



Optimization of cutting forces on turning of Ti-6Al-4V alloy by 3D FEM simulation analysis

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Abstract

The turning process is widely used in the critical parts of machine tools used in the manufacturing industry, aerospace industry, and automobile and mold parts. However, the turning process is desired to obtain the lowest cutting force by variable cutting parameters. Therefore, estimation of optimum parameters and minimum cutting force is essential for Ti-6Al-4V, known as difficult-to-machine materials. This study aimed to investigate the impact of process parameters on the cutting force of Ti-6Al-4V alloy in turning operation by numerical analysis. Analyses were performed at three levels of cutting speeds (55, 75, and 95 m/min), feed rates (0.12, 0.17, and 0.22 mm/rev), and depths of cut (1, 1.5, and 2 mm), respectively. Using Third Wave AdvantEdge software in finite element method (FEM), modeling and analysis of cutting forces. In addition, Signal/Noise (S/N) ratios were calculated to determine the optimum levels of cutting parameters, and Analysis of Variance (ANOVA) was used to determine the effects of cutting parameters on cutting force based on the outputs of numerical simulation results. As a result, FEM analysis and the results of similar studies in the literature overlap. The optimum cutting parameter was obtained in A1B1C1 in the results of the experimental and statistical analyzes. ANOVA results demonstrated that the depth of cut was the most significant parameter on the cutting force.

Keywords: Ti-6Al-4V, cutting force, turning, finite element method, optimization.

1. Introduction

Today, the processing of Ti-6Al-4V alloy stands out as a developing field in the industry [1]. A few important features such as high strength, low weight, and biocompatibility are among the main reasons why titanium alloys are preferred in the aerospace, automobile, and medical industries [2]. On the other hand, the drawbacks of the titanium alloys such as high-stress formation at the tool tip and poor thermal conductivity classified them into difficult-to-machine materials. Therefore, improving the machining properties of titanium alloys is still an open research area for researchers and industrialists [3, 4].

Among the metal cutting methods turning is the commonly used one to produce parts of different shapes and sizes [5]. Determination of cutting force is an important factor to minimize output parameters such as cutting tool wear, surface roughness, and power consumption in turning Ti-6Al-4V alloy, which is considered difficult to machine. Optimizing the process parameters may reduce the cutting force which leads reduction in power consumption as well. Determining the optimum levels of cutting

parameters helps greener and more environmentally friendly production processes [6]. Therefore, a lot of research has been done to understand the mechanics of the process to obtain more effective, efficient, and environmentally friendly manufacturing process plans. These empirical investigations are the primary method for evaluating machinability and optimizing cutting parameters. However, experimental designs of machining processes with various process parameters would be insufficient concerning cost and time [7]. In addition, some physical quantities that occur on the tool/workpiece pair during experiments are difficult to obtain, such as stress contours, strain rates, and temperature field. To avoid these difficulties, the finite element method (FEM) is a preferable approach in machining operations [8]. In order to predict the deformations, stresses, and strains in the workpiece and the loads on the tool operating under certain cutting parameters, FEM extensively used [7]. In recent years, FEM analysis has been used as a useful and effective method in a lesser time to achieve cutting mechanics results in a cheaper and more environmentally friendly approach

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[9-11].

There are many studies conducted with the finite element method in machining [12-16]. Machinability of Ti-6Al-4V alloy widely studied in various research. For instance, the effect of axial and tangential feed on shear forces and borehole quality during helical milling of CFRP and Ti-6Al-4V material was investigated [12]. In that study, it is found that axial feed and tangential feed per tooth have a strong influence on the appearance of the undeformed chips during helical milling. In another study, a 2D FE model was developed to simulate the orthogonal cutting of the Ti-6Al-4V alloy [17]. Here, the authors investigated the impacts of coefficient of friction, cutting speed, and rake angle on chip

morphology through the developed numerical cutting model. In another study, Yuan et al. stated that importance of process planning and optimization in micro end milling to predict the cutting forces [18]. The result of this study proposed an innovative uncut chip thickness algorithm for the exact estimation of cutting forces.

In this study, the relationship between turning cutting parameters of Ti-6Al-4V alloy and cutting force was trying to be explained with FEM. In this way, it is thought that it will make a significant contribution to the estimation of the cutting forces occurring during turning with a more environmentally friendly operation by eliminating the costly, time-consuming experiments.

