OPTIMIZACIJA PROCESNIH PARAMETARA ČEONOG GLODANJA LEGURE AW 7075 PRIMJENOM SIVE RELACIONE ANALIZE I TAGUCHIJEVOG EKSPERIMENTALNOG DIZAJNA

OPTIMIZATION OF FACE MILLING PROCESS PARAMETERS FOR AW 7075 ALLOY USING GREY RELATIONAL ANALYSIS AND TAGUCHI EXPERIMENTAL DESIGN

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U cilju optimizacije procesnih parametara čeonog glodanja izvršen je eksperiment, gdje su za ulazne veličine odabrana tri procesna parametra – broj obrtaja, dubina rezanja i posmična brzina. Svaki parametar je variran na 4 nivoa, s tim da se vodilo računa o finoj i gruboj obradi. Mašinski sistem na kome se vršila obrada glodanjem je CNC mašina proizvođača HURCO, a rezni alat je VHM tvrdometalno glodalo sa 4 rezne oštrice. Eksperiment je realizovan uz pomoć Taguchijevog ortogonalnog niza L16 (4^3). Izlazne vrijednosti procesa su hrapavost obrađene površine (Ra) i količina odnesenog materijala u jedinici vremena (MRR). Optimizacija procesnih parametaraje izvršena primjenom višekriterijske optimizacione metode (GRA), dok se primjenom analize ANOVA ispitivala statistička značajnost parametara. Istraživanjem je utvrđeno da se optimalne vrijednosti MRR-a i Ra-a dobiju kombinacijom fizikalnih vrijednosti ulaznih parametara: n = 6000 o/min, a = 2 mm i f = 800 mm/min.

Professional paper

ABSTRACT

In order to optimize the process parameters of face milling, an experiment was carried out in which three machining parameters were selected as input variables – spindle speed, axial depth of cut, and feed rate. Each parameter was varied at four levels, considering both rough and finish machining. The milling process was performed on a HURCO CNC machine, using a solid carbide end mill with four cutting edges. The experiment was conducted using the Taguchi orthogonal array L16 (4^3). The output responses of the process are the surface roughness (Ra) and the material removal rate (MRR). Process parameter optimization was carried out using the multi-criteria optimization method - Grey Relational Analysis (GRA), while the statistical significance of the parameters was examined by using ANOVA. The research established that the optimal values of MRR and Ra are obtained through the combination of the physical values of the input parameters: n = 6000 rpm, a = 2 mm, and f = 800 mm/min.

1. INTRODUCTION

The modern market is characterized as global and is therefore subject to various influences. In such conditions, manufacturing companies must respond to numerous challenges to maintain their competitiveness and ensure sustainability. The fast-paced nature of life, emerging technologies, and market responsiveness require companies to adopt entirely new approaches, both in organizational and production aspects. Today, manufacturing companies are increasingly compelled to find and implement new production methods and systems to meet market demands within given deadlines while maintaining the required quality of their products [9].

In their study [9], Topćić and Lovrić describe the challenges of the global market and the necessity of cost reduction in relation to product competitiveness. This approach has introduced a new chapter in market competition, defining a product as competitive only if it is produced on time, with the highest quality, and at a lower cost than equivalent products from competing suppliers. Accordingly, the following calculation has been established:

PROFIT = PRODUCT COST PRICE - PRODUCTION COSTS

Reducing production costs is a continuously present objective that engineers and researchers strive to achieve by implementing various techniques and methods. One well-known approach is process optimization [3]. A similar approach is discussed in the work of Begović and Ekinović [3].

One of the key indicators of milling success is the quality of the machined surface, which is one of the primary requirements of customers in modern industry. Surface quality largely depends on various process parameters, which are more complex to monitor than the control of a product's physical dimensions.

The primary parameter used to assess surface quality is the arithmetic mean roughness (Ra), which represents the average absolute deviation of surface irregularities over a given measuring length *l*. For the purpose of process optimization, this parameter should have the lowest possible value, meaning that the workpiece should have the highest possible surface quality. Previous research in this field has demonstrated that milling parameters significantly impact surface finish, making their optimization a crucial factor in achieving the desired quality. First- and second-order mathematical models have frequently been developed based on experimental results to establish the response of surface quality to machining parameters [8]. In their study, Dilbag and Venkateswara Rao developed first- and second-order models using classical mathematical modeling techniques, followed by an optimization process [8].

The second key parameter is the **Material Removal Rate (MRR)**, which represents the volume of material removed per unit of time. This parameter is inherently contradictory to surface quality; MRR is associated with rough machining, while surface quality is linked to fine machining. In this particular case, the maximum value of this parameter will be considered as the desirable outcome. Ultimately, optimization involves balancing these values. The objective of this research, conducted at the company *Mann+Hummel*, was to align the milling quality of the AW 7075 alloy with satisfactory process productivity. For this purpose, the fundamental machining parameters selected were spindle speed, depth of cut, and feed rate.

