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Experiment Study on Efficient Flank Milling of Ti6AL4V Thin-walled Components

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Abstract

Flank milling is a method of line contact machining and also is an important method in machining aerospace structures components, turbine blades and so on. In this paper, flank milling of Ti6AL4V is conducted with carbide tools on CNC machining center. First, acquired cutting force signals are analyzed in time domain and frequency domain based on Matlab software to obtain the distribution of cutting force energy. Second, the flank milling force experimental formulas are established by means of regression analysis. Finally, the influence of cutting parameters such as feed per tooth, the axial depth of cut, cutting width and cutting speed on cutting force is studied. The curves between cutting parameters and cutting force are obtained by analyzing the flank milling experiment. This research has certain guiding significance in selecting cutting parameters for flank machining Ti6AL4V.

***Keywords**: flank milling, frequency domain, cutting force, cutting parameters*

1. Introduction

Flank milling is the forming method of linear contact machining. It has the advantages of short machining time, low machining cost, good cutting conditions, forming part surface once and so on. So flank milling is the important method of machining the thin wall parts such as turbine blade, integral impeller blade, aerospace structure and so on.Ti6Al4V (TC4) is a typical α-β titanium alloy which is stable at 400℃. While from the perspective of processing performance, TC4 is a typical difficult-to-machine material, its poor thermal conductivity, high chemical activity, small elastic modulus and severe hardening make a low cutting speed, short tool life and low processing efficiency [1-3]. In order to improve machining titanium alloy efficiency and understand the flank milling mechanism of titanium alloy better, researchers at home and abroad studied flank milling actively. Yan Guohong [4] carried on flank milling experiments of TC4 and studied the influence law of milling parameters on milling surface roughness. The work-piece surface roughness increases with the increasing of average cutting thickness and the influence of radial depth of cut is the most significant. Yao Di [5] studied the whole impeller surface quality of the aluminum alloy, obtained the influence of the factors on the roughness and determined the optimum parameters of the aluminum alloy blade. Chen Ming [6] studied the finishing flank milling of the high temperature alloy blade. Zhou Zitong [7], Shi Kaining [8] studied the surface morphology, surface roughness, working hardening and surface integrity of the titanium alloy TB6 after flank milling. A. Larue [9] presents prediction of cutting forces when flank milling ruled surfaces with tapered, helical, ball end mills. Liu Xianli [10] respectively puts forward the target prediction model based on the prediction of milling parameters and the parameter optimization model based on the genetic algorithm aiming for development requirements of disc milling/plunge milling/flank milling cutters and cutting parameters optimization system of blisk.

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Flank milling experiment is designed on the CNC machining center with carbide cutter in this paper. First, the acquired cutting force signal of time domain and frequency domain is analyzed and the distribution of cutting force energy is obtained. Second, the effect of feed per tooth, axial depth of cut, radial depth of cut and cutting speed on flank milling force is researched. The curve of cutting parameters and milling force is obtained by analyzing the experiment. Finally, the milling force experience formula is established by means of regression analysis. The research is useful in selecting cutting parameters in machining this kind of alloy.

2. Flank Milling Tests Study on TC4

2.1. Experiment Material

The material is TC4. It is $\alpha+\beta$ Ti alloy which consists of α and β two phases. α is the main phase and β is less than 30%. TC4 has stable organization, good toughness and plastic. The chemical composition and the mechanical properties of the material tested in this study is shown in Table 1 and Table 2. The shape of the work-piece is shown in Figure1 and its machining dimension is $50\,mm \times 50\,mm \times 6\,mm$.

