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OPTIMIZATION OF HIGH-SPEED MACHINING PARAMETERS OF THIN-WALLED ALUMINIUM STRUCTURES IN THE FUNCTION OF SURFACE ROUGHNESS

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A B S T R A C T

Due to their homogeneity and excellent ratio between load capacity and weight, thin-walled aluminum structures are used as structural parts in the aerospace, automotive and military industries. The manufacture of these thin-walled structures is mainly done by removing a large amount of material from full raw pieces, sometimes up to 95% of their initial mass. Because of a large volume of material removing, it is necessary to achieve high productivity, which is limited by the lack of rigidity of the thin walls of these structures. As a result, errors occur, while reducing accuracy and machining quality. The main subject and objective of this paper is related to the optimization of high-speed machining parameters of linear thin-walled structures made of aluminum alloy Al7075 from the aspect of surface quality of processed superficial as a goal function. For this purpose, experiments were carried out based on which conclusions were made of the influence of input parameters on the surface roughness.

1. INTRODUCTION

Theory of optimization as a scientific discipline has a great application in solving engineering problems, where based on the set criteria of optimization, using optimization methods, the best solution is found on the selected object of optimization for certain conditions (Lukic et al., 2020).

Due to their homogeneity, corrosion resistance and excellent ratio between the load capacity and mass of thin-walled aluminum parts are increasingly used as structural parts in the aerospace, automotive, military, and other branches of the electro-mechanical industry. The production of thin-walled parts is mainly carried out by removing materials from full raw pieces. Due to such a large volume of material removal, it is necessary to achieve high productivity while ensuring the required accuracy and quality (Hirsch et al., 2013, Huang et al., 2015; Izamahah et al., 2011, Scippa et al., 2014, Sredanovic et al, 2022).

The object of research in this paper are linear type of thin-walled parts of aluminium alloy Al7075, thin-wall thickness 0.5-1.5 mm, moderate and large height in relation to wall thickness (20:1, 30:1 and 60:1).

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Machining process of these parts is very complex, because it requires the fulfillment of numerous structural and technological characteristics, for the realization of which it is necessary to use high-quality machining systems (machines, tools, fixtures, measuring instruments, workers), machining parameters, cooling and lubrication agent, etc. (Borojevic et al., 2018, Vukman, 2022).

The main subject and objective of the research in this paper refers to the optimization of parameters of high-speed machining of thin-walled linear parts made of aluminum alloy from the aspect of the quality of the surface roughness as a goal function.

2. REVIEW OF THE PROBLEM AND RESEARCH METHODOLOGY

By increasing the market demands for the machining of thin-walled parts, at the same time, research is being realized that is oriented towards optimizing the construction and technological processes of manufacturing these components. Optimization of the structure is carried out in order to reduce mass, deformation, vibration, or increase the loading capacity and strength, while the optimization of technological processes is carried out in order to reduce machining time and cost, increase the accuracy and surface roughness, etc. (Bolar, 2017; Borojevic, et al., 2018; Lukic et al., 2020; Popma, 2010; Vukman, 2022; Zhang et al., 2015). To analyze the influence of the parameters of thin-walled parts on the surface roughness, it was necessary to set up and realize experimental research, and then to analyze the results and make certain conclusions.

Taguchi's method of experiment planning is a unique and very powerful technique for experimental analysis and optimization of products, processes, etc. In order to eliminate the disadvantages of the classical planning of experiments, which are reflected in the too complex and time-consuming execution of a large number of experiments, an alternative was found in the Taguchi method based on the application of special, partial factorial plans obtained from orthogonal plans that cover the entire experimental space of interest, and with a minimum number of experiments (Athreya and Venkatesh, 2012, Dean et al., 2017; Deresse et al., 2020; Taguchi et al., 2005). Taguchi proposed an aggregate statistical evaluation that combines information about mean and variance into a single measure of performance, known as the signal-to-noise ratio (S/N ratio). For a more detailed examination of the importance of the influence of the main factors and their interactions on the response, analysis of variance (Analysis of Variance - ANOVA) can be used. Taguchi recommended analysis of mean values and S/N ratios using 2D response graphs instead of ANOVA analysis. Analysis of Means (ANOM) is a statistical approach that serves to determine the mean S/N ratios for each factor and each of its levels. There are three categories of S/N ratios, the smaller the better, the bigger the better and nominally the best (Montgomery, 2001; Taguchi et al.., 2005).

