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GREY RELATIONAL MULTI-PARAMETRIC TAGUCHI BASED OPTIMIZATION OF THE PROCESS PARAMETERS IN ALUMINIUM FACE MILLING

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Abstract: For investigation of a process parameter effect for a given set of factor values in this paper grey relational analysis is used. In order to find multi-parametric optimization of arithmetical mean deviation of the assessed profile as the surface roughness characteristic and for the material removal rate, the grey relational analysis is implemented. The analysis combined with Taguchi methods and based on the L9 orthogonal array experimental design was used. Obtaining the insight into the characteristics of the process, even with a smaller number of experimental runs by utilization of these methods is allowed. In terms of the machining process and material, the face milling for pure aluminium is performed. The machining of the workpiece through the different combination of settings for the spindle speed, feed and depth of cutting, as the main parameters, was performed
Keywords: Grey relational analysis, Face milling, Taguchi method, Multi-parametric optimization

1. INTRODUCTION

Lowering the costs of a production is one of the always present goals which engineers and scientists are trying to achieve through implementation of different techniques and methods. One of the well-known techniques is optimization. Ekinovic and Brdarevic showed successful application of different optimization approaches with emphasis on the most efficient method considering a number of experimental runs [1]. Zschieschang et al. have done optimization of material flow networks for chemical processes in terms of resource efficiency perspective [2]. The successful application of optimization was done in power system optimization regard to gas fuel [3]. Haitao et al. have successfully done optimization of the electric aircraft actuation system improving the efficiency based on the safe reliability requirements and reducing the weight [4]. For a thermal power plant cycles in terms of exergy efficiency optimization technique can be done [5]. Sonmez and Akbulut optimized the placement of the tape for thermoplastic composites considering residual stress and speed of the process [6]. Andrew Kusiak and Haiyang Zheng optimized the set points of the pitch blade angle and torque for the increased power output of the wind turbine [7]. The maximizing power in the optimization of the thermodynamic process based on Brayton cycle is obtained [8]. Nguyen and Bagajewicz used a genetic algorithm in combination with Montecarlo simulation to optimize preventive maintenance scheduling in processing plants [9]. As can be seen from previous optimization techniques is applied successfully in many scientific fields.

Taguchi methods can be seen in various fields of science especially in machining as the base part of the production engineering. Begovic and Ekinovic successfully used Taguchi methods in the analysis of the white layer properties for a various chemical composition of the steel [10]. This method was utilized for the optimization and analysis of the surface roughness in turning of the titanium alloy, which showed that surface roughness decreased with cutting speed increase and feed decrease.[11]. Balaji et al. have investigated the optimization through Taguchi methods and ANOVA in the drilling of AISI 304 stainless steel [12]. In terms of surface roughness for the deep drilling that usually involves drilling of the hole with depth at least ten times its diameter, for AISI 321 Steel, this method was successfully applied [13]. Routara et al. have performed this method for CNC end milling of medium leaded brass [14]. Pang et al. have shown that these methods can be used for the CNC end milling optimization in terms of machining parameters of the aluminum reinforced epoxy matrix hybrid composite [15]. Ekinovic et al. have successfully applied Taguchi methods in the optimization of the surface finish roughness for hardened steel machined by turning [16].

When the optimization of the multiple response characteristics is considered, the grey relational analysis in the last few decades has shown remarkable results regarding it. Nair et al. have successfully applied grey relational analysis in end milling of the aluminum and shown a comparison between grey relational method and other optimization methods such as utility theory and TOPSIS [17]. The optimization based on the grey relational method in minimum quantity lubrication (MQL) end milling of aluminum Al6063 was successfully performed [18]. Kuram and Ozcelik have used Taguchi based grey relational analysis in a multi-objective micro-milling optimization of the aluminium Al 7075 [19]. In the milling of the superalloy such as Inconel 718, the optimization based on Taguchi relational analysis was successfully applied [20].

2. EXPERIMENTAL SETUP

We used the five-axis milling machine Deckel Maho DMU 60 monoBLOCK to carry out the experimental procedure. This milling machine is shown in Fig. 1. The cutting tool used in this experiment was high-speed Steel Austria 2286 So56 NC X10 HSS-ECo8x flat mill with four cutting edges in combination with milling chuck and spring milling clamps as can be seen in Figure 2.