The selection and variation of machining parameters primarily depended on the material being processed, followed by operational experience and validation through literature review and previous research. Due to its softness, aluminum and its alloys are prone to the formation of built-up edge (BUE) during cutting, which can negatively affect both surface quality and dimensional accuracy. Literature sources [2], [4], and [5] indicate that researchers used similar process parameters. To mitigate built-up edge formation, higher cutting speeds, increased spindle speeds, and a depth of cut not exceeding 5 mm for rough machining are recommended. In a study by Keong et al. (2006), aluminum alloy 7075-T6 was machined at different cutting speeds, showing that increasing spindle speed reduces surface roughness [11]. As previously mentioned, the arithmetic mean roughness (Ra) is associated with fine machining, while material removal rate is related to rough machining. Consequently, the process parameters were varied accordingly.

The primary reason for selecting this material was its practical significance, as *Mann+Hummel's* tool shop primarily performs CNC milling on this alloy for manufacturing air filter molds, which require a specific surface quality. Besides the automotive industry, this material is widely used in the defense industry [11]. In this context, Turkish authors describe the impact of vibrations on surface quality [11].

For data analysis and processing, the Taguchi orthogonal array L16 was used. Furthermore, statistical analysis of output values was conducted using Grey Relational Analysis (GRA) to determine the optimal milling process parameters.

2. EXPERIMENTAL RESEARCH

2.1. Objective of the Experiment

The aim of the experimental study is to analyze and evaluate the surface roughness of the machined surface and the material removal rate (MRR) for the aluminum alloy AW 7075. Subsequently, the optimization of machining parameters is performed using Grey Relational Analysis (GRA).

2.2. Material Characteristics, Machining System, and Cutting Tool

The experiment was conducted using the AW 7075 aluminum alloy. Aluminum and its alloys, with an increasingly broad range of applications, are widely used in industries such as aerospace, automotive, machinery manufacturing, defense, construction, home appliances, heating and cooling systems, and many other sectors. The advantages of aluminum over other materials, as well as its alloying capabilities, allow for the achievement of desirable properties, which has led to its increased usage, making it a competitive alternative to steel [11]. This particular alloy was chosen as it is one of the most commonly used alloys in cutting processes within the studied industrial company. The workpiece dimensions used in the experiment are 300 × 150 × 15 mm (Figure 1).

Figure 1 *AW 7075 Workpiece*

The chemical composition of the AW 7075 alloy used for the experimental tests is shown in Table 1.

Table 1 Chemical Composition of AW 7075 Alloy

Chemical composition of the material						
Al	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Zn**
87,1-91,4	**0,18-0,28**	**1,2-2,0**	**<0,50**	**2,1-2,9**	**2,1-2,9**	**5,1-6,1**

The characteristics of the HURCO CNC milling machine are given in the following table:

Table 2 Technical and Technological Specifications of the CNC Milling Machine

Path and Capacity	
X, Y, Z Range	610 x 508 x 610 mm
T-table size	5 x 18 mm
Maximum table load	1500 kg
Worktable size	760 x 508 mm
Spindle to table range	152 mm
Spindle	
Maximum spindle speed	12 000 revolutions
Spindle power	9 kW
Spindle torque	143 Nm @ 600 RPM
Tool changer	
Tool type	CAT 40/ Big Plus
Number of tools	30
Maximum tool diameter	80 mm
Maximum tool length	300 mm
Maximum tool weight	7 kg
Feed rates	
Rapid traverse X, Y, Z	38, 38, 32 m/min
Maximum programmable feed rate	32 m/min
Work envelope	
Maximum operating space	3807 x 4053 mm
Machine height	2715,3 mm
Machine weight	4460 kg

For the purposes of the experiment, a spindle milling cutter was used, which is almost the most commonly used tool in everyday practice when it comes to machining aluminum alloys—VHM carbide milling cutter with 4 cutting edges. The basic characteristics of the milling cutter are as follows:

- 4 cutting edges, short design, 35°/38° right-hand twist;
- Unequal helix angle and spacing between teeth for milling with minimal vibration;
- With relief;
- With chamfering treatment F for longer service life;
- Material: VHM fine grain;
- Cutter diameter: 12 mm.

