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Research Article

DETERMINATION OF OPTIMUM CUTTING PARAMETERS ON FREE FORM SURFACES IN TERMS OF FORM ERRORS AND MACHINING TIMES

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ABSTRACT

In this study, the most suitable cutting conditions were determined from which obtained the lowest form error. Freeform surfaces were machined in CNC milling machine. In experiments, Al7075 series material was used because of its special features. Because Al7075 series material is frequently used in many areas with high strength and easy machinability. Firstly, four factor consisting of cutting speed, feed rate, step over, machining strategies were determined. Later, 4 levels were selected for the each factor according to manufacturer catalog of the cutting tool. After an experiment list was created. The Taguchi method was used while the creating of L_{16} ortogonal array. At the end of the experiments, form errors were found and signal noise (S/N) ratios determined with using the Taguchi method. The most suitable cutting conditions were determined as a result of the analyzes of expeiments. According to Taguchi method, the *2-3-1-1* orthogonal array outside the designed L_{16} was the optimum condition; So, the smallest form error value was obtained by 140 m/min cutting speed, 800 mm/min feed rate, 0.5 mm step over and parallel machining strategy. Also in this study, it was appeared that the cutting factors that affect form error, which are the step over, cutting speed, feed rate and machining strategies in order of importance. Moreover, in ANOVA results, step over showed significance at the 95% confidence level on form error. It is possible to comment on the best machining conditions according to the obtained machining times and form errors.

Keywords: Machining of Al7075, ANOVA, form error, Taguchi Method, 3D scanning.

1. INTRODUCTION

Today, freeform surfaces are widely using in many areas. It is very common in production of injection molds and bending molds, aircraft and space industry, automotive field, production of medical devices and manufacturing of precision machine parts [1]. The fact that the expense items of manufacturing expenditures are large and therefore the costs are also large and the tolerances are very low in the field of manufacturing, causes the production planning to become complicated [2]. In order to reduce these costs and to provide efficiency in the production of desired geometries and to obtain better quality surfaces, it is very important to define the cutting

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parameters which cause the surface roughness and the increase of the form errors, to reduce the possible errors to the minimum level [3, 4].

The determination of the form error from the indicia of surface accuracy and quality of the obtained product is generally referred to the comparison method [5]. In this method, the surface of the workpiece is scanned with a 3D optical scanner and the finished surface is obtained in computer environment. The surface found is compared with the designed surface, that is to say the CAD data, in the computer environment [6, 7].

Lacalle et al. presented a new methodology for the selection of the milling toolpaths on complex surfaces that minimize dimensional errors due to tool defection. In their study, optimum toolpath was selected for minimum deflection cutting forces in milling complex surfaces [8].

Wang et al. made a theoretical and experimental investigation into the effect of the workpiece material on surface roughness in the ultra-precision milling process. They proposed a new method to characterize material-induced surface roughness on the raster-milled surface. And they defined a new parameter to characterize the extent of surface roughness profile distortion induced by the materials being cut [9].

Wojciechowski and Mrozek investigated the measurement of acceleration of vibrations during the micro milling tests with variable feed per tooth and tool's axis inclination angle values. They predicted the micro ball end milling forces on the basis of mechanistic model considering run out, variable edge forces, and kinematics of low radial immersion milling with tool axis inclination. Subsequently, they conducted the optimization of the micro ball end milling process. They found that micro ball end milling with the optimally selected tool's axis slope along the toolpath and feed per tooth affects the minimization of milling vibrations and improvement in surface finish [10].

Karabulut produced AA7039/Al2O3 metal matrix composites using powder metallurgy and investigated the effect of milling parameters on surface roughness and cutting force using an uncoated carbide insert. The milling tests were performed based on the Taguchi design of experiment method using L_{18} 21x32 with a mixed orthogonal array. Also he determined the effects of the cutting parameters on surface roughness and cutting force using analysis of variance (ANOVA). In the analysis results, material structure was the most effective factor on surface roughness and feed rate was the dominant factor affecting cutting force [11].

Gök et al. analized the effects of cutting parameter and tool path style on cutting force and tool deflection in machining of convex and concave inclined surfaces. They determined that the increase of cutting force adversely affected on form error. And they also claimed that cutting forces are increasing with the growth of cutting speed [12].

In this study, the most suitable cutting parameters are determined to obtain the lowest form error in milling of freeform surfaces. Al7075 material which is frequently preferred today was used in our experiments. Form errors were measured at the end of these experiments. The influence of cutting parameters on the form error was determined using the Signal to Noise (S/N) values. At the end of the study, we determined the best cutting conditions on milling of free form surface and machining times.

