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MODELING OF CUTTING FORCES IN BALL-END MILLING USING RESPONSE SURFACE METHODOLOGY AND GENETIC ALGORITHM

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ABSTRACT
The paper presents the development of the equations for cutting forces in ball-end milling using response surface methodology (RSM) and genetic algorithm (GA). The RSM was used to develop basically the reduced second-order polynomial response surface mathematical model for prediction of cutting forces in ball-end milling. The GA was used for fine-tuning of the constants in the reference models, which were obtained from RSM. The fine-tuning of the constants in GA is performed in order to find the minimum value of the fitness function. The obtained results show that developed GA equations fit better with experimental data than RSM equations.
Keywords: modeling, cutting forces, ball-end milling

1. INTRODUCTION
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]. Ball-end milling is one of the modern technologies which is usually applied in machining complex surfaces.Modeling of cutting forces is very important for the ball-end milling process research because of cutting forces often cause wear of cutting tools, thus resulting in poor quality machined surface. Numerous researchers have studied the influence of input cutting parameters on cutting forces in ball-end milling process. For this purpose, a number of modeling techniques were used: RSM [2], analytical models [3, 4, 5], mechanistic models [6, 7, 8, 9] and artificial intelligence based models (ANN, GP) [10, 11].
The aim of this work is to present the various approaches to predict cutting forces in ball-end milling process and developing a predictive model to obtain cutting forces as a function of machining parameters: spindle speed (n), feed per tooth (f_z), axial depth of cut (a_p) and radial depth of cut (a_e), using Response Surface Methodology (RSM) and Genetic Algorithm (GA). RSM is conventional modeling approach, and GA is a part of evolutionary algorithms.

2. EXPERIMENTAL SETUP AND RESULTS
The experimental work explained in this paper referenced the work of Pejic V. [12], and was performed at the Department of Production Engineering, Faculty of Technical Sciences, at University of Novi Sad and at the company "ELMETAL" doo in Senta, Serbia. The experiments were conducted on HAAS VF-3YT vertical three-axis CNC milling machine and on hardened steel X210CR12 with

58 HRC. The cutting tools used were TiAlN-T3 coated two-flutes solid carbide ball-end milling cutters of diameter 6 mm (Emuge-Franken, type 1877A). Machining parameters and their levels are presented in Table 1.

Table 1. Machining parameters and their levels

Parameters	Levels				
	-2	-1	0	1	2
Spindle speed, n (min^{-1})	3981	4777	5573	6369	7169
Feed per tooth, f_z (mm/tooth)	0,018	0,024	0,030	0,036	0,042
Axial depth of cut, a_p (mm)	0,04	0,08	0,12	0,16	0,20
Radial depth of cut, a_e (mm)	0,20	0,40	0,60	0,80	1,00

During the experiments, orthogonal cutting forces were measured using Kistler dynamometer and sampled using a PC based data acquisition system with LabVIEW software. Applying the rotatable central composite design (RCCD), the Design of experiment (DOE) was obtained. Using different combinations of the input parameters levels performed was a total of 30 experiments.Measured results of cutting forces are presented in Table 2.

Table 2. Experimental results for cutting forces

Trial No.	Code					Parameters				Measured value F_x (N)	Measured value F_y (N)	Measured value F_z (N)
	x_0	x_1	x_2	x_3	x_4	n (min^{-1})	f_z (mm/z)	a_p (mm)	a_e (mm)			
1	1	-1	-1	-1	-1	4777	0.024	0.08	0.40	41.02	38.52	50.04
2	1	1	-1	-1	-1	6369	0.024	0.08	0.40	35.76	36.31	50.39
3	1	-1	1	-1	-1	4777	0.036	0.08	0.40	45.42	37.91	53.51
4	1	1	1	-1	-1	6369	0.036	0.08	0.40	42.71	35.71	55.87
5	1	-1	-1	1	-1	4777	0.024	0.16	0.40	65.56	46.32	65.32
6	1	1	-1	1	-1	6369	0.024	0.16	0.40	51.60	39.74	60.55
7	1	-1	1	1	-1	4777	0.036	0.16	0.40	77.49	53.75	69.44
8	1	1	1	1	-1	6369	0.036	0.16	0.40	67.96	45.06	66.78
9	1	-1	-1	-1	1	4777	0.024	0.08	0.80	61.22	35.24	68.73
10	1	1	-1	-1	1	6369	0.024	0.08	0.80	53.43	31.66	70.53
11	1	-1	1	-1	1	4777	0.036	0.08	0.80	71.91	36.18	77.13
12	1	1	1	-1	1	6369	0.036	0.08	0.80	68.78	37.81	73.21
13	1	-1	-1	1	1	4777	0.024	0.16	0.80	89.03	48.26	76.70
14	1	1	-1	1	1	6369	0.024	0.16	0.80	69.30	37.40	67.08
15	1	-1	1	1	1	4777	0.036	0.16	0.80	90.92	80.06	78.22
16	1	1	1	1	1	6369	0.036	0.16	0.80	68.27	36.70	68.93
17	1	0	0	0	0	5573	0.030	0.12	0.60	53.50	24.48	57.74
18	1	0	0	0	0	5573	0.030	0.12	0.60	73.83	29.71	71.25
19	1	0	0	0	0	5573	0.030	0.12	0.60	65.44	34.26	75.96
20	1	0	0	0	0	5573	0.030	0.12	0.60	49.17	35.20	78.25
21	1	-2	0	0	0	3981	0.030	0.12	0.60	65.37	37.56	59.23
22	1	2	0	0	0	7166	0.030	0.12	0.60	55.96	36.19	57.87
23	1	0	-2	0	0	5573	0.018	0.12	0.60	51.45	24.12	69.36
24	1	0	2	0	0	5573	0.042	0.12	0.60	67.24	38.63	77.44
25	1	0	0	-2	0	5573	0.030	0.04	0.60	44.89	29.39	56.45
26	1	0	0	2	0	5573	0.030	0.20	0.60	114.69	55.03	89.12
27	1	0	0	0	-2	5573	0.030	0.12	0.20	64.90	43.72	55.83
28	1	0	0	0	2	5573	0.030	0.12	1.00	166.67	56.04	84.16
29	1	0	0	0	0	5573	0.030	0.12	0.60	59.51	48.78	74.87
30	1	0	0	0	0	5573	0.030	0.12	0.60	62.27	49.88	80.64