The procedure for planning experiments is based on a statistical approach and involves several activities: (a) identifying and formulating problems, (b) selecting dependent (output) variables (c) selecting independent (input) variables as well as levels and ranges of intervals, (d) choosing an experiment plan, (e) conducting experiments, (f) statistical processing and analysis of experimental data, (h) conclusions and recommendations.

3. EXPERIMENTAL RESEARCH

The main optimization task is to define the influence of input parameters: wall thickness (*a*), number of revolutions (*n*), feed ratio (*f*), depth of cut (*δ*) and tool path - TPS (*Tool Path Strategy*), on the surface roughness (*Ra*), Figure 1. Material of thin-walled parts is aluminum *alloy Al7075* (*AlZnMgCu 1.5*). Diameter of end mill for machining is 8 mm and consist of two cutting edges (Manuf. YG E5909080). The machine is a high-speed five-axis CNC machining center for milling - *DIGMA HSC 850*.

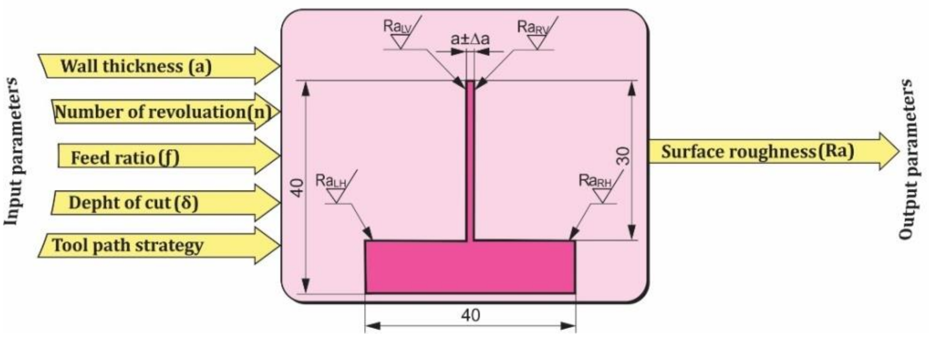


Figure 1. Model of experimental research (Lukić et al 2020; Vukman 2022)

For purpose of generated numerical control programs is used software *Cimatron 11*, where they were used machining strategies *climb, convencional and mixed.* Assuming that the mathematical relations between input parameters and process performance are complex and nonlinear, three levels of variation were selected for each of the five input parameters (Table 1). Based on selected variable process factors and corresponding levels of variation, an experimental matrix plan was created in accordance with *the standard Taguchi* orthogonal sequence L27. As stated in the research plan, the surface roughness was measured in 4 places, directed to the direction of tool movement (Table 2). Since it is a linear part, it is divided into left and right sides, so that the roughness of the left side of the horizontal and vertical *surfaces of* Ra_{LH} and Ra_{LV}, as well as the right sides *of* Ra_{RH} and Ra_{RV}, is measured. Roughness measurement was carried out using *the Mitutoyo SJ-301* device.

Table 1. Input parameters and leves of variations

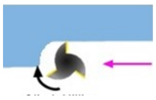
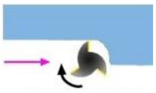
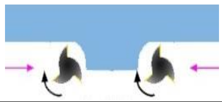
Parameter and label	Units	Level		
Wall tickness (a)	mm	0,5	1,0	1,5
Number of revolutions (n)	o/min	6000	12000	24000
Feed ratio (f)	mm/min	600	1200	2400
Depth of cut (δ)	mm	1	2	3
Tool Path Strategy (TPS) - Cimatron	-	Path 1 - climb 	Path 2 - convencional 	Path 3 - mixed 