2. MATERIALS AND METHOD

2.1. Materials

In this work, Al7075 material with free form surfaces, which are often used in plastic injection molds, is used. This material has been selected because its mechanical features are improved and machinability is high [13].The specimens were machined on a 3 axis CNC machine with ball nose end mill. The mechanical features and chemical composition of the material are shown in Table 1, designed surface and dimensions are given in Figure 1.

Table 1. Mechanical features and chemical composition of Al7075

Mechanical features		**Chemical composition**	
		Material	**(%)**
Tensile Strength	570 MPa	Zn	5.50
Yield Strength	505 MPa	Si	0.13
Density	2.8 gr/cm^3	Mn	0.30
Elongation	%11	Cr	0.28
Hardness	102 HRb	Ti	0.20
		Cu	2
		Mg	2.9
		Al	Base

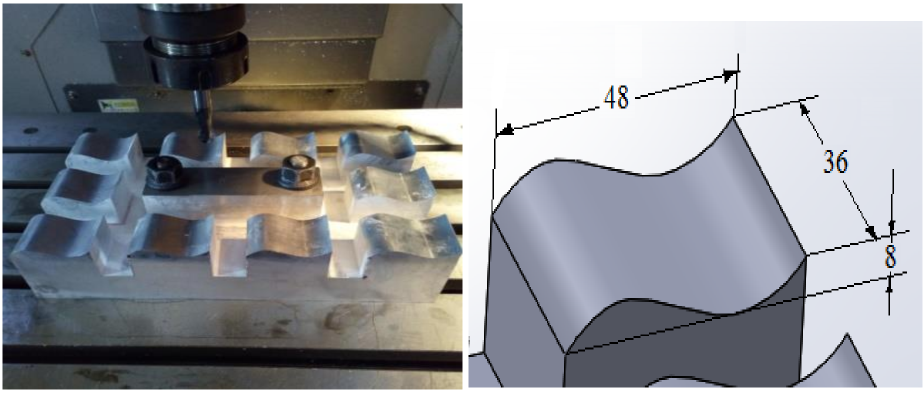


Figure 1. Overview of the machined surface and dimensions of the workpiece

It has been found that ball nose end mills are used when free form surfaces are machined according to the results of both industrial applications and literature researches. Therefore, in our experiments, TaeguTec branded (SBE 2120T TT1040) externally cooled tungsten carbide ball nose end mill of 12 mm of diameter with two cutting teeth, coated with TiAlN as 4 mm of thickness was selected as the cutting tool. The experiment specimens were machined on a 3-axis TAKUMA brand CNC machine tool. In Table 2, the geometric characteristics of the cutting tool and in Figure 2, 3 axis CNC machine tool's view are given. The workpieces were subjected to finish machining after the rough machining. 1 mm chip was allowed to finish machining. That is, the cutting depth was applied as 1 mm in finish process. The CNC tool paths are generated by using TEBIS V3.4 software employing 0.01 mm of tolerance.

Table 2. Geometric characteristics of the cutting tool

Geometric Features	**Value/Geometry**
Cutter type	Ball Nose End Mill
Cutting diameter (Dc)	12
Number of teeth (z)	2
Shank diameter (Dm)	12 mm
Cutting tool length (L)	110 mm
Cutting depth max. (L_1)	26 mm
Tip radius (R)	6 mm
Helix angle (yp)	30°

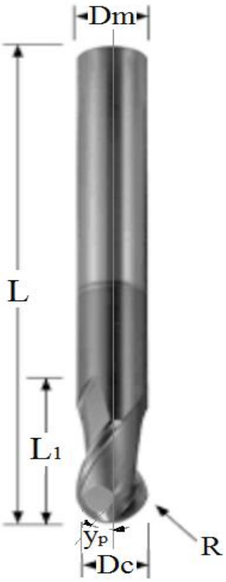


Figure 2. 3-axis CNC machine

2.2. Method

For the experiments, four cutting parameters were chosen. The levels of the determined cutting parameters have been selected according to catalog of the manufacturer of the cutting tool has specified. The selected cutting parameters and the determined levels are given in Table 3.

Table 3. Cutting parameters and levels.