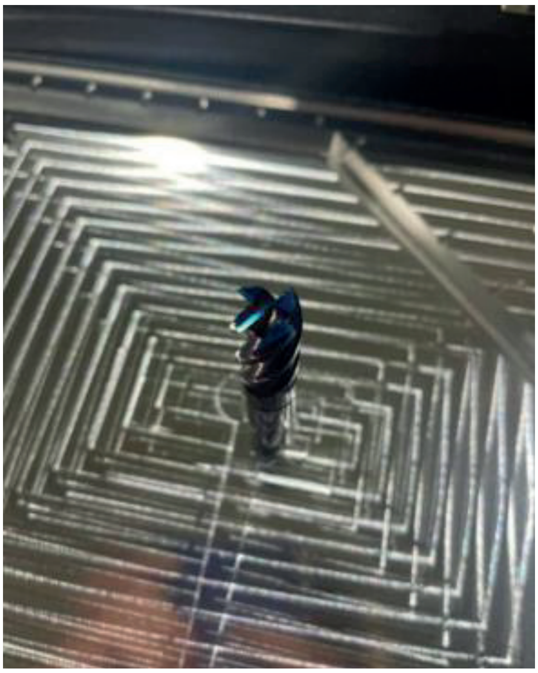

***Figure 2** VHM spindle milling cutter with 4 cutting edges*

2.2. Experimental Design

For the experimental research, the Taguchi methodology was used. This method is based on orthogonal arrays of experiments, which allow for reducing variation in the experiment, resulting in the optimal adjustment of process control parameters [1]. As mentioned earlier, similar studies use classical mathematical modeling as a methodology, which leads to robust experimental plans, including repetitions of the experiment at the central point of the experimental design. The Taguchi approach uses a statistical performance measure that takes into account the value (signal) and standard deviation (noise). Typically, for each factor, 2 or 3 levels of variation are chosen. Proper selection of levels and the amount of data is a key part of robust design planning [1]. The study covers three parameters and four levels of variation, presented in the Table 3:

Table 3 Input parameters for milling process

	Parameters	Unit of measurement	Levels of variation			
			1	2	3	4
A	Spindle speed (*n*)	RPM	3000	4000	5000	6000
B	Cutting depth (*a*)	mm	0,5	1	1,5	2
C	Feed rate (*f*)	mm/min	800	1200	1600	2000

The experiment was conducted using the Taguchi orthogonal array L16 (4^3), and the Table 4 defines the coded matrix and the matrix with natural coordinates.

Table 4 Display of the L16 experimental array with coded and natural coordinates

No.	Parameters			Parameters		
	Spindle speed (*n*)	**Cutting depth (*a*)**	**Feed rate (*f*)**	**Spindle speed**	**Cutting depth**	**Feed rate**
1.	1	1	1	3000	0,5	800
2.	1	2	2	3000	1	1200
3.	1	3	3	3000	1,5	1600
4.	1	4	4	3000	2	2000
5.	2	1	2	4000	0,5	1200
6.	2	2	1	4000	1	800
7.	2	3	4	4000	1,5	2000
8.	2	4	3	4000	2	1600
9.	3	1	3	5000	0,5	1600
10.	3	2	4	5000	1	2000
11.	3	3	1	5000	1,5	800
12.	3	4	2	5000	2	1200
13.	4	1	4	6000	0,5	2000
14.	4	2	3	6000	1	1600
15.	4	3	2	6000	1,5	1200
16.	4	4	1	6000	2	800

Before the actual execution of the experiment, the semi-finished product with dimensions 300 x 150 x 15 mm was clamped in a vice and face milled from all sides to obtain the best possible measurements during the 16 defined passes, as there was no room for errors when entering the coordinates. To improve the machining process, a cooling and lubrication fluid was used for each pass. The SHIP was delivered by the main nozzle along with an additional eight nozzles from the tool holder, type Hysol T15, manufactured by Castrol. Lubrication was fixed for all 16 passes. The start of the machining process with the defined spindle milling cutter and the clamped semi-finished product is shown in Figure 3a), while Figure 3b) shows the workpiece after machining.

Figure 3 a) *Display of the clamped semi-finished product and spindle milling cutter before the start of the experiment;* ***b)*** *AW 7075 plate after 16 passes*

The reference value processed in the experimental work was the arithmetic average of the profile deviation Ra. Since the machining process is face milling, the measurement of the material removal rate, as one of the responses to be optimized, was carried out through calculations for each experimental series and the corresponding factor levels. The calculation is performed using the expression (1) [3]:

$$MRR = \frac{d\cdot w\cdot f}{1000} = \frac{a_p\cdot a\cdot n\cdot z\cdot f}{1000}\, cm^3/_{min} \cdot \quad (1)$$

This is the general formula for calculating the material removal rate (MRR). For each experimental point, it remains unchanged regardless of how many times the experiment is repeated at that specific point.

3. ANALYSIS OF EXPERIMENTAL RESULTS

Within the scope of experimental research, two repetitions of the experiment were conducted. Both experiments were carried out under the same conditions using a single cutting tool, in order to include tool wear in the analysis. Surface roughness measurement, after device calibration, was performed using a digital contour measuring instrument Mitutoyo SJ-210, shown in Figure 4, for each pass, in accordance with the DIN 1990 standard (DIN EN ISO 4287:1998). The material removal rate was calculated based on expression (1).