2. Materials and method

2.1. Workpiece cutting tool

In this study, Ti-6Al-4V alloy with a ϕ 30 mm and a length of 30 mm was selected due to its wide range of applications. Table 1 and Table 2 represents the chemical composition and mechanical properties of

the Ti-6Al-4V, respectively. In the experiments, an uncoated carbide tool in the form of SNMA120408 produced by Kennametal company in the K68 quality group was used.

Table 1. Ti-6Al-4V alloy’s chemical composition

Element	Al	V	C	Fe	Si	O	Fe	Ti.
Wt.%	5.30	3.50	0.08	0.30	0.05	0.20	0.30	Balance

Source. Refs. [1-5]

Table 2. Ti-6Al-4V Thermomechanical properties [19]

Properties	Ti-6Al-4V
Young’s Modulu (MPa)s	0.714T + 113.34*103
Density (kg/m ³)	4430
Poisson’s ratio	0.34
Heat capacity (J/kg °C)	50.564exp(0.0007T)
Conductivity (W/m °C)	7.039exp(0.0011T)
Expansion (µm(m °C))	3*10 ⁻⁹ +7*10 ⁻⁶

2.2. Numerical analysis

Third Wave AdvantEdge program, which is finite element software, was used to turning the Ti-6Al-4V alloy. In cutting simulations, deformation occurs in workpieces due to high plastic strain, strain rate, and temperature. Therefore, when defining the stress-strain behavior of workpieces, material models are used depending on the strain rate, work hardening, and temperature [20]. Here, the Johnson-Cook yield surface forming material model was applied to define the workpiece’s mechanical behavior. The Johnson-Cook material model is used for the flow stress of the workpiece as in equation 1.

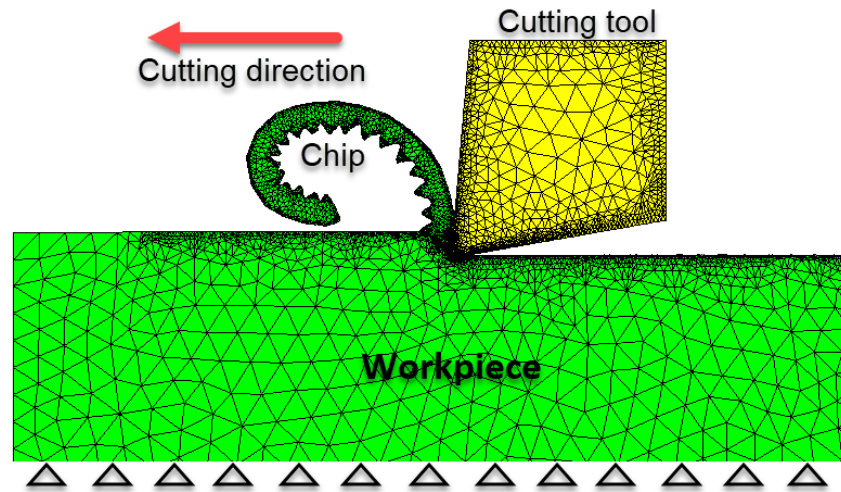
$$\sigma = \underbrace{[A + B\varepsilon^n]}_{\text{Elasto-Plastic}} \underbrace{\left[1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]}_{\text{Viscosity}} \underbrace{\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right]}_{\text{Thermal Softening}}$$

Coulomb friction that stated below used in AdvantEdge™ as a friction coefficient [21]:

$$F_f = \mu F_n \tag{2}$$

2D orthogonal and Lagrangian methods were used in the analyses. The workpiece and cutting tool mesh structure is modeled as a maximum tool element size of 0.1 mm, a minimum tool element size of 0.02 mm, and a mesh grading of 0.4 mm. The cutting model

created is shown in Figure 1.



• Figure 1. Orthogonal cutting model

2.3. Workpiece cutting tool

Taguchi is a statistical approach used to increase product quality, reduce the cost by minimizing the number of experiments and increase the competitiveness of enterprises. In the analyzes made, the observations were converted into signal-to-noise (S/N) ratios to find the quality characteristics using the Taguchi method using the “Smaller is Better” approach since the study aimed to minimize the forces were used during the experiments. Equation (3) is used for this [22-24].