Symbol	Cutting Parameters	Level 1	Level 2	Level 3	Level 4
A	Cutting speed (m/min)	100	140	180	220
B	Feed rate (mm/min)	200	500	800	1100
C	Stepover (mm)	0.5	0.8	1.1	1.4
D	Machining Strategy	Parallel	ZigZag	Spiral	One way

Four different machining strategies were determined for the experiments. Appropriate selection of tool path style affects the production time, surface condition and manufacturing cost [12]. In this study, parallel, zigzag, spiral and one-way machining strategies were selected. These are frequently used in the processing of free form surfaces. Selected machining strategies were shown in Figure 3.

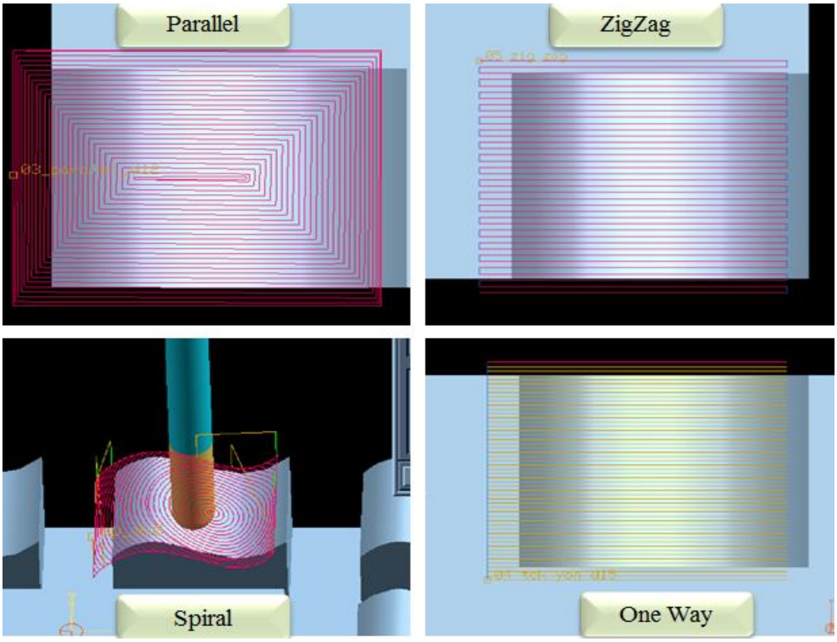


Figure 3. Machining strategies

Machined surfaces were scanned by optical scanning method to determine the form errors occurred on the surfaces. Scanning was performed with Qscan 3D optical scanner device. The data obtained by scanning were divided into sections for each test surface, and compared with the individual design surfaces. The form error values obtained by experiment design using L_{16} orthogonal array were found. 3D Scanning of surfaces were given in Figure 4.

Figure 4. The figure of 3D scanning of surfaces

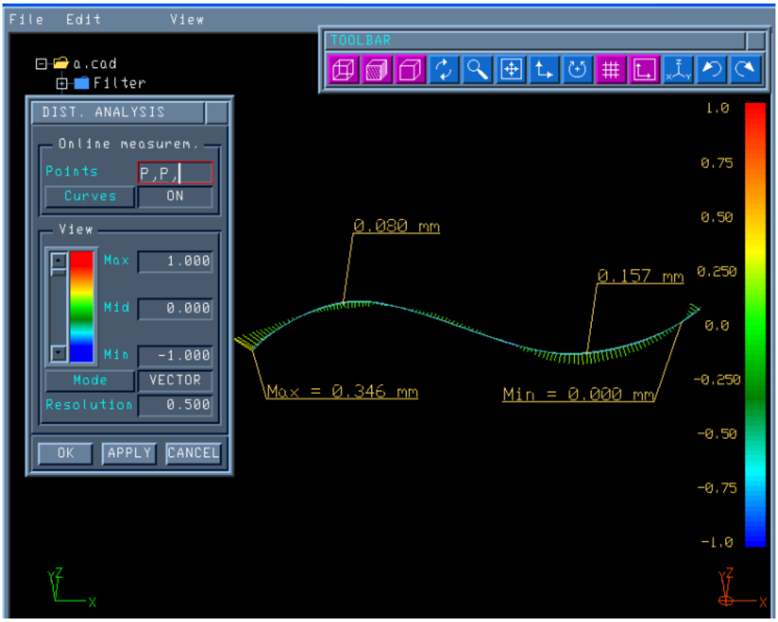
In the detection of the form errr, the data obtained from the scan results were divided into sections for each test surface, and the design surface and scanned surfaces were overlapped separately. A curve was created in the TEBIS V3.4 software to traverse the surface from the midpoints of the scanned surfaces and CAD data surfaces before the surfaces were overlapped. Points were determined randomly in equal coordinates over both lines. Maximum positive and negative deviations were investigated by the points along the two curves. In addition, the information about areas prone to most of the form errors were also obtained in this way. Thus, form errors on the surfaces were detected. The obtained form error values are shown in Table 4. In Figure 5, determination of form error values for initial experiment in TEBIS V3.4 software was given.