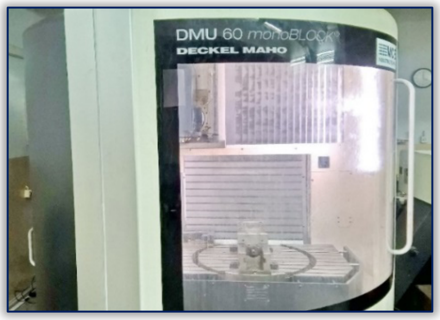

Figure 1. Machine used for machining

Figure 2. Tool and tool holder used for machining

In this research, we investigated the effect of three main parameters, i.e. cutting feed, cutting depth and spindle speed. The setup workpiece was of commercially pure 1100 grade aluminum. The lubrication and cooling during the process were done by water-oil cutting fluid.

3. TAGUCHI METHOD

Finding an optimal setting for the available factor levels, can be done through various available techniques such as full factorial analysis, simplex techniques and special cases such as Doehlert design and gradient-based techniques. Dr . Genici Taguchi in the middle of the last century presented Taguchi design based on special orthogonal arrays. With this method effects of the main factors as well as interactions can be investigated. These plans are combined with linear graphs to determine a proper position of factors and interactions in orthogonal arrays tables. The controlled factors and their levels are presented in Table 1.

Table 1 – Factors and level settings

Level:	Factor:		
	Spindle speed $[RPM]$	Feed per tooth $\left[\frac{mm}{tooth}\right]$	Depth of cut $[mm]$
1	1500	0.01	0.5
2	2800	0.015	1.3
3	4700	0.025	2

Taguchi plans are successfully applied to many branches of science, especially in engineering. The experimental design based on Taguchi methods compared to the full factorial design requires far less number of runs, e.g. for the current experimental setup in order to study these factors on three levels full factorial design with at least twenty-seven runs should be performed. An experimental setup is simplified by choosing the Taguchi design, and the number of runs is reduced to nine. Experimental setup with the randomized run order is shown in Table 2.

Table 2 – Experimental setup run order

Run order	Series order	Spindle speed $[RPM]$	Feed per tooth $\left[\frac{mm}{tooth}\right]$	Depth of cut $[mm]$
9	1	1500	0.01	0.5
6	2	1500	0.015	1.3
4	3	1500	0.025	2
3	4	2800	0.01	1.3
1	5	2800	0.015	2
8	6	2800	0.025	0.5
5	7	4700	0.01	2
7	8	4700	0.015	0.5
2	9	4700	0.025	1.3

4. MEASUREMENTS OF RESPONSES

The data regarding surface roughness was collected, for all nine newly created surfaces, by optical microscope Mahr MarSurf TS 50 which is shown in Figure 3(a). The analysis of the surfaces was done through ODSCAD software, as it is shown in Figure 3(b), which allows 2D coordinate measurement setting as well as choosing different modes for proper selection and involvement of the desired filter.

Since the machining process was face-milling, measuring of the material removal rate as one of the responses that were endeavored to be optimized, were done through calculation for each experimental run and the appropriate factor levels. The calculation is done with Equation (1):

$$MRR = \frac{d \cdot w \cdot f}{1000} \quad (1)$$

where MRR is material removal rate in $\left[\frac{cm^3}{\min}\right]$, d is the depth of cut in $[mm]$, w is the width of the pass in $[mm]$ and f is feed in $\left[\frac{mm}{\min}\right]$. The measurements and calculation of aforementioned responses are presented in Table3.

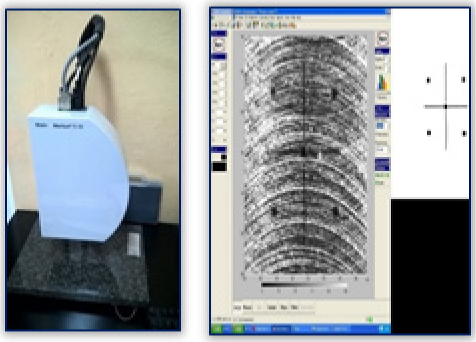

Figure 3. Optical microscope used for measuring (a) and measuring software (b)

Table 3. Measuring results of the performed experiment

Series order	Spindle speed $[RPM]$	Feed per tooth $\left[\frac{mm}{tooth}\right]$	Depth of cut $[mm]$	Ra $[\mu m]$	MRR $\left[\frac{cm^3}{\min}\right]$
1	1500	0.01	0.5	1.5	0.3
2	1500	0.015	1.3	1.2	1.17
3	1500	0.025	2	1.6	3
4	2800	0.01	1.3	1.3	1.456
5	2800	0.015	2	2	3.36
6	2800	0.025	0.5	1.7	1.4
7	4700	0.01	2	2.3	3.76
8	4700	0.015	0.5	1.4	1.41
9	4700	0.025	1.3	1.4	6.11