Smaller is better:

$$S/N = 10 \log_{1/n}(\sum y^2) \tag{3}$$

This study aimed to decide the optimum process parameters to lower the cutting force values while increasing the machining quality of the Ti-6Al-4V alloy during turning operation. First, Taguchi L9 orthogonal array was chosen to determine the optimum values of the cutting parameters. Then, the effects of cutting parameters on output parameters justified by performing the Analysis of variance (ANOVA). The selected cutting parameters were determined as a result of the manufacturer's catalogs and literature research [25, 26]. Determined cutting parameters and levels are shown in Table 3.

Table 3. Cutting parameters and levels for the turning process.

Code	Cutting Parameters		Level 1	Level 2	Level 3
A	Depth of cut (mm)	A	1	1.5	2
B	Cutting Speed (m/min)	V	55	75	95
C	Feed rate (mm/rev)	f	0.12	0.17	0.22

3. Experiment results and analysis

3.1 Analysis of S/N ratios

Table 4 shows the cutting force values and S/N ratios obtained as a result of turning the Ti-6Al-4V alloy. The "smaller is better" approach was used in the calculation of the S/N ratios. The averages of the cutting force values and S/N ratios obtained as a result of the turning experiments were calculated as 761.263 N and -572.381 dB, respectively. The S/N response table was used in the analysis of each

cutting parameter on the cutting force, and the S/N response table is given in Table 5. This table shows the optimum levels of cutting parameters for each cutting force. The levels of the cutting parameters for the cutting force values are given in Table 4 and the graphs of these values are presented in Figure 2.

Table 4. Cutting force and corresponding S/N ratios based on process parameters

Experiment No	A	V	f	Cutting force (N)	SNRA1
1	1	55	0.12	451.1867	-53.0871
2	1	75	0.17	492.6467	-53.8507
3	1	95	0.22	547.046	-54.7605
4	1.5	55	0.17	783.8888	-57.8851
5	1.5	75	0.22	851.3204	-58.6019
6	1.5	95	0.12	682.8968	-56.6871
7	2	55	0.22	1131.001	-61.0693
8	2	75	0.12	921.1518	-59.2866
9	2	95	0.17	990.2321	-59.9147

Table 5. Response table for signal-to-noise ratios.

Level	A	V	f
1	-53.90	-57.35	-56.35
2	-57.72	-57.25	-57.22
3	-60.09	-57.12	-58.14
Delta	6.19	0.23	1.79
Rank	1	3	2

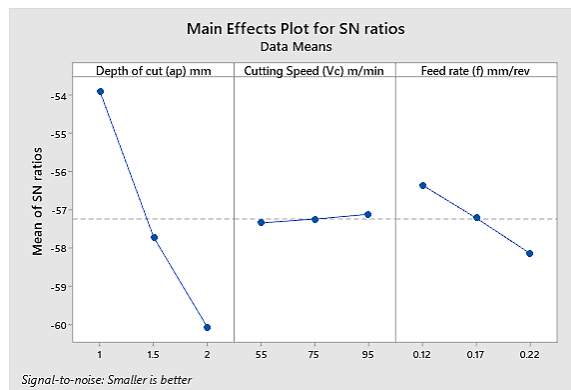


Figure 2. Smaller is better S/N ratios of process parameters

The best level for all cutting parameters was determined by the largest S/N ratio at all levels of that cutting parameter. Accordingly, when Table 5 and Figure 3 are examined, the levels for the cutting parameters that give the optimum cutting force value as a result of turning the Ti-6Al-4V alloy are A1, B3, C1.

3.2 Analysis of variance

In this study, ANOVA was performed in Minitab 17 at a 95% confidence level based on the process parameters were given in Table 3. Variance analysis

results for shear force results are given in Table 6 and the contribution ratios are given in Figure 3.