Table 4. Generated L_{16} experiment design results, S/N rates and machining times

Experiment Number	**Symbol**				**Form Error (mm)**	**Signal/Noise (S/N)**	**Machining Time (s)**
	A	**B**	**C**	**D**			
1	1	1	1	1	0.346	9.143	1515
2	1	2	2	2	***0.334***	***9.319***	370
3	1	3	3	3	0.506	4.166	204
4	1	4	4	4	0.820	1.670	150
5	2	1	2	3	0.431	7.535	1040
6	2	2	1	4	0.369	8.946	782
7	2	3	4	1	0.664	3.715	149
8	2	4	3	2	0.554	4.989	125
9	3	1	3	4	1.248	-2.028	827
10	3	2	4	3	1.324	-2.516	276
11	3	3	1	2	0.394	6.357	370
12	3	4	2	1	0.642	4.082	181
13	4	1	4	2	1.527	-3.613	560
14	4	2	3	1	0.727	2.745	296
15	4	3	2	4	0.363	8.777	329
16	4	4	1	3	0.436	7.130	293

2.3. Analyze of Results in Taguchi Method

In this section, with Taguchi method, we have determined the most appropriate machining conditions to reach the lowest form error. A large number of experiments have to be carried out when the number of the process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. This is accomplished by choosing the signal to noise ratio (S/N), which is the smaller is better [15]. For the form error analysis, MINITAB software was used to find the best value of the smallest equation and the level values of the signal noise ratios were found [16]. The levels of S/N ratios found at the end of the equation are given in Table 4.



Points P,P,
Curves ON
Max 1.000
Mid 0.000
Min -1.000
Mode VECTOR
Resolution 0.500

Figure 5. Determination of form error values for initial experiment in TEBIS V3.4 software

The signal/noise ratios were high in experiments where the form error was smaller. The response table of form errors were given in Table 5 and parameter levels were given in Figure 6 according to the smaller-better of form error. The smallest form error among the 16 experiments is seen in second experiment. But according to Taguchi analysis, as can be seen in Figure 6, the 2-3-1-1 orthogonal array was the most appropriate condition outside the L_{16}. So the smallest form error value was obtained by 140 m/min cutting speed, 800 mm/min feed rate, 0.5 mm step over and parallel machining strategy. The order of significance of factors affecting the form errors are shown in Table 5. We also understand in this table, the cutting factors that affect form error, which are the step over (C), cutting speed (A), feed rate (B) and machining strategy (D) by order of importance.

Table 5. The response table of form errors

Level	A	B	C	D
1	6.075	2.759	**7.894**	**4.921**
2	**6.296**	4.623	7.428	4.263
3	1.473	**5.754**	2.468	4.079
4	3.760	4.468	-0.186	4.341
Delta	4.822	2.995	8.080	0.842
Rank	2	3	1	4