5. GREY RELATIONAL ANALYSIS

The grey relational analysis is a concept that Chinese professor Julon Deng successfully developed in order to find the best process characteristic since many of the investigated processes do not contain absolutely precise information. This information is taken to be in the so-called grey field of research. The grey relational analysis can be combined with Taguchi experimental design setup so as to many conclusions may be drawn. The obtained data are processed through zero to one normalization for each run and for multiple responses as it is shown in Table 4.

Table 4. Normalized experimental results for the arithmetical mean deviation of the assessed profile (Ra) and Material removal rate (MRR)

Run order	Series order	Spindle speed $[RPM]$	Feed per tooth $\left[\frac{mm}{tooth}\right]$	Depth of cut $[mm]$	Ra $[\mu m]$	MRR $\left[\frac{cm^3}{\min}\right]$	Norm Ra	Norm MRR
9	1	1500	0.01	0.5	1.5	0.3	0.7273	0
6	2	1500	0.015	1.3	1.4	1.17	1	0.1497
4	3	1500	0.025	2	1.6	3	0.6364	0.4647
3	4	2800	0.01	1.3	1.3	1.456	0.9091	0.199
1	5	2800	0.015	2	2	3.36	0.2727	0.5267
8	6	2800	0.025	0.5	1.7	1.4	0.5455	0.1893
5	7	4700	0.01	2	2.3	3.76	0	0.5955
7	8	4700	0.015	0.5	1.2	1.41	0.8182	0.191
2	9	4700	0.025	1.3	1.4	6.11	0.8182	1

Taguchi analysis is performed regarding signal to noise ratio (S/N ratio). For each case of the experimental setting considering specific observed characteristic, this ratio should be calculated. In this case larger the better S/N ratio is applied, obtained by Equation (2).

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

where n is the number of performed experiments is and y_i is the value of the response for each appropriate experimental run.

For the calculation of normalized values of the arithmetical mean deviation of the assessed profile, the corresponding characteristic is "smaller the better" which can be expressed as Equation (3). The deviation-sequences, for all experimental runs, are presented in Table 4.

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{3}$$

The normalized values for the material removal rate are obtained for the "larger the better" characteristic using the Equation (4), and appropriate deviation sequence is presented in Table 5.

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{4}$$

where $y_i(k)$ represents the original sequence for the appropriate targeted value, *k* takes values from 1 to *n*, which represents a total number of parameters and in this case, i.e. 3, *i* represents the number of performed experiments. The values of the deviation sequences for the surface roughness and material removal rate are shown in Table 5.

Table 5. The deviation sequence for given experimental results

Run order	Series order	Spindle speed $[RPM]$	Feed per tooth $\left[\frac{mm}{tooth}\right]$	Depth of cut $[mm]$	Ra $[\mu m]$	MRR $\left[\frac{cm^3}{\min}\right]$	Deviation sequence Ra	Deviation sequence MRR
9	1	1500	0.01	0.5	1.5	0.3	0.2727	1
6	2	1500	0.015	1.3	1.4	1.17	0	0.8503
4	3	1500	0.025	2	1.6	3	0.3636	0.5353
3	4	2800	0.01	1.3	1.3	1.456	0.0909	0.801
1	5	2800	0.015	2	2	3.36	0.7273	0.4733
8	6	2800	0.025	0.5	1.7	1.4	0.4545	0.8107
5	7	4700	0.01	2	2.3	3.76	1	0.4045
7	8	4700	0.015	0.5	1.2	1.41	0.1818	0.809
2	9	4700	0.025	1.3	1.4	6.11	0.1818	0

After the process of normalization, calculation of the grey relational grade coefficient is performed using the following Equation (5):

$$\xi_i(k) = \frac{\Delta\min + \zeta\Delta\max}{\Delta ij - \zeta\Delta\max} \tag{5}$$

where Δij is the absolute value of the difference between targeted(referent) sequence and the comparative sequence and where $\Delta\min$ and $\Delta\max$ take minimum and maximum obtained values. In this particular case $\Delta\min = 0$ and $\Delta\max = 0$.

