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Optimization of Cutting Process Parameters of the Ti6Al4V Alloy

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Abstract: *In this paper, a two-dimensional orthogonal cutting simulation model of Ti6Al4V was established. And the simulation results were verified by experiments. The effects of rake angle, clearance angle, tool nose radius, cutting speed, and feed rate were studied using the Taguchi method. The optimal processing parameters were obtained.*

Keywords: *Cutting force, optimal parameter, Taguchi method, finite element simulation*

1. Introduction

In recent years, titanium alloy has been extensively used in aeronautics, automotive, and other fields due to its excellent comprehensive performances [1]. It has some properties such as low density, high strength, good mechanical properties, and excellent thermal resistance [2]. These materials, on the other hand, are thought to be tough to cut [3]. In the metal cutting process, cutting force is an incredibly essential physical component. The magnitude of cutting force, in particular, has a substantial impact on machining precision, tool wear, and tool life [4]. While the cutting parameters have a obvious influence on the cutting force. As a result, for the processing of titanium alloys, the cutting parameters are critical.

The finite element method is widely used as it can be cross-validated with experimental studies, while it can make accurate predictions about factors that are hard to procure experimentally [5]. In 1973, B.E. Klamecki first applied finite element techniques to machining [6]. Y. Karpat [7] constructed a finite element model for cutting titanium alloy and studied the simulation results. Riaz Muhammad etc [8] established a finite element model of hybrid and traditional oblique turning processes of titanium alloy, and studied cutting force and temperature. However, the above studies were all qualitative and did not consider how to obtain the optimal parameters.

This work uses ABAQUS to create a simulation model for turning titanium alloy. The Taguchi approach was used to investigate the impact of cutting parameters on cutting forces and to determine the best combination of cutting parameters. The cutting force was found to be related to rake angle, feed rate, etc, providing strong support for identifying appropriate parameters in the titanium alloy cutting process.

2. Establishment of simulation model based on ABAQUS

The tool was assumed to be rigid in the finite element model, ignoring the effect of tool vibration and deformation on the results, and the simulation took place in two dimensions. In the vicinity of the cutting area, the grid of the tool and working part was denser, while elsewhere the grid was sparser. TC4 was adopted as the working part material. Due to the difficulty in obtaining the physical and thermomechanical properties of the tools used in this study, similar tool material data from the literature was used as simulation data. YG8 was used as the material for the tool.

2.1. Constitutive model

The working component material frequently undergoes elastic-plastic flow at high strain rates throughout the cutting process [9]. The simulation analysis focuses on the construction of a reasonable flow stress model, which takes into account the influence of numerous elements on the flow stress of the working part material. The Johnson-Cook model [10] organically links the roles of strain hardening, strain rate hardening, and softening temperature. Its mathematical expression is as follows.

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(1)

Where A, B, n, C, and m are the constants determined by the material itself, T_m is melting point, T_r is reference temperature, $\dot{\varepsilon}_0$ is reference strain rate. Table 1 lists the parameters of the Johnson-Cook material model [11]. Table 2 describes the material attribute of TC4 and tool.

Table 1: Constitutive Model Parameters of TC4

$A(MPa)$	$B(MPa)$	n	C	m
910	780	0.47	0.035	1

Table 2: Material Attribute

	TC4	Tool
Density (kg/m^3)	4430	15700
Young's mod(MPa)	113800	705000
Poisson's ratio	0.342	0.23
Conductivity($W/(m\cdot℃)$)	7	27
Specific heat ($J/(kg\cdot℃)$)	233	178
Melting temp (℃)	1580	/
Transition temp (℃)	20	/

2.2. Simulation model

In order to investigate the effect of cutting parameters on cutting forces, the accuracy of the simulation results was first verified. For the sake of verifying the reliability of the simulated cutting forces, we looked for experimental data from relevant papers for comparison. In the article by LYU Sixiao, the first set of cutting parameters is shown in Table 3. Figure 1 shows the simulation results for the first set of cutting parameters. The cutting force values could be output in the post-processing module of the software after the simulation experiments have been completed. Line chart of cutting force over time are shown in Figure 2.