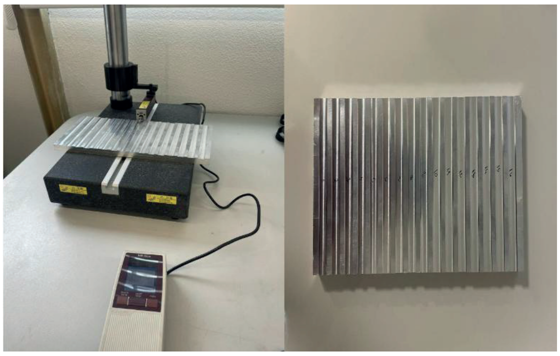

Figure 4 *Surface roughness measurement of machined surfaces using a digital contour measuring instrument – Mitutoyo*

The calculation of the S/N ratio based on the **'smaller-is-better'** criterion will be used for the surface roughness results, as a lower surface roughness value is considered desirable. The formula for calculating the **'smaller-is-better'** criterion is presented in expression (2) [5]. Generally speaking, the objective function of rough machining is to remove as much material as possible per unit time. In that case, the '**larger-is-better**' criterion is applied for the S/N ratio, which is obtained using expression (3) [3], [6].

$$S/_N = -10\log\left(\frac{1}{n}\cdot\sum_{i=1}^{n} y_i^2\right), \quad (2)$$

$$S/_N = -10\log\left(\frac{1}{n}\cdot\sum_{i=1}^{n} \frac{1}{y_i^2}\right). \quad (3)$$

The following table presents the results of the experimental work:

Table 5 Experimental result values and S/N ratio calculations for surface roughness and MRR

Input parameters			Output parameters			S/N ratio	
Spindle speed	**Cutting depth**	**Feed rate**	**Ra1**	**Ra2**	**MRR**	**S/N Ra**	**S/N MRR**
3000	**0,5**	**800**	0,69	0,397	4,8	4,991401	13,62482
3000	**1**	**1200**	1,06	0,899	14,4	0,150676	23,16725
3000	**1,5**	**1600**	1,006	1,197	28,8	-0,87221	29,18785
3000	**2**	**2000**	1,214	1,178	48	-1,55561	33,62482
4000	**0,5**	**1200**	0,605	0,945	7,2	2,00987	17,14665
4000	**1**	**800**	0,695	0,999	9,6	1,304673	19,64542
4000	**1,5**	**2000**	1,031	1,571	36	-2,46868	31,12605
4000	**2**	**1600**	1,126	1,094	38,4	-0,90736	31,68662
5000	**0,5**	**1600**	0,926	0,681	9,6	1,800493	19,64542
5000	**1**	**2000**	1,116	1,023	24	-0,59182	27,60422
5000	**1,5**	**800**	0,476	0,963	14,4	2,388449	23,16725
5000	**2**	**1200**	0,804	1,092	28,8	0,364766	29,18785
6000	**0,5**	**2000**	0,914	0,942	12	0,648052	21,58362
6000	**1**	**1600**	0,869	0,962	19,2	0,755643	25,66602
6000	**1,5**	**1200**	0,629	0,95	21,6	1,877081	26,68908
6000	**2**	**800**	0,383	0,635	19,2	5,607352	25,66602

3.1. S/N Ratio Analysis for Surface Quality

Statistical performance measures expressed through S/N ratios based on the '**smaller-is-better**' criterion result in a diagram of the effects of process parameters on the surface quality, shown in Figure 6. From the main effects plot, it is evident that the spindle speed and depth of cut exhibit a nonlinear nature, while the feed rate shows the most dominant influence on the value of the arithmetic mean deviation of the profile and is inversely proportional to it. The individual effects of the process parameters influence the arithmetic mean deviation of the profile in different ways. Higher S/N ratio values correspond to better responses, and based on this, the minimum arithmetic mean deviation of the profile is obtained at a maximum spindle speed of n = 6000 rpm, minimum depth of cut a = 0,5 mm, and minimum feed rate f = 800 mm/min.

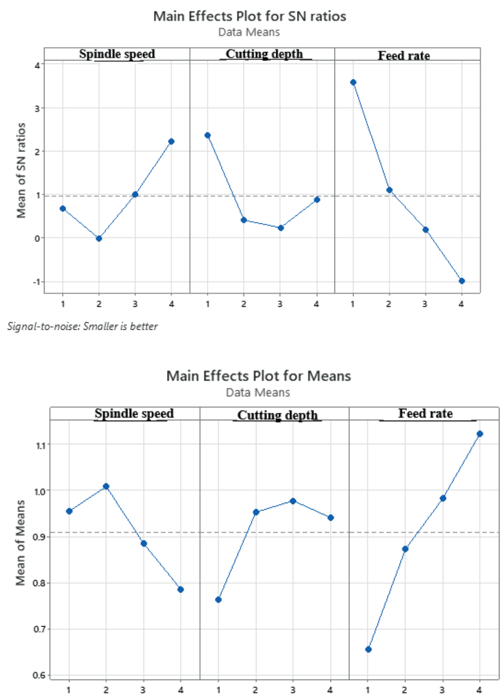

Figure 5 *Effect diagram for S/N ratios based on the 'smaller-is-better' criterion for the arithmetic mean deviation of the profile, and effect diagram for mean values*

Statistical analysis of the data using ANOVA software clearly confirms the above observations, indicating that the feed rate is the most dominant parameter, ranked first. The remaining two parameters follow in decreasing order of significance. All parameters fall within the defined significance threshold of 5% ($p \leq 0{,}05$), classifying them as statistically significant.