Table 2. Measuring results of surface roughness - Ra

Exp. no	A	B	C	D	E	Ra_{vl}	Ra_{vd}	Ra_{hl}	Ra_{hd}	Ravsr= (Ravl+Ravd)/2	Rahsr= (Rahl+Rahd)/2	Rasr= (Ravsr+Rahsr)/2
1	0,5	6000	600	1	1	0,28	0,23	0,26	0,23	0,255	0,245	0,250
2	0,5	6000	1200	2	2	1,73	2,97	0,23	0,31	2,350	0,270	1,310
3	0,5	6000	2400	3	3	0,67	1,4	0,69	0,56	1,035	0,625	0,830
4	0,5	12000	600	2	3	0,57	1,45	0,81	0,54	1,010	0,675	0,843
5	0,5	12000	1200	3	1	0,52	0,54	0,15	0,14	0,530	0,145	0,338
6	0,5	12000	2400	1	2	1,35	1,41	0,36	0,32	1,380	0,340	0,860
7	0,5	24000	600	3	2	0,88	0,42	0,22	0,12	0,650	0,170	0,410
8	0,5	24000	1200	1	3	0,84	0,27	0,21	0,26	0,555	0,235	0,395
9	0,5	24000	2400	2	1	0,32	0,23	0,36	0,26	0,275	0,310	0,293
10	1,0	6000	600	2	2	2,56	2,94	0,36	0,27	2,750	0,315	1,533
11	1,0	6000	1200	3	3	0,2	0,21	1,68	0,23	0,205	0,955	0,580
12	1,0	6000	2400	1	1	0,56	0,29	0,54	0,65	0,425	0,595	0,510
13	1,0	12000	600	3	1	0,13	0,16	0,11	0,15	0,145	0,130	0,138
14	1,0	12000	1200	1	2	0,89	1,2	0,28	0,16	1,045	0,220	0,633
15	1,0	12000	2400	2	3	0,38	0,3	0,61	2,73	0,340	1,670	1,005
16	1,0	24000	600	1	3	0,34	0,15	0,11	0,14	0,245	0,125	0,185
17	1,0	24000	1200	2	1	0,3	0,15	0,15	0,17	0,225	0,160	0,193
18	1,0	24000	2400	3	2	0,6	0,25	0,17	0,2	0,425	0,185	0,305
19	1,5	6000	600	3	3	0,61	0,16	0,13	0,13	0,385	0,130	0,258
20	1,5	6000	1200	1	1	0,66	0,22	0,36	0,29	0,440	0,325	0,383
21	1,5	6000	2400	2	2	3,27	2,22	1,35	1,08	2,745	1,215	1,980
22	1,5	12000	600	1	2	2,05	1,92	0,3	0,37	1,985	0,335	1,160
23	1,5	12000	1200	2	3	2,93	1,39	0,45	0,54	2,160	0,495	1,328
24	1,5	12000	2400	3	1	0,39	0,7	0,28	0,26	0,545	0,270	0,408
25	1,5	24000	600	2	1	0,16	0,11	0,21	0,12	0,135	0,165	0,150
26	1,5	24000	1200	3	2	0,45	0,3	0,13	0,21	0,375	0,170	0,273
27	1,5	24000	2400	1	3	1,36	0,22	0,27	0,17	0,790	0,220	0,505

4. OPTIMIZATION OF MACHINING PARAMETERS IN THE FUNCTION OF SURFACE ROUGHNESS

In the analysis of the obtained surface roughness following factors are observed wall tickness (A), number of revulation (B), feed ratio(C), depth of cut (D) and tool path strategy (E). Since the goal is to make the surface roughness as low as possible, Smaller is better) was chosen.

The S/N values for each factor are shown in Table 3. The mean S/N response for each influential factor is shown in Table 4.

Figure 2 shows the S/N response for the surface roughness by influence factors, while Figure 3 shows the response of the medium arithmetic surface roughness of influence factors.