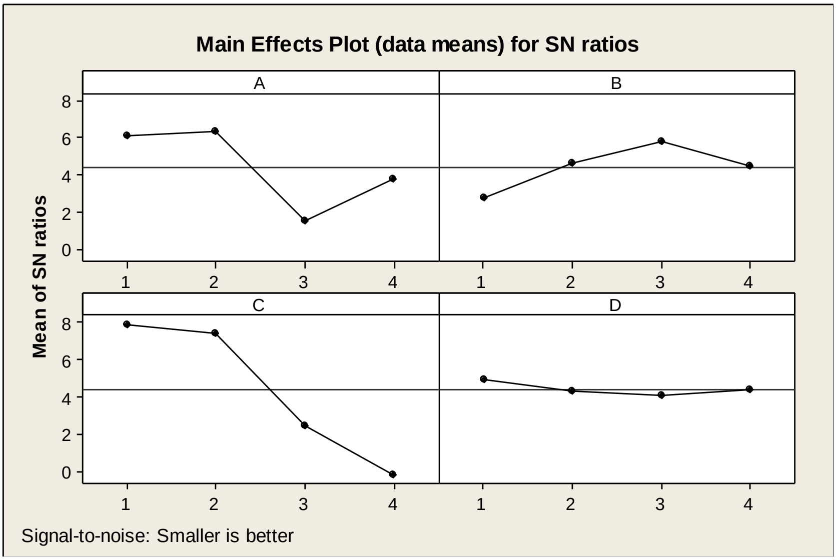


Figure 6. Parameter levels according to the smaller-better of form error

As a result of the Taguchi analysis, the form error values were measured by performing a control experiment for the 2-3-1-1 array that gives an optimal form error. It was machined with the cutting parameters in the 2-3-1-1 array. Then the machined surface was scanned and compared to the design surface.The measured form error value confirms Taguchi's analysis. Among the experiments conducted, the smallest form error was found as a result of this process. Form error values are shown in Table 6.

Table 6. Control experiment for 2-3-1-1 orthogonal array

Symbol				**Form Error (mm)**	**Machining Time (s)**
A	**B**	**C**	**D**		
2	3	1	1	0.321	480

2.3.1. ANOVA results of form error

When determining the most suitable cutting conditions at S/N ratios using with the Taguchi, the correlation among the factors was determined through analysis of variance. That is, the correlation among the feed rate, the cutting speed, the step over, and the machining strategy of S/N ratios, can be assessed. The ANOVA output of the S/N ratios is given in Table 7.

Table 7. The correlation among the four factors in S/N for form error

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A	3	2.28	2.28	1.14	9.07	*0.099*
B	3	0.25	0.25	0.12	0.99	*0.504*
C	3	51.06	51.06	25.53	82.83	***0.005***
D	3	0.08	0.08	0.06	0.21	*0.740*
Residual Error	3	0.18	0.18	0.07		
Total	15	53.67				

P value during a comparison about the amount of a possible mistake tells us “there is a statistically significant difference”, we want to make. If the P value falls below 0.05 found the results of experiments, there is a meaningful difference in the comparison results [17,18]. According to ANOVA results, the step over, cutting speed, feed rate, machining strategy are in order of the most significant value. Also the step over showed meaningfulness at the 95% confidence level with 0.005 P.

2.3.2. The Effect of Cutting Parameters on Form Error

In Figure 7, it appears that as the cutting speed increases, the S/N rates increases in parallel with this. It was observed that the form erros are decreased while the cutting speed is increased. When the step over increased, the form error were obviously increased. The increase in the step over negatively affects the form error. At different levels of feed rates, the form error also appears to decreased. This may be due to environmental factors during machining , tool deflection or from the vibration on the table. However, in generally, increases in feed rates values were caused the rise in form error. As shown in Figure 7, optimum levels for form error are second level for cutting speed (140 m/min), third level for the feed rate (800 mm/min), first level for step over (0.5 mm) and first level for machining strategies (Parallel).