Table 6 Analysis of variance and ranking of machining process parameters for the S/N ratio '**smaller is better**'

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Rank
Spindle speed	3	10,496	10,496	3,4985	4,75	0,05	2
Cutting depth	3	11,251	11,251	3,7505	5,09	0,044	3
Feed rate	3	44,976	44,976	14,9919	20,35	0,002	1
Residual error	6	4,420	4,420	0,7366			
Total	15	71,142					

For the 'smaller is better' criterion, lower values of the ratio on the mean values effect diagram represent better responses. The graphical interpolation of the machining parameters' impact on surface roughness shows the parameter values that allow for achieving the highest surface quality. Based on Figure 6, it can be concluded that the highest surface quality is achieved with the combination of process parameter values $n = 6000$ rpm, $a = 0{,}5$ mm, and $f = 800$ mm/min. Residual analysis (Figure 7) shows that the residuals follow a normal distribution, confirming that the previous statements are valid.

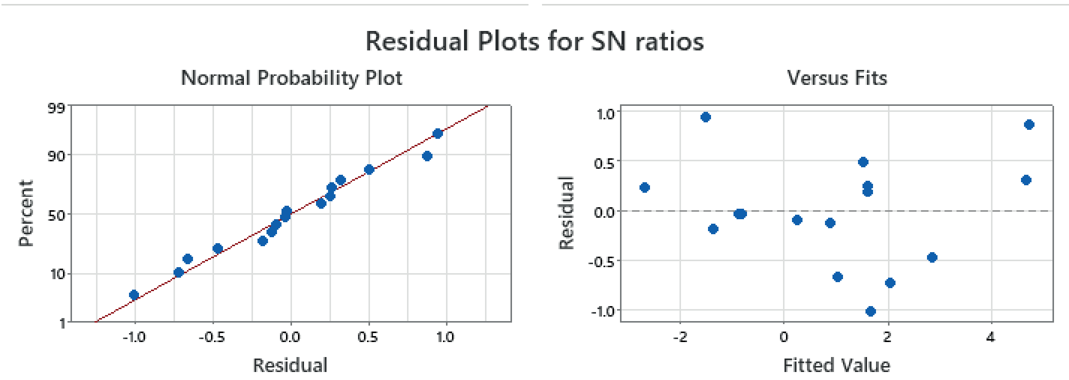

Figure 6 *Residual analysis and the residual dispersion diagram for surface roughness*

3.2. Analysis of the Mean Values of Material Removal Rate (MRR)

The material removal rate (MRR) per unit time is determined based on expression (1) and, as such, is not subject to changes regardless of how many times the experiment is repeated. This approach is considered deterministic. According to the effect diagram for mean values (Figure 8), it can be clearly concluded that the relationships between machining parameters are of a linear nature, with cutting depth and feed rate being directly proportional to the material removal rate. As the values of cutting depth and feed rate increase, so does the material removal rate. The cutting depth has the most significant impact on MRR.

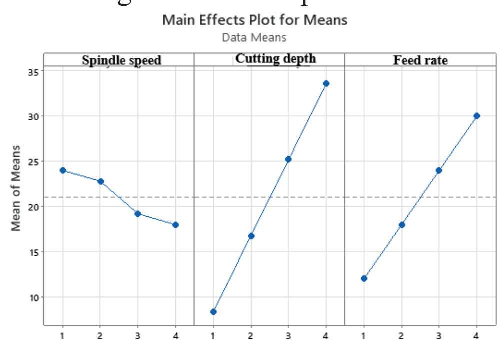

***Figure** 7 Effect diagram for mean values based on the 'larger is better' criterion for material removal rate (MRR)*

Statistical analysis of the data using ANOVA software, within the defined significance threshold of 5% (p ≤ 0,05), clearly confirms the above statements, according to which the cutting depth is the most dominant parameter and is ranked first. The other two parameters follow in order. The only parameter that is not statistically significant is the spindle speed.

Table 7 Analysis of variance for the value of MRR (Material Removal Rate)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Rank
Spindle speed	3	97,92	97,92	32,64	4,25	0,062	3
Cutting depth	3	1411,2	1411,2	470,4	61,25	0	1
Feed rate	3	720	720	240	31,25	0	2
Residual error	6	46,08	46,08	7,68			
Total	15	2275,2					

Graphical interpolation of the impact of machining parameters on material removal rate (MRR) shows the parameter values that allow achieving the objective function. Based on Figure 8, it can be concluded that the objective function is achieved with the combination of parameters n = 3000 rpm, a = 2 mm, and f = 2000 mm/min.