Table 3. S /N response for surface roughness

Level	A	B	C	D	E
1	5,560	3,598	8,492	6,544	11,352
2	7,480	4,161	6,151	3,163	2,374
3	5,772	11,053	4,169	9,106	5,086
Difference	1,921	7,455	4,323	5,943	8,978
Rank	5	2	4	3	1

Table 4. Response of surface roughness by influencing factors

Level	A	B	C	D	E
1	0,6142	0,8481	0,5472	0,5422	0,2956
2	0,5644	0,7456	0,6033	0,9592	0,9403
3	0,7158	0,3008	0,7439	0,3931	0,6586
Difference	0,1514	0,5472	0,1967	0,5661	0,6447
Rank	5	3	4	2	1

By analyzing the results, which are presented in Table 3 and Figure 2, it can be concluded that the greatest impact on the surface roughness has the tool path strategy, the number of revolutions and the depth of cut.

Based on Table 4 and Figure 3, the optimal input parameters within the offered factor levels can be determined, based on the goal function "the lower the value the better".

The results of the ANOVA analysis show that of the five inputs, f-values of factors related to number of revolutions, depth of cut and tool path strategies are greater than the critical value of Fcr (Fcr = 3.35, for a confidence level of 95%), implying that these factors are significant compared to the error factor and have a significant impact on the responsive surfaces. While on the other hand wall thickness and feed ratio do not have a significant impact because their F-values are less than the critical Fcr value.

