za planiranje procesa obrade, za konstrukciju mašina alati, optimizaciju rezne geometrije alata, kao i on-line praćenje i upravljanje procesom. Planiranje i izvođenje eksperimenta je realizovano na osnovu rotirajućeg centralnog kompozitnog plana eksperimenata, gde su za ulazne nezavisne parametre izabrani brzina rezanja, odnosno broj obrtaja alata (n), pomak po zubu (f_z), dubina rezanja (a_p) i širina rezanja (a_e). Za odzivne promenljive su izabrane komponente sila rezanja (F_x, F_y, F_z) i rezultujuća sila rezanja (F_R). Korištenjem metodologije odzivne površine (RSM) dobijeni su pouzdani matematički modeli za sile rezanja u obliku kvadratnog polinoma.

Ključne reči: Modelovanje, Sile rezanja, Metodologija odzivne površine, Tvrdi (kaljeni) čelik, Glodanje vretenastim loptastim glodalima

1. INTRODUCTION

The field of application of modeling processing operations is extremely wide, as there are many different operations. For each operation, from different aspects, models may also be required from several different modeling techniques. The primary goal of modeling processing operations is to develop predictable processing performance capabilities in order to facilitate the effective planning of processing operations to achieve optimum productivity, quality and costs [1]. The cutting forces modeling are performed by using empirical, analytical, mechanistic, numerical and AI-based methods. At the moment, the analytical and mechanistic approach is most often used because of its speed and precision. In the future, these models are expected to be developed for new engineering materials, advanced geometry of tools and coatings. Milling is a mechanical processing operation where the tool has one or more teeth. In this era of globalization, milling is becoming popular because of its characteristics such as maximum productivity, minimal processing costs, and good quality of the treated surface. End milling with ball end mills plays an important role in three-dimensional machining, because it has the ability to easily handle three-dimensional curves. While the curved surface is milled, the tangential cutting speed is minimal (equal to zero) at the top of the ball, because of the rotation the tool radius is zero. The maximum radius value is on the

periphery of a ball end mill. Changing the cutting speed along the blade causes the change in the cutting forces along the three-dimensional blade. This is the main difference between milling with end mills and ball-end mills. End milling with ball-end mills is commonly used in industry for the production of parts with a complicated free surface shape. These parts are very often made of hardened steel, and the process itself is carried out under conditions of high-speed processing.

2. RESPONSE SURFACE METHODOLOGY

Response Surface Methodology (RSM) is a set of statistical and mathematical methods that are useful for modeling and optimization engineering scientific problems. A measurable output performance of a process is called a response. The response is the measurable size of the processing process (the dependent variable size being tested). In this technique, the main goal is to optimization responses that are influenced by different input parameters of the machining. RSM also quantifies the relationship between the manageable input parameters and the received responses, or attempts to analyze the effect of independent variables on a specific dependent - response. In modeling and optimization manufacturing processes using RSM, it is enough to collect data using carefully designed experiments.

2.1 Response function

In the process of modeling the output performance of the process, it starts from the fact that the response function is unknown and it is approximated by the first-order polynomial:

$$\hat{y} = b_0x_0 + \sum_{i=1}^k b_ix_i + \varepsilon \quad (1)$$

If it turns out that the first-order model is inadequate, then a model with interactions is analyzed:

$$\hat{y} = b_0x_0 + \sum_{i=1}^k b_ix_i + \sum_{i<j}^k b_{ij}x_ix_j + \varepsilon \quad (2)$$

In case that this model is not adequate too, it continues with the approximation of the response function in the form of a second-order polynomial:

$$\hat{y} = b_0x_0 + \sum_{i=1}^k b_ix_i + \sum_{i=1}^k b_{ii}x_i^2 + \sum_{i=1}^k \sum_{j>i}^k b_{ij}x_ix_j \pm \varepsilon \quad (3)$$

where:

- $\hat{y}$ – predicted system response
- k – number of factors
- b_0 – segment
- b_i – coefficient of tested factors
- b_{ij} – coefficient of factor interactions
- b_{ii} – coefficients of the squares of the tested factors effects
- ε – residual.

3. CUTTING FORCES

Based on the cutting forces that occurs in the milling process, it is possible to directly or indirectly evaluate the output performance of the process, such as the wear and tool life, the surface roughness, etc. The ability to model the cutting forces provides an analytical basis for planning the process, for machine tool construction, optimization cutting tool geometry, as well as on-line tracking and process management. Determining the cutting forces is often difficult due to the complexity of the process and the geometry of the cutting tool. Analytical determination of the cutting forces is difficult due to the large number of connected cutting parameters. A large number of connected cutting parameters that affect cutting forces (cutting speed, feed, cutting depth, cutting tool geometry, tool wear, physical and chemical properties of the workpiece, etc. make the finding of an appropriate model extremely difficult [2].