4. PROCESS OPTIMIZATION – GREY RELATIONAL ANALYSIS

Grey Relational Analysis (GRA) is used to determine the optimal conditions of different parameters in order to achieve the best quality characteristics [7]. One of the features that distinguishes grey relational analysis from conventional statistical methods is that this approach allows the evaluation of quantitative and qualitative relationships between process parameters and output variables based on relatively small amounts of data. Using this method, the degree of relationship between sequences is measured through grey relational grading. Grey relational analysis has been applied by several researchers for the optimization of control parameters with multiple responses through grey relational grading. Using this method, it is possible to determine the optimal parameter settings for each input factor, with the analysis consisting of several steps:

1. Normalization of experimentally measured characteristics to a dimensionless quantity in the range of 0-1, as follows:

- For surface roughness based on the ‘smaller is better’ criterion:

$$x_i^*(\mathrm{k}) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - min\, x_i^0(k)}, \quad (4)$$

- For material removal rate (MRR) based on the ‘larger is better’ criterion:

$$x_i^*(\mathrm{k}) = \frac{x_i^0(k) - \max x_i^0(k)}{\max x_i^0(k) - min\, x_i^0(k)}, \quad (5)$$

2. Calculation of deviation according to expression (6):

$$x_i^*(\mathrm{k}) = 1 - \frac{|x_i^0(k) - x_i^0|}{\max x_i^0(k) - x_i^0(k)}, \quad (6)$$

3. Determination of the Grey Relational Coefficient (GRC):

$$\xi_i(\mathrm{k}) = \frac{\Delta_{min} + \xi \cdot \Delta_{max}}{\Delta_{0i}(\mathrm{k}) + \xi \cdot \Delta_{max}}, \quad (7)$$

4. Calculation of the Grey Relational Grade (GRG) using expression (8):

$$y_i = \frac{1}{n} \cdot \sum_{k=1}^{n} \xi_i(\mathrm{k}). \quad (8)$$

The following table will present the calculated values of normalized values using expressions (4) and (5), deviations calculated using expression (6), the calculation of the Grey Relational Coefficient (GRC) using expression (7), and finally, the calculation of the Grey Relational Grade (GRG) using expression (8), based on which the experimental parameters are ranked. Since equal importance is given to both parameters, the recognizability coefficient is $\xi = 0{,}5$.

Table 8 The calculated values of the Grey Relational Coefficient, Grey Relational Grade, and S/N ratio for the Grey Relational Grade:

No.	Normalized parameters		Deviation		Grey Relational Coefficient (GRC)		Grey Relational Grade (GRG)		
	Ra	MRR	Ra	MRR	Ra	MRR	Grade value	Rank	S/N
1.	0,956439394	0	0,0435606	1	0,9198606	0,3333333	0,62659698	3	-4,060234
2.	0,405934343	0,22222222	0,5940657	0,7777778	0,457011	0,3913043	0,424157656	16	-7,4494538
3.	0,251893939	0,55555556	0,7481061	0,4444444	0,400607	0,5294118	0,465009372	11	-6,6507659
4.	0,132575758	1	0,8674242	0	0,365651	1	0,682825485	2	-3,3138056
5.	0,664141414	0,05555556	0,3358586	0,9444444	0,5981873	0,3461538	0,472170579	9	-6,5180216
6.	0,573232323	0,11111111	0,4267677	0,8888889	0,5395095	0,36	0,449754768	13	-6,9404845
7.	0	0,72222222	1	0,2777778	0,3333333	0,6428571	0,488095238	8	-6,2299086
8.	0,241161616	0,77777778	0,7588384	0,2222222	0,3971916	0,6923077	0,544749634	4	-5,2760611
9.	0,628156566	0,11111111	0,3718434	0,8888889	0,5734975	0,36	0,466748733	10	-6,618337
10.	0,29229798	0,44444444	0,707702	0,5555556	0,4140094	0,4736842	0,44384681	14	-7,0553379
11.	0,734217172	0,22222222	0,2657828	0,7777778	0,6529266	0,3913043	0,522115488	5	-5,6446685
12.	0,445707071	0,55555556	0,5542929	0,4444444	0,4742515	0,5294118	0,501831631	7	-5,9888394
13.	0,470959596	0,16666667	0,5290404	0,8333333	0,4858896	0,375	0,430444785	15	-7,321651
14.	0,486742424	0,33333333	0,5132576	0,6666667	0,4934579	0,4285714	0,461014686	12	-6,7257048
15.	0,645833333	0,38888889	0,3541667	0,6111111	0,5853659	0,45	0,517682927	6	-5,7187232
16.	1	0,33333333	0	0,6666667	1	0,4285714	0,714285714	1	-2,922560

The optimal value of the output parameters is represented by the highest value of the grey relational grade. According to the Table 8, the number of experimental design which has the highest Grey Relational Grade value is appointed. It can be concluded that this combination of process parameters will achieve the optimum balance between surface quality and material removal rate (MRR). The research determined that the optimal values of MRR and Ra are achieved with the input parameter combination A4-B4-C1, corresponding to the following input values: spindle speed $n = 6000$ rpm, depth of cut $a = 2$ mm, and feed rate $f = 800$ mm/min.