Table 6. ANOVA results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	443118	73853	276.44	0.004
A	2	401784	200892	751.95	0.001
V	2	3722	1861	6.97	0.126
f	2	37612	18806	70.39	0.014
Error	2	534	267		
Total	8	443652			

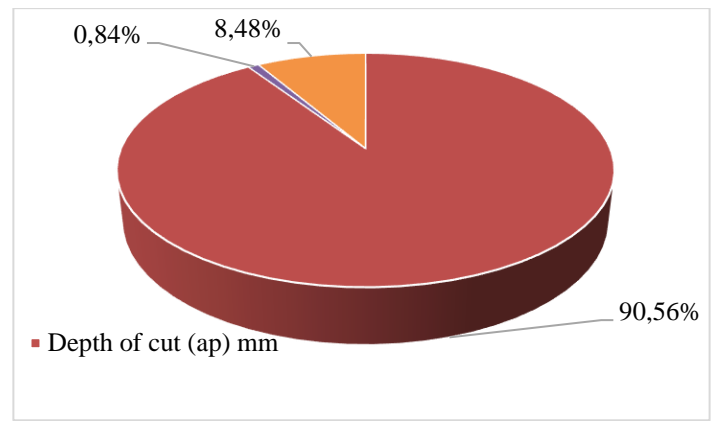


Figure 3. % Contribution rates of cutting parameters as a result of ANOVA on cutting force

The percentage contribution of the cutting parameters to the shear force is presented in the pie chart in Figure 4. The most effective cutting parameter on

cutting force was the depth of cut 90.56%, followed by feed rate 8.48% and cutting speed 0.84%.

3.3 Evaluation of experiment results

The changes in the cutting force obtained consequently turning the Ti-6Al-4V alloy at different cutting parameters with an uncoated carbide tool are given in Figure 4.

Cutting force values in turning of Ti-6Al-4V alloy varied between 451.187 N and 1131.001 N. A minimum cutting force of 451.187 N was measured in experiment 1. By keeping the depth of cut constant and increasing the cutting speed and feed rate, an increase of 21.25% was observed in the cutting force in the experiment performed at a cutting speed of 95 m/min and a feed rate of 0.22 m/rev. In general, it has been reported in other studies that the cutting

force decreases as the cutting speed increases [27, 28]. It has been reported that the cutting force will decrease with the decrease in the yield strength of the workpiece material due to the formation of high temperatures in the cutting zone at high cutting speeds [29]. At another striking point in the graph, the highest cutting force of 1131.001 N occurred with the increase in feed rate and depth of cut at minimum cutting speed. This situation is in agreement with other studies in the literature that the increase in the chip cross-section will cause an increase in the cutting force values because of an increase in the depth of cut and the feed rate [28].

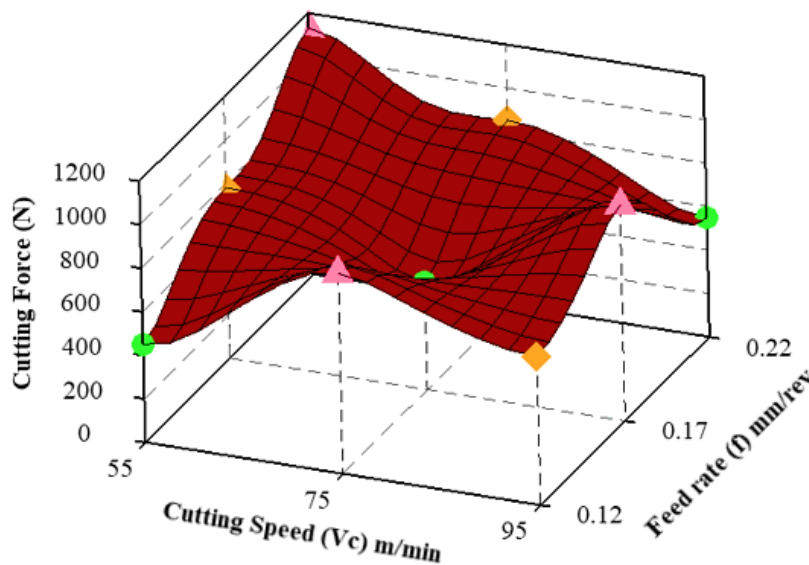


Figure 4. Effect of cutting parameters on cutting force a) ● 1 mm b) ◆ 1.5 mm c) ▲ 2 mm

4. Conclusions

In this study, the effects of cutting parameters on cutting force in turning Ti-6Al-4V alloy with uncoated carbide tool were investigated using the finite element method. In addition, the Taguchi method was used to evaluate the effects of optimum cutting parameters and cutting parameters on the cutting force. As a result of the study, the following conclusions were reached.

- ✓ The lowest cutting force (451.187 N) was obtained at the lowest values of each process parameter.

Conflict of Interest

No conflict of interest was declared by the authors.

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