Below is a review of the significant results of previous research in the field of modeling of cutting forces in milling with ball end mills.

Yang and Park [3] developed a model for the prediction of the cutting forces based on the analysis of the cutting geometry of the ball end mills. The cutting edge of the ball end mills is observed as a series of infinite elements and the geometry of each cutting edge element is considered to be true. The slice cutting process is analyzed as an orthogonal cutting process in a level that contains cutting speeds and chips. Orthogonal cutting data were obtained from experiments in the scratching of thin-walled tubes.

Lee and Altintas [4], on the basis of orthogonal

cutting experiments, including the end ball mills geometry and kinematics, determined with great accuracy the cutting forces in three orthogonal directions. The geometry of the mill is modeled analytically.

Milfelner and others [2] developed an equation for the calculation of maximum cutting force in the end ball milling using genetic programming. The developed intelligent model of maximum cutting force in axial depth, radial depth, feed per tooth and cutting speed showed good match of calculated values with experimental data.

4. EXPERIMENTAL PROCEDURES AND RESULTS

4.1 Experimental procedures

The experimental work was carried out at the company "ELMETAL" doo in Senta (Serbia). The experiments were conducted on vertical machining center type "HAAS VF-3YT" in dry condition, using a carbide coated (TiAlN-T3) ball-end mill with Ø6 mm diameter ("EMUGE FRANKEN" type 1877A). All experiments were carried out using hardened steel X210CR12 (Č4150) with hardness 58 HRC by orthogonal arrays with five levels (coded by: -2, -1, 0, 1 and 2), Table 1. The arrangement of workpiece preparation is shown in Fig. 1.

Fig. 1. Workpiece arrangement

Sym	Parameters	Levels				
		-2	-1	0	1	2
A	Spindle speed, n (min ⁻¹)	3981	4777	5573	6369	7169
B	Feed per tooth, f _z (mm/tooth)	0,018	0,024	0,030	0,036	0,042
C	Axial depth of cut, a _p (mm)	0,04	0,08	0,12	0,16	0,20
D	Radial depth of cut, a _e (mm)	0,20	0,40	0,60	0,80	1,00

Table 1. Machining parameters and their levels

4.2 The results

Experimental researches were first performed according to the central compositional plan and under the conditions described in the previous section. The measurement results for the central composite four-factor plan are shown in Table 2.

Ord. No.	Factor				Measurement results			
	n (min ⁻¹)	f _z (mm/z)	a _p (mm)	a _e (mm)	F _x (N)	F _y (N)	F _z (N)	F _R (N)
1	4777	0.024	0.08	0.40	41.02	38.52	50.04	65.24
2	6369	0.024	0.08	0.40	35.76	36.31	50.39	54.02
3	4777	0.036	0.08	0.40	45.42	37.91	53.51	67.94
4	6369	0.036	0.08	0.40	42.71	35.71	55.87	60.04
5	4777	0.024	0.16	0.40	65.56	46.32	65.32	96.06
6	6369	0.024	0.16	0.40	51.60	39.74	60.55	73.12
7	4777	0.036	0.16	0.40	77.49	53.75	69.44	110.01
8	6369	0.036	0.16	0.40	67.96	45.06	66.78	89.23
9	4777	0.024	0.08	0.80	61.22	35.24	68.73	72.61
10	6369	0.024	0.08	0.80	53.43	31.66	70.53	72.09
11	4777	0.036	0.08	0.80	71.91	36.18	77.13	83.20
12	6369	0.036	0.08	0.80	68.78	37.81	73.21	77.53
13	4777	0.024	0.16	0.80	89.03	48.26	76.70	118.21
14	6369	0.024	0.16	0.80	69.30	37.40	67.08	88.33
15	4777	0.036	0.16	0.80	90.92	80.06	78.22	121.87
16	6369	0.036	0.16	0.80	68.27	36.70	68.93	89.25
17	5573	0.030	0.12	0.60	53.50	24.48	57.74	66.40
18	5573	0.030	0.12	0.60	73.83	29.71	71.25	89.09
19	5573	0.030	0.12	0.60	65.44	34.26	75.96	86.75
20	5573	0.030	0.12	0.60	49.17	35.20	78.25	81.25
21	3981	0.030	0.12	0.60	65.37	37.56	59.23	84.30
22	7166	0.030	0.12	0.60	55.96	36.19	57.87	75.67
23	5573	0.018	0.12	0.60	51.45	24.12	69.36	76.45
24	5573	0.042	0.12	0.60	67.24	38.63	77.44	90.74
25	5573	0.030	0.04	0.60	44.89	29.39	56.45	61.01
26	5573	0.030	0.20	0.60	114.69	55.03	89.12	126.00
27	5573	0.030	0.12	0.20	64.90	43.72	55.83	70.81
28	5573	0.030	0.12	1.00	166.67	56.04	84.16	170.52
29	5573	0.030	0.12	0.60	59.51	48.78	74.87	92.31
30	5573	0.030	0.12	0.60	62.27	49.88	80.64	91.12