To confirm the previous analysis, an additional verification is introduced using the statistical performance measure of the S/N ratio for the Grey Relational Grade (GRG) with the "larger is better" criterion. The S/N ratio value for this criterion is calculated based on expression (3). From the effect diagram shown in Figure 8, it can be concluded that all three parameters have a curvilinear nature of influence, with cutting depth having the most dominant role on GRG. Higher values of the S/N ratio correspond to a better response. From the effect diagram, it can be concluded that the optimal values of the process parameters in coded form will be A1-B4-C1, with the corresponding natural values: $n = 3000$ rpm, $a = 2$ mm, and $f = 800$ mm/min.

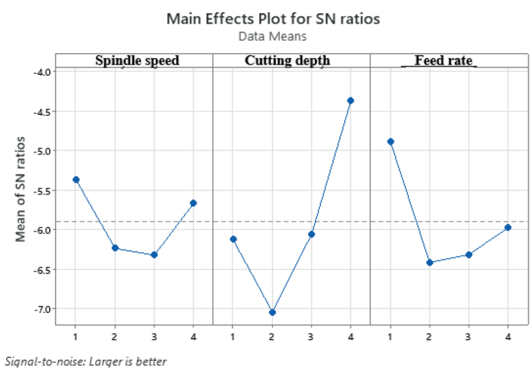

***Figure 8** The effect diagram for S/N ratios based on the 'larger is better' criterion for the Grey Relational Grade (GRG)*

The coefficient of determination for the Grey Relational Grade (GRG) is 81,45%. The analysis of variance through the defined significance threshold of p ≤ 0,05 shows that cutting depth is the only parameter that significantly affects the given dataset. This confirms the statement presented in Figure 8.

Table 9 The analysis of variance for the Grey Relational Grade (GRG) values is as follows:

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Rank
Spindle speed	3	2,531	2,531	0,8438	0,96	0,471	3
Cutting depth	3	14,837	14,837	4,9455	5,61	0,036	1
Feed rate	3	5,864	5,864	1,9548	2,22	0,187	2
Residual error	6	5,293	5,293	0,8821			
Total	15	28,525					

The main effects diagram (Figure 9) revealed the cause of the relatively low coefficient of determination. Specifically, according to Table 8, optimization is achieved with the processing parameters A4-B4-C1, while the diagram showed a new combination A1-B4-C1. This combination is not included in the Taguchi experimental design. In addition to the influence of parameters not covered by the Taguchi experimental plan, the authors Hakan Arslan and Faruk Onmaz in [11] describe the significant impact of vibrations on surface quality. Uncontrolled vibrations can result in uneven contact between the tool and the material, leading to an unstable cutting process and increased tool wear. In order to ultimately determine the optimal values of the output parameters, it is necessary to predict the grey relational grade for the parameter combination A1-B4-C1. To finally determine the optimal values of the process parameters, it is necessary to predict the Grey Relational Grade for the combination of parameters A1-B4-C1. This predicted value is then compared with the Grey Relational Grade value from Table 8. The Grey Relational Grade value for the combination of input parameters A4-B4-C1 is 0,71428, while the predicted value for the combination of input parameters A1-B4-C1 is 0,71234. This grade indicates that the computational/table approach will be adopted for the optimal value. Based on the optimization model from Table 8, and the combination of input processing parameters A4-B4-C1, a control experiment was conducted, and the results were shown in Table 10.

Table 10 Comparison of the values for the surface quality and the amount of material removed

Ra_{sr}	Ra_{opt}	MRR
0,509	0,512	19,2

The deviation in the surface quality achieved by applying the optimized parameters compared to the experimental surface quality value is:

$$\varepsilon_{Ra} = \frac{Ra_{opt} - Ra_{sr}}{Ra_{sr}} \cdot 100\% = \frac{0,512 - 0,509}{0,509} \cdot 100\% = \mathbf{0,59\ \%.}$$

According to Table 10, it can be clearly concluded that the combination of parameters A4-B4-C1 achieves optimal machining performance when milling. This combination of input parameters results in a surface roughness of 0,512 μm and a material removal rate (MRR) of 19,2 cm^3/min. The obtained surface quality value falls within the roughness class between N5 and N6, which categorizes it as a fine machining process.