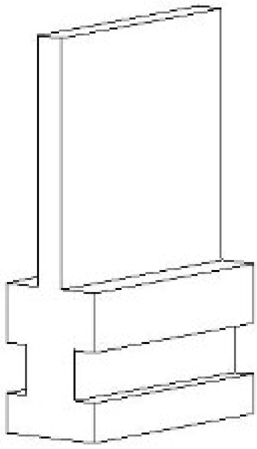

Figure 1. The Machining Work-Piece

Table 1. The Chemical Composition of TC4

The composition of the Titanium	Al	V	Fe	C	N	H	O	Other	Ti
The quality ratio	5.6-6.8	3.5-4.5	0.3	0.1	0.5	0.1	0.1	<0.5	Bal

Table 2. The Mechanical Properties of TC4 (at the Room Temperature)

The tensile strength σ_b / MPa	The tensile strength $\sigma_{0.2} / MPa$	The Elongation $\delta\%$	The Shrinkage $\Psi\%$
1027	983	18.5	20.1

2.2. Experiment Equipment and Testing Instruments

The milling test were conducted on Mikron HSM(high-speed machining) 600U five-axis CNC machining center in dry condition, which the maximum spindle speed is 42000r/min, the spindle power is 13KW, and the feed rate is 40 m / min. The cutting tool is carbide solid ball-end mill with four teeth. The diameter of the tool is 8mm and its helix angle is $\beta = 42^{\circ}$.

The momentary cutting forces on *x*, *y*, *z* axis are obtained by piezoelectric dynamometer Kistler9257B. After magnified by multi-channel charge amplifier Kistler5070A, the data are acquisitioned by America National Instruments PXLe8133 and saved in computer. The experimental principle of milling force is shown in Figure2.

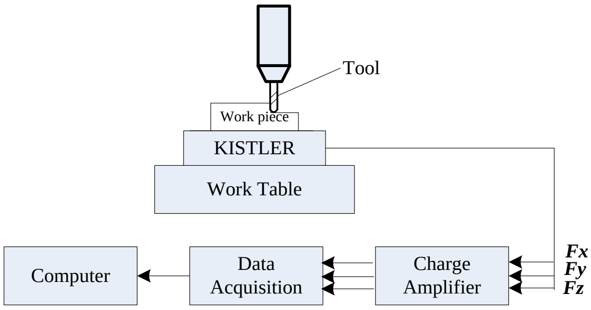

Figure 2. The Experimental Principle of Milling Force

2.3. Experiment Methods

In the research of the flank milling of TC4, the cutting parameters of this experiment are higher than the conventional values. The scheme of the milling is as follows: first, the influence of cutting parameters on the milling force is analyzed on the single factor of cutting parameters (v_c, f_z, a_e, a_p). v_c:50/80/ 110/140m/min, f_z:0.03/0.05/0.08/0.1mm/z, a_e:0.1/0.2/ 0.3/0.4mm, a_p:6/9/12/15mm.Second, orthogonal experiment with four factors and four levels is designed and the milling method is climb milling without cooling liquid. The orthogonal cutting experiment scheme and measurement results are shown in Table 3.

Table 3. The Test Program and Measure Result of Orthogonal Cutting

No.	a_p/mm	a_e/mm	v_c/（m/min）	f_z/(mm/min)	F_x	F_y	F_z	F
1	15	0.3	110	0.05	11.8106	43.2428	28.1059	52.9091
2	15	0.1	80	0.1	15.7801	26.1795	17.2048	35.0768
3	15	0.2	140	0.03	12.3838	25.2174	15.3713	32.0243
4	15	0.4	50	0.08	12.2815	53.1921	31.5734	63.0644
5	12	0.2	50	0.05	17.4003	41.0595	23.455	50.3864
6	12	0.4	140	0.1	20.1762	16.4276	10.3621	28.0057
7	12	0.3	80	0.03	20.6289	31.2616	19.884	42.4053
8	12	0.1	110	0.08	13.1669	24.4966	13.0399	30.7163
9	9	0.3	50	0.1	20.7207	31.1849	23.1588	44.0247
10	9	0.1	140	0.05	18.6419	15.0845	11.672	26.6702
11	9	0.2	80	0.08	32.6788	16.2099	10.6327	37.9963
12	9	0.4	110	0.03	28.7773	27.2933	17.9235	43.5237
13	6	0.2	110	0.1	14.6548	16.1963	12.2926	25.0637
14	6	0.4	80	0.05	10.8933	17.6416	11.4587	23.6895
15	6	0.3	140	0.08	16.7177	18.9763	13.4466	28.6425
16	6	0.1	50	0.03	9.4468	8.0456	6.841	14.1694