Table 3: The First Set of Cutting Parameters

rake angle/°	clearance angle/°	cutting speed/m/min	feed rate/mm
0.9	6.3	80	0.3

A good displacement agreement in the results of both the FEA computation and the experiment has been reliably confirmed. In the article by LYU Sixiao, the average cutting force for the first set of experiments is 230 N, while the average cutting force for the simulation results is 259 N. The error is 12.6%, which is within the reliable range and can be continued for the next step of the study. The source of the 12.6% error is mainly the choice of material parameters, changing the corresponding material parameters will result in a certain change in cutting forces.

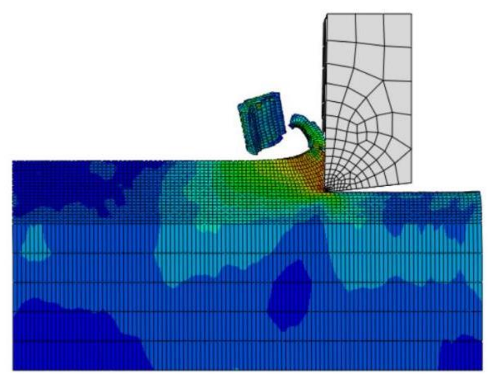

Figure 1: Simulation Results

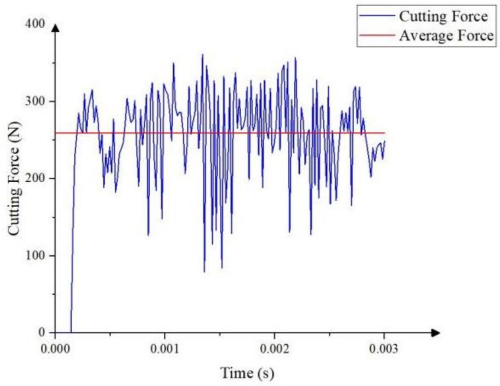

Figure 2: Curve of Simulated Cutting Force

ISSN 2522-3488 Vol. 6, Issue 2: 69-73, DOI: 10.25236/IJNDES.2022.060212

3. Simulation and result analysis

3.1. The effect of different cutting parameters on the cutting forces in TC4

In order to investigate the effect of cutting parameters on cutting forces, this paper referred to experimental data from the literature and then designed a set of tables by the Taguchi method, as shown in Table 4. ANSYS simulation test analysis was done according to the table parameters, and the last column shows the average force obtained from ANSYS simulation.

Table 4: Experiment Design and Results

test number	rake angle/°	clearance angle/°	tool nose radius/mm	cutting speed/m/min	feed rate/mm	mean force/N
1	-16	0	0.08	30	0.15	148.6
2	-16	5	0.01	80	0.2	202.3
3	-16	10	0.03	150	0.3	285.3
4	-16	15	0.06	300	0.4	371.7
5	-16	20	0.1	500	0.5	372.7
6	-8	0	0.01	150	0.4	289.1
7	-8	5	0.03	300	0.5	401.2
8	-8	10	0.06	500	0.15	71.3
9	-8	15	0.1	30	0.2	106.3
10	-8	20	0.08	80	0.3	257.0
11	0	0	0.03	500	0.2	190.9
12	0	5	0.06	30	0.3	267.7
13	0	10	0.1	80	0.4	357.1
14	0	15	0.08	150	0.5	419.9
15	0	20	0.01	300	0.15	135.2
16	8	0	0.06	80	0.5	410.8
17	8	5	0.1	150	0.15	152.9
18	8	10	0.08	300	0.2	168.2
19	8	15	0.01	500	0.3	259.8
20	8	20	0.03	30	0.4	314.9
21	16	0	0.1	300	0.3	263.4
22	16	5	0.08	500	0.4	340.3
23	16	10	0.01	30	0.5	366.1
24	16	15	0.03	80	0.15	124.7
25	16	20	0.06	150	0.2	154.2

Based on the experimental results, a simple intuitive analysis was carried out in this paper to roughly determine the role and priority of each parameter, as shown in Table 5.