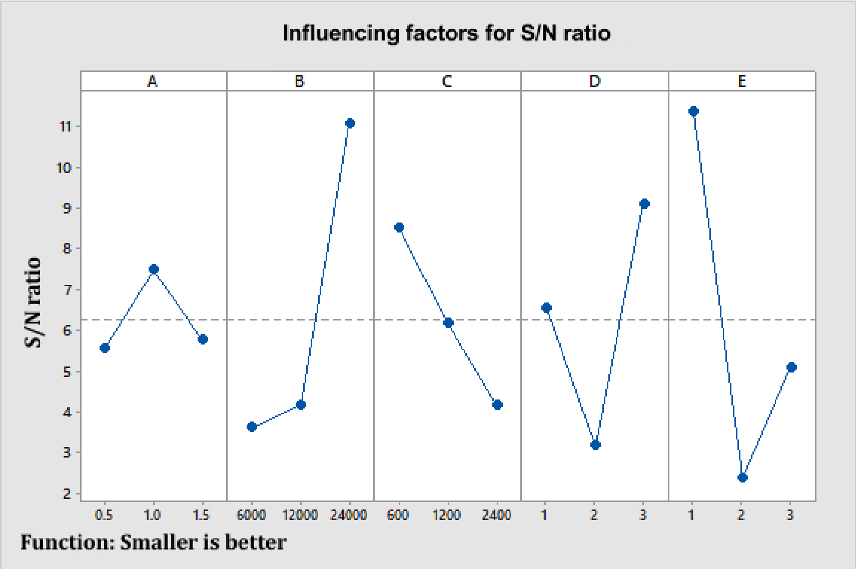


Figure 2. S/N response for surface roughness

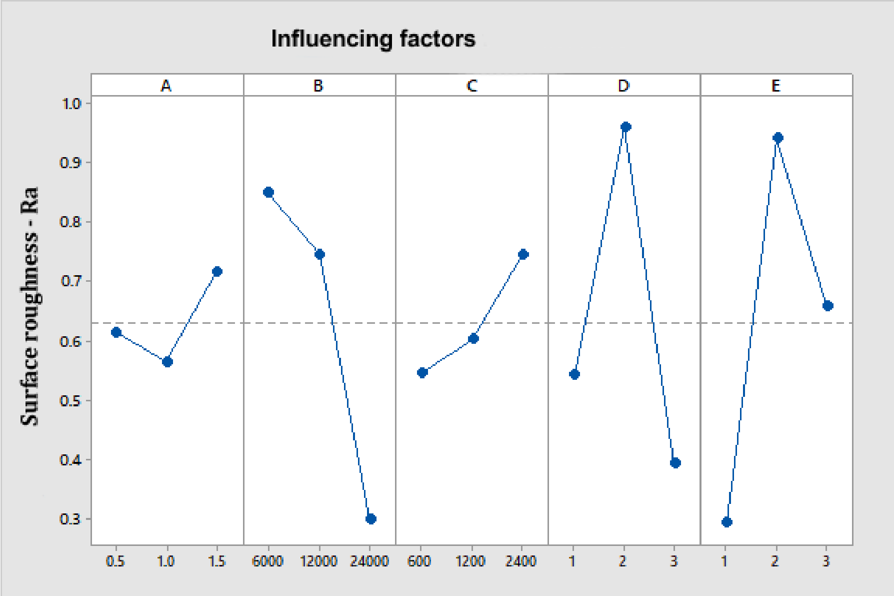


Figure 3. Response of surface roughness by influencing factors

The use of percentage share (%P) in ANOVA analysis is an auxiliary solution for quantitative evaluation of impact factors on responsive surfaces. Wall thickness affects with 1.80%, the number of revolutions affects with 25.51%, feed ratio affects with 3.09%, the depth of cut affects with 25.95%, and the greatest impact on the surface roughness a tool path strategy with 31.49%. The error of the experiment is 12.51%, that is, the influence of other factors that were not considered in this experiment.

After defining optimal input parameters, optimal responses are predicted using Taguchi and ANOVA methods. The prediction of optimum input parameters in order to obtain the least surface roughness applied by Taguchi's method was found at the following level: A2-B3-C1-D3-E1.

Figure 4 shows Taguchi's predictive results for optimal input parameters using MiniTab software. After finding the optimal input parameters of the obtained S/N response, the dependence of the input factors on the surface roughness Ra was obtained.

Using regression analysis, a regression equation (1) was obtained for a linear model of input factor.

Ra=0,6315 - 0,0173 A_0,5 - 0,0670 A_1,0 + 0,0844 A_1,5 + 0,2166 B_6000 + 0,1141 B_12000 - 0,3306 B_24000 - 0,0843 C_600 - 0,0281 C_1200 + 0,1124 C_2400 - 0,0893 D_1+ 0,3277 D_2 - 0,2384 D_3 - 0,3359 E_1 + 0,3088 E_2 + 0,0271 E_3 (1)

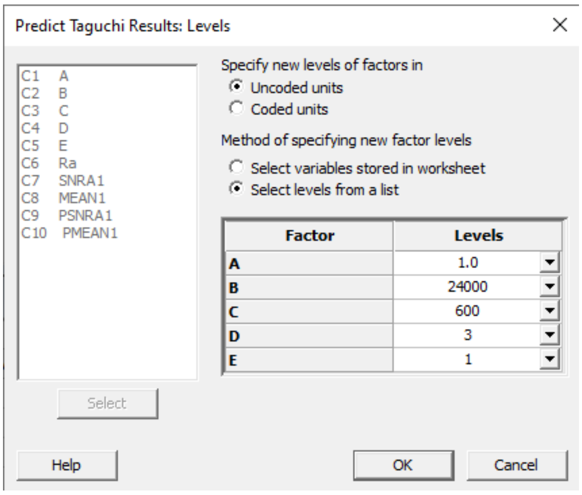


Figure 4. Taguchi predictive results for optimal input parameters

Table 5 shows the optimal input parameters, significant parameters as well as the prediction of the optimal response of the target function.

Table 5. Output results of analysis and optimization

Response	Optimal input parameters	Significant parameters	Prediction of optimal response	
			S/N Response	Value
Ra	A2-B3-C1-D3-E1	B-D-E	22,4003	0,0183

5. CONCLUSION

Based on the obtained results of the experiments, ANOVA analysis, regression analysis and finally optimization of the parameters of high-speed machining process of thin-walled linear parts made of alloy AL

7075 was performed. The paper implemented a one-criterion optimization of the criterion of surface roughness depending on the input factors, wall thickness, number of revolutions, feed ratio, depth of cut tool path strategies.

The analysis of the results concluded that the greatest impact on the surface roughness has the tool path strategy, depth of cut and the number of revolutions, and the smallest impact has wall thickness.

The tool path strategy has the greatest impact on the surface roughness, because the tool, depending on the path or the tool-contour movement, leaves a trace, while the wall thickness at lower machining cutting conditions does not affect because the vibration smaller.

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