3. Experimental Procedure and Results Analysis

3.1. Frequency Domain Analysis of Cutting Force

The fast discrete Fourier transform (FFT) is used to processing cutting force data in this paper. The time domain signal is converted into frequency domain by Fourier transform. The phase frequency characteristic of the system can be seen by the spectrum analysis. Figure 3 shows some selected spectrums through which the influence of cutting parameters on the spectrum chart is found. Through frequency domain analysis, the influence of cutting parameters on the spectrum chart is found. According to Figure 3, the cutting speed has a decisive effect on the energy distribution, and the energy distribution points are different with different cutting speed. In the case of the same cutting speed, the energy distribution points are same while the amplitude increases with the increasing of feed rate per tooth f_z, the axial depth of cut a_p, and the radial depth of cut a_e.

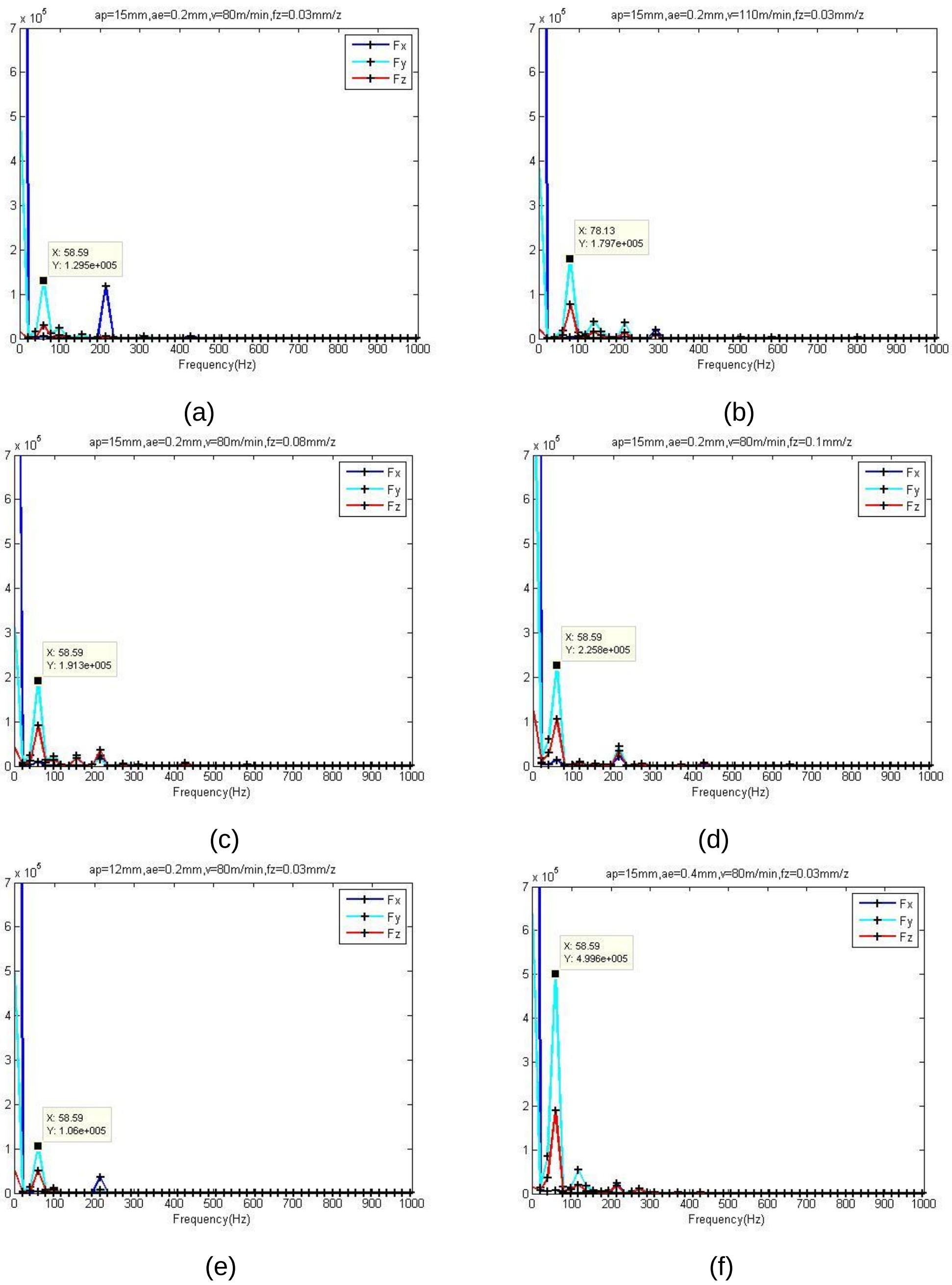

Figure 3. Spectrums under Different Cutting Parameters

3.2. Experimental Formula Modeling and Analysis

Cutting force empirical model is shown in Eq. 1. The factors influenced milling force include cutting speed v_c, feed rate per tooth f_z, the axial depth of cut a_p, and the radial depth of cut a_e. K represents a correction coefficient while $a1$, $a2$, $a3$ and $a4$ are the affecting index.

$$F = K\, a_p^{\,a1} a_e^{\,a2} f_z^{\,a3} v_c^{\,a4} \quad (1)$$

Based on the F_x, F_y, F_z, F values in Table 3, using the multiple linear regression analysis method, the flank milling cutting force empirical formulas of TC4 are established. The exponential milling force formulas are shown in Eq.2- Eq.5.

$$F_x = 14.9039 a_p^{0.0203} a_e^{0.1371} f_z^{0.0971} v_c^{0.1169} \quad (2)$$

$$F_y = 18.5370 a_p^{0.9474} a_e^{0.3644} f_z^{0.0626} v_c^{-0.2726} \quad (3)$$

$$F_z = 19.5254 a_p^{0.7237} a_e^{0.3172} f_z^{0.0467} v_c^{-0.2874} \quad (4)$$

$$F = 34.1507 a_p^{0.6987} a_e^{0.3039} f_z^{0.0894} v_c^{-0.1980} \quad (5)$$