Table 2. Experimental results

The display of a separate enlarged part of the diagram of the measured values of the cutting forces components for one experimental point is given in Diagram 1.

Diagram 1. Part of diagram of cutting forces

4.3 Mathematical models obtained using the response surface methodology (RSM)

For the statistical processing of experimental data, there are a lot of commercial software that greatly simplifies processing and data analysis. From the experiment planning software group, and for applying the response surface methodology, the Design-Expert v.7.0 software was used. In order to obtain reliable mathematical models based on the previously described procedures and experimental data obtained from the central compositional plan, the statistical processing and analysis was initiated. The significance of the model and the members of the response polynomial was determined by the analysis of the variance (ANOVA). After excluding minor members of the second degree polynomial, the variation analysis for the remaining members is given in Table 3:

Response 1 Fx					
ANOVA for Response Surface Reduced Quadratic Model					
Analysis of variance table [Partial sum of squares - Type III]					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	13448.18	5	2689.64	14.01	< 0.0001
A-n	447.03	1	447.03	2.33	0.1400
B-fz	401.15	1	401.15	2.09	0.1612
C-ap	3737.01	1	3737.01	19.47	0.0002
D-ae	5071.55	1	5071.55	26.42	< 0.0001
D^2	3791.43	1	3791.43	19.75	0.0002
Residual	4606.42	24	191.93		
Lack of Fit	4222.94	19	222.26	2.90	0.1210
Pure Error	383.49	5	76.70		
Cor Total	18054.60	29			

Tabela 3. Analysis of the variance for a reduced square model of cutting force F_x

After the analysis, the F_x force model in the form of a reduced square polynomial in the decoded form has the appearance:

$$F_x = 89.32 - 5.42 \cdot 10^{-3} n + 681.39 f_z + 311.96 a_p - 271.53 a_e + 286.84 a_e^2 \quad (4)$$

The resulting model can also be presented using a contour or 3D diagram, which can be seen in Diagram 2 or Diagram 3.

Diagram 2. Contour diagram of response surface for F_x cutting force

Diagram 3. 3D diagram of response surface for F_x cutting force

The same variance analysis methodology was also performed in the process of obtaining a model for cutting forces F_y , F_z i F_R :

$$F_y = -30.22 + 0.01n + 546.88f_z + 846.06a_p - 96.93a_e - 0.12na_p + 86.78a_e^2 \quad (5)$$

$$F_z = -185.19 + 0.067n + 346.60f_z + 362.73a_p + 82.20a_e - 398.05a_p a_e - 6.12 \cdot 10^{-6}n^2 \quad (6)$$

$$F_R = 91.54 - 7.79 \cdot 10^{-3}n + 610.90f_z + 378.53a_p - 168.50a_e + 193.69a_e^2 \quad (7)$$

The reliability of these models can be accomplished based on their relative deviation from the experimental data. The display is given in Table 4.

AVERAGE DEVIATION OF MODEL			
%			
F_x	F_y	F_z	F_R
11,98	13,86	5,51	10,13

Table 4. Relative deviation of the model from the experimental data

5. CONCLUSIONS

The structural form of mathematical models for the cutting forces F_x , F_y , F_z i F_R was determined by analysis of the second-order starting four-factor polynomial. Analysis of the ANOVA variance proved to be an excellent tool for determining the finite reduced structural forms of mathematical models by removing insignificant factors from the starting four-factor polynomials by "ejecting backwards". RSM has several advantages over conventional experimental methods. The first RSM offers a large amount of information from a small number of experiments. Second, in RSM it is possible to observe the interactive effect of independent parameters on the response. In addition, to obtain process information, an empirical model is used, which links the response to an independent variable. By analyzing the relative deviation of the model from the experimental results, a very good reliability of the obtained models can be established.

6. REFERENCE

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