The value of the identification or distinguishing coefficient ζ can take values between zero and one. The intention of introducing this coefficient is to highlight the characteristics of the grey relational coefficient through a direct effect on the maximum for the absolute value difference between referent and comparative sequence. In this case, the value of ζ is taken as 0.5 since it provides a balanced effect on the grey relational coefficient.

The generated grey relational coefficients allow calculation of the grey relational grade by the following Equation (6).

$$\gamma_i(k) = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{6}$$

where *n* is the number of observed responses in all cases, *k* is the value in the range from zero to *n* for each grey relational grade γ_i and calculated grey relational coefficient ξ_i. The grey relational grade values vary from zero to one for the lowest and highest ranking respectively. The calculated values of the grey relational coefficients for the surface roughness and the material removal rate, as well as the grey relational grade, are presented in Table 6.

Table 6 . GRA coefficients and GRA grade for each experimental setting

Series order	Norm. Ra	Norm. MRR	GRA coeff. Ra	GRA coeff. MRR	GRA grade	Rank	S/N ratio
1	0.7273	0	0.6471	0.3333	0.4902	6	-6.1926
2	0.8182	0.1497	1	0.3703	0.6851	2	-3.2843
3	0.6364	0.4647	0.5789	0.483	0.531	5	-5.4989
4	0.9091	0.199	0.8462	0.3843	0.6152	3	-4.2192
5	0.2727	0.5267	0.4074	0.5137	0.4606	7	-6.7344
6	0.5455	0.1893	0.5238	0.3815	0.4526	8	-6.8848
7	0	0.5955	0.3333	0.5528	0.4431	9	-7.0706
8	1	0.191	0.7333	0.382	0.5577	4	-5.0726
9	0.8182	1	0.7333	1	0.8667	1	-1.243

For all given parameters and the appropriate levels, delta values are calculated and shown by means of the response table in terms of means. The results are presented in Table 7.

For the given process parameters spindle speed, feed per tooth and depth of cut the reference graphs regarding grey relational grade and selected process parameter level are presented in Figure 4.

Table 7. Response table for each parameter levels

Response Table for Means			
Level	Spindle speed	Feed per tooth	Depth of cut
1	0.5688	0.5162	0.5002
2	0.5095	0.5678	0.7223
3	0.6225	0.6168	0.4782
Delta	0.1130	0.1006	0.2442
Rank	2	3	1

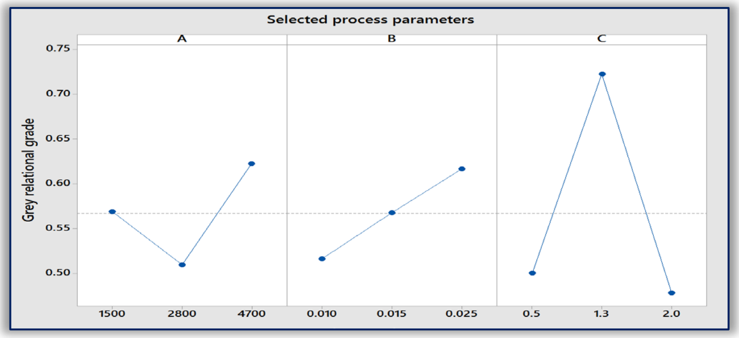

Figure 4 : The grey relational grade reference graph for the process parameters

6. CONCLUSIONS

Through grey relational analysis optimization in the milling process is performed. The Grey relational analysis was based on Taguchi method used for experimental setup. Optimal settings for three parameters (spindle speed, feed per tooth and depth of cut) are determined. This analysis showed that the most influential parameter considering multiple-parametric characteristic in terms of the surface finish roughness and the material removal rate is cutting depth, followed by the spindle speed and the feed per tooth. Since the determined level of spindle speed is at the largest level this is a good predictor of a surface roughness that usually increases with speed decrease. The expected level of the feed in terms of the surface roughness was at the lowest setting. The performed analysis showed that optimal level of the surface roughness is at the highest level setting. This can be caused due to multi-parametric optimization since the material removal rate in milling is directly proportional to the feed rate. The obtained optimal results considering surface roughness and material removal rate for each parameter were found to be Ra of 1.4 $[\mu m]$ and MRR of 6.11 $\left[cm^3/\min\right]$. These results were acquired with following experimental setup: for the spindle speed of 4700 $[RPM]$ (level 3), the feed per tooth of 0.025 $[mm]$ (level 3) and the depth of cut of 2 $[mm]$ (level 2).

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