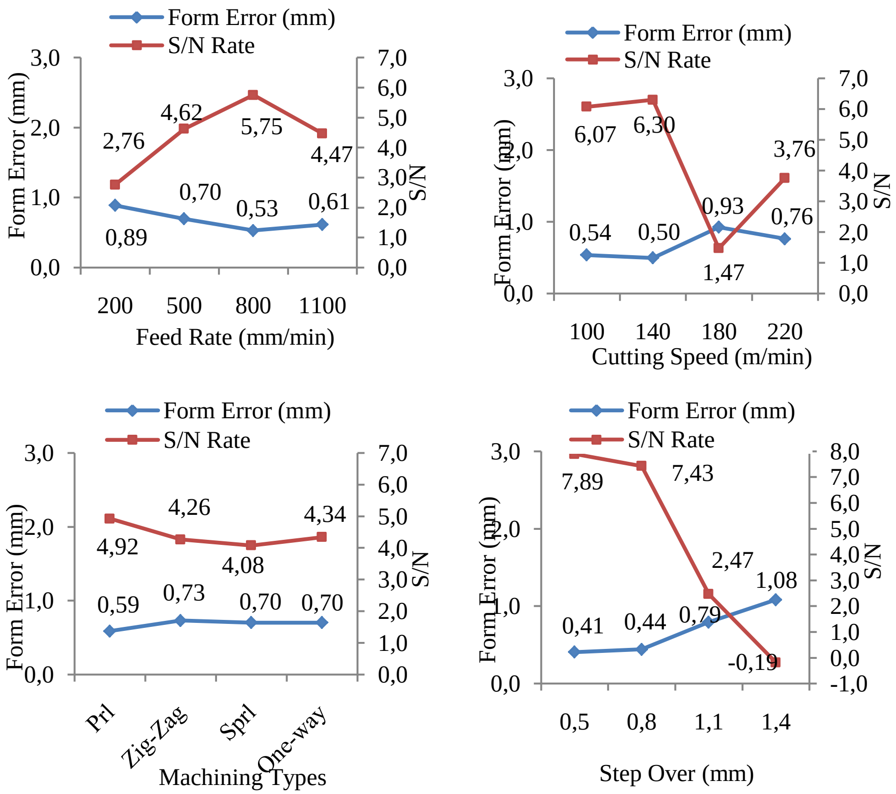


Figure 7. The effect of cutting parameters on form error

2.4. Evaluation of Machininig Times

The form errors and the machining times arising as a result of the experiments are given in Figure 8. When the given graph is examined, the lowest form error appears to be in the control experiment out of L_{16} array, but the machining time is not too low compared with the other experiments. When the machining time is not important, this machining condition can be selected. However, if we want to select low values both the machining time and the form error, we can decide on 15th or 16th experiments. Because both values are lower than the others. In the future, such freeform materials can be manufactured taking into account form errors and machining times for the similar works.

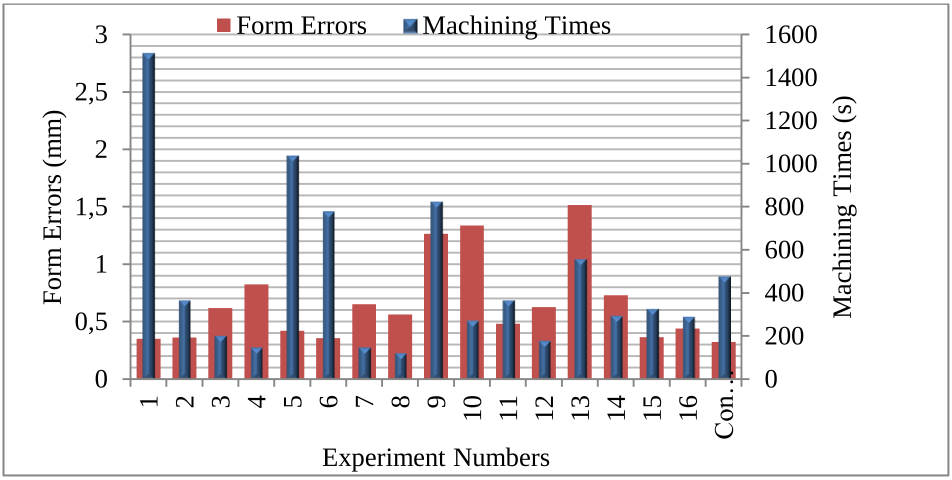


Figure 8. The relationship between form error and machining time

3. CONCLUSIONS

At the end of this study, the most suitable cutting conditions were determined in terms of form error and machining time. The results found are given below.

- In experiment design using Taguchi optimization method, the lowest form error appears to be in the second experiment with the 1-2-2-2 array. But as a result of Taguchi analysis, the lowest form error was found in the 2-3-1-1 array, which was outside the L_{16} orthogonal array. That is, the smallest form error value was obtained by 140 m/min cutting speed, 800 mm/min feed rate, 0.5 mm step over and parallel machining. The form error values were measured by performing a control experiment for the 2-3-1-1 array that gives an optimal form error. , the smallest form error was found as a result of this process with *0.321mm.*
- The effect of cutting factors on form error were step over (C), cutting speed (A), feed rate (B), machining strategy (D) by order of importance.
- The relationship levels of the cutting parameters on the form error were obtained by using ANOVA to the signal/noise (S/N) ratios. The step over in the value of form error was significant at 95% confidence level according to ANOVA.
- It was seen that when the feed rate and the step over increase in the experiments, the form error generally increases.
- The form error was seen to increase or decrease in different levels of feed rate. This could be due to environmental factors or vibration on the table during machining. But in general, we can

say that the feed rate increase is a negative effect on the form error.

- The machining time was reached in the 8th experiment with a minimum of 125 seconds. But in this experiment the form error is 0.563 mm and this value is not too small.
- We could prefer 15th or 16th experiments. Because both machining time and form error were lower than the other experiments. In the next study, we can decide on machining conditions according to these results.

It is understood that, high feed rate and step over increase the form error but high cutting speed decrease the form error. In further studies, cutting parameters can be optimizated with the measured of cutting force and tool deflections.

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