5. CONCLUSIONS

In this study, Grey Relational Analysis (GRA) based on the Taguchi method was used to determine the optimal parameter values for the arithmetic average surface roughness (Ra) and the material removal rate (MRR) in the milling process of the aluminium alloy AW 7075, which is one of the most commonly used alloys at the production facility of the company Mann+Hummel in Tešanj.

The input parameters in the milling process were the machining conditions: spindle speed, cutting depth, and feed rate. The machining system used was a HURCO CNC milling machine with constant lubrication conditions and a cutting tool, a 12 mm diameter end mill with 4 cutting edges. The final result of the experimental research is the optimization of the output parameters of surface quality, measured by the arithmetic average deviation Ra, and the material removal rate (MRR) in terms of the quantity of material removed per unit time. Based on the conducted experimental research, the following conclusions can be drawn:

- The application of Grey Relational Analysis based on the Taguchi method allows for the direct combination of multiple qualitative responses (Ra and MRR) into a single performance indicator through the Grey Relational Grade (GRG). Based on the highest GRG value, it is shown that the optimal values for surface quality and material removal rate per unit time are achieved with a spindle speed of $n = 6000$ rpm, a cutting depth of $a = 2$ mm, and a feed rate of $f = 800$ mm/min. The optimal process parameter levels can be abbreviated as A4-B4-C1.
- The analysis of variance of the Grey Relational Grade values has shown that the cutting depth has the most significant impact on the multiple performance characteristics compared to the other parameters.
- Based on the optimal parameter levels, a third experiment was conducted, resulting in a surface quality of 0,512 μm and a material removal rate of 19,2 cm^3/min.

6. REFERENCES

[1] Simeone, S., D. Sanpeng, Z. Shengcheng, M. Yaser, Y. Xianqi, W. Tong, and D. Jingle. *Study and investigate effects of cutting surface in CNC milling process for aluminum based on Taguchi design method. International Journal of Engineering Research & Technology (IJERT)* 2, No. 12 (2019): 288–295.

[2] Ranganath, M. S., V. P. Vipin, S. M. Radhey, and R. D. Nikhil. *Optimization of surface roughness in CNC turning of aluminium 6061 using Taguchi techniques. International Journal of Engineering Research & Technology (IJERT)* 5, No. 5 (2015): 42–45.

[3] Begović E., S. Ekinović, and D. Ključanin. *Grey relational multi-parametric Taguchi based optimization of the process parameters in aluminium face milling. Annals of Faculty Engineering Hunedoara – International Journal of Engineering* 16 (2018): 165–170. ISSN 2601-2330 (online).

[4] Subham, Ch., S. Bikramjeet, S. Jasgurpreet, A. H. Shanin, and Sh. Ankusha. *Measuring of surface roughness of Al-6061 alloy by CNC milling by using of Taguchi method. E3S Web of Conferences* 588 (2024): 03025.

[5] Putra, Y. M., G. E. Timuda, N. Darsono, N. Chollacoop, and D. S. Khaerudini. *Optimization of machining parameters on the surface roughness of aluminum in CNC turning process using Taguchi method. International Journal of Innovation in Mechanical Engineering & Advanced Materials (IJIMEAM)* 5, No. 2 (2023): 56–62.

[6] Pang, J. S., M. N. M. Ansari, S. Omar, H. Moaz, and M. S. Sapuan. *Taguchi design optimization of machining parameters on the CNC end milling process of halloysite nanotube with aluminium reinforced epoxy matrix (HNT/Al/Ep) hybrid composite. Housing and*

Building National Research Center, HBRC Journal (2014): 138–144.

[7] Mustafic, A., S. Lovric, E. Nasic, J. Halilovic, M. Osmic, and D. Becirovic. *Taguchi-based grey relational analysis of performance characteristics in the MQL turning process of X5CrNi18-10 steel.* Presented at the 13th International Scientific Conference, Novi Sad, Serbia, September 28–29, 2018.

[8] Dilbag, S., and P. Venkateswara Rao. *Optimization of tool geometry and cutting parameters for hard turning*. *Materials and Manufacturing Processes* 22 (2007): 15–21. ISSN 1042-6914.

[9] Lovrić Sladjan, A. Topčić, E. Cerjakovic, and Herić M. *Techno-economic analysis of reverse engineering usage in design applications*. *Technics Technologies Education Management* 12, No. 2 (2017): 139–148.

[10] A. Mustafić, M. Mehmedović, and Becirovic D. *Influence of processing parameters of environmental-friendly cooling/lubrication strategy (MQCL) in turning of X5CrNi18-10 stainless steel*. *Technics Technologies Education Management* 15, No. 1 (2020): 18–29.

[11] Hakan, A., O. Faruk, and O. Sadettin. *Determination of optimum cutting parameters during operation with a double spindle milling machine of 7075 aluminum material. Uluslararası Mühendislik Araştırma ve Geliştirme Dergisi – International Journal of Engineering Research and Development (UMAGD)* 16, No. 1 (2024): 117–126.

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