Table 5: Result Analysis

Factors	rake angle	clearance angle	tool nose radius	cutting speed	feed rate
One-level mean of each factor	276.12	260.56	266.8	240.7	126.54
Two-level mean of each factor	224.98	272.88	250.5	270.4	164.4
Three-level mean of each factor	274.16	249.6	263.4	260.3	266.64
Four-level mean of each factor	261.32	256.48	255.14	267.9	334.6
Five-level mean of each factor	249.74	246.8	250.48	247.0	394.14
Range	51.14	26.08	16.32	29.66	267.6
Priority	2	4	5	3	1
Optimal parameter	-8°	20°	0.1mm	30m/min	0.15mm

The following conclusions can be drawn from Table 5. When the rake angle is positive, the larger the angle, the smaller the average cutting force. The larger the clearance angle, the lower the average cutting force. The effect of tool nose radius was negligible in this set of experiments. The higher the cutting speed, the lower the cutting force; the smaller the feed rate, the lower the average cutting force, but in practice there are efficiency issues to consider. Broadly speaking, the feed rate has the greatest influence, followed by the rake angle, cutting speed, clearance angle and tool nose radius respectively.

3.2. Optimal cutting parameters for machining TC4

Based on the results of the previous set of tests, another set of orthogonal tests was designed in this paper by the Taguchi method, as shown in Table 6. This time the tests focused on the effect of the rake angle, clearance angle and tool nose radius on the cutting forces as well as their priority and optimum

ISSN 2522-3488 Vol. 6, Issue 2: 69-73, DOI: 10.25236/IJNDES.2022.060212

parameters. The last column shows the average cutting forces obtained from the ANSYS simulation.

Table 6: Experiment Design and Results

test number	rake angle/°	clearance angle/°	tool nose radius/mm	cutting speed/m/min	feed rate/mm	mean force/N
1	-15	5	0.04	200	0.2	205.5
2	-15	10	0.08			203
3	-15	15	0.12			203.8
4	-10	5	0.08			225.6
5	-10	10	0.12			187.2
6	-10	15	0.04			217.2
7	-5	5	0.12			202.5
8	-5	10	0.04			200.4
9	-5	15	0.08			167.7

Based on the simulation results, this paper first carried out an intuitive analysis to initially determine the priorities and optimal parameters, as shown in Table 7.

Table 7: Analysis of Intuitiveness

	rake angle(A)	clearance angle(B)	tool nose radius(C)	error(D)
K1	612.3	633.6	623.1	560.4
K2	630	590.6	596.3	622.7
K3	570.6	588.7	593.5	629.8
k1	204.1	211.2	207.7	186.8
k2	210	196.9	198.8	207.6
k3	190.2	196.2	197.8	209.9
R	19.8	15	9.9	23.1
conclusion	Priority: D>A>B>C, Optimal parameter: A3,B3,C3			

As shown in Table 8, the paper uses an ANOVA to find the significant effects.

Table 8: Analysis of Variance

	Sum of squares of deviations	degrees of freedom	Mean Square	F-value	P-value
A	620.26	2	310.03	0.638	0.611
B	429.85	2	214.92	0.442	0.693
C	178.03	2	89.01	0.183	0.845
D	972.01	2	486	/	/
conclusion	None of these factors had a significant effect, so it could be intuitively judged				

4. Conclusions

The main conclusions of this paper are summarised below. In general, within a certain range, rake angle, clearance angle, tool nose radius, cutting speed and average cutting force are inversely related, while the feed and average cutting force are positively related. In the second set of experiments, the optimal cutting parameters, after orthogonal analysis, were a rake angle of -5°, a clearance angle of 15° and a tool nose radius of 0.12 mm.

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