3. RESULTS AND DISCUSSION

3.1. Modeling of cutting forces by RSM

Response surface methodology (RSM) is a collection of statistical and mathematical methods which are can be used in modeling and optimization of different machining processes. This methodology represents the empirical statistical technique, which is applied for the regression analysis of the data obtained through the experiment in order to obtain the equation which represents the response function (depending on the variable size being examined).

Applying Design Expert software created were RSM models for cutting forces. The mathematical models for cutting forces as a function of machining parameters were developed by using a reduced second-order polynomial response surface mathematical equation. The developed mathematical models to predict cutting forces F_x, F_y, and F_z are:

$$F_x=89.32-5.42\cdot10^{-3}\cdot n+681.39\cdot f_z+311.96\cdot a_p-271.53\cdot a_e+286.84\cdot a_e^2 \quad (1)$$

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

$$F_z=-185.19+0.067\cdot n+346.60\cdot f_z+362.73\cdot a_p+82.20\cdot a_e-398.05\cdot a_p\cdot a_e-6.12\cdot10^{-6}\cdot n^2 \quad (3)$$

3.2. Modeling of cutting forces by GA

The GA is a search algorithm, based on a Darwinian theory of evolution and on the concept of "survival of the fittest". The two most significant advantages of the GA approach are its simplicity of operation and computational efficiency. GA deals with chromosome populations. Using the real analogy with biology, the chromosome is presented as the genotype, whereas the solution it describes is called the phenotype. For using this algorithm, a problem solution is defined in terms of the fitness function. A fitness function is used to evaluate each of the solutions in the population, represented by the chromosomes. Defining this function for the given problem is one of the most difficult tasks in creating a good genetic algorithm.

The RSM was used to develop basically the reduced second-order polynomial response surface mathematical models for prediction of cutting forces in ball-end milling and GA was used for fine-tuning of the constants in Eq. 1-3, which obtained from RSM. The fine-tuning of the constants in GA is performed in order to find the minimum value of the fitness function.

The fitness function is defined as:

$$\Delta=\frac{1}{n}\sum_{i=1}^{n}\frac{|E_i-G_i|}{E_i}\cdot100\% \quad (4)$$

where n is the size of sample data, E_i the measured F_i (i=x,y,z) and G_i the predicted F_i calculated by GA.

The lower the values of Eq. 4, the better agreement of the model is to the experimental data. For implementing GA GATool was used in MATLAB. The GA predictive model is developed using 25 datasets selected based on experimental results, without 6 datasets on the average level (center points), Table 2. Six datasets on the average level were used as one average value. The best result was obtained with 1500 population size. The developed mathematical models to predict cutting forces F_i using GA are:

$$F_x=38.55-4.0\cdot10^{-3}\cdot n+677.45\cdot f_z+300.71\cdot a_p-100.45\cdot a_e+124.88\cdot a_e^2 \quad (5)$$

$$F_y=-19.48+5.0\cdot10^{-3}\cdot n+252.26\cdot f_z+418.69\cdot a_p-98.07\cdot a_e-0.058\cdot n\cdot a_p+79.88\cdot a_e^2 \quad (6)$$

$$F_z=-142.76+0.052\cdot n+324.99\cdot f_z+306.18\cdot a_p+71.47\cdot a_e-300.04\cdot a_p\cdot a_e-4.69\cdot10^{-6}\cdot n^2 \quad (7)$$

3.3. Comparison of RSM, and GA model performance

Predicted values for cutting forces as obtained in the RSM, and GA are compared with the experimental values. The error of each datasets was calculated using Eq. 8:

$$E=\frac{|Model\_pred_i-Expt\_value_i|}{Expt\_value_i}\cdot100\% \quad (8)$$

The average error of the RSM, and GA models are presented in Table 3.

Table 3. Comparison of RSM, and GA model performance

Average error of RSM models			Average error of GA models		
F_x	F_y	F_z	F_x	F_y	F_z
11.98%	13.86%	5.51%	10.15%	11.84%	5.10%

4. CONCLUSION

This paper presents the predictive models for cutting forces F_x, F_y, and F_z during ball-end milling process which were developed using RSM, and GA. In the first step of the research basic mathematical models were developed by the use of RSM. These reduced quadratic models were used in next steps as basic shape for a build-up of predictive models using GA. For implementing GA was used toolbox in MATLAB. The predictive capability developed models were compared. Experimental results were compared with predicted values for both types of models. The predictive models developed using GA providing better prediction accuracy than models developed using RSM. On comparison RSM, and GA models were found that nature-inspired algorithms show the good ability for prediction of cutting forces in ball-end milling process.

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