From the above empirical formulas Eq.2- Eq.5, the cutting forces along y and z direction have the same trend with the total cutting force. While the cutting force along x direction is slightly different. In flank milling TC4 process, the axial depth of cut ap influenced the cutting force greatly(index number: 0.6987) ,the cutting force increases with the axial depth of cut increasing and the cutting forces rise significantly, and the variety range are high. The influence of the radial depth of cut ae takes the second place (index number: 0.3039), the cutting force increases with the radial depth of cut increasing gradually, however, the variety range are gentle. The feed per tooth fz also takes the second place (index number: 0.0894), the cutting force increases slowly with feed per tooth increasing. The influence of the spindle speed on cutting force is contrary to the above three parameters(index number: -0.1980), the cutting force reduces with the spindle speed increasing. However, the decline is relatively gentle and its variety range is slightly.

3.3. Influence of Cutting Parameters on Milling Force

Flank milling force measurement results of single factor are shown in Figure4- Figure7. According to the milling force curve, there is no difference between F_x, F_y and F_z in the process of large axial milling. F has the same trend with F_y and F_z while have some different with F_x. The milling forces have little change with the increase of cutting speed (shown in Figure 4). With the increase of feed per tooth, the milling force is increasing (shown in Figure 5). As the cutting thickness and cutting area increases with the feed per revolution increasing. Then the force will increase. Figure6 and Figure7 are milling force influenced by axial depth of cut a_e and radial depth of cut a_p respectively. With the increasing of a_e or a_p, the contact length between the tool and work-piece increases. Then the milling area increases. Finally, the cutting force increases. The accuracy of the empirical formula is verified by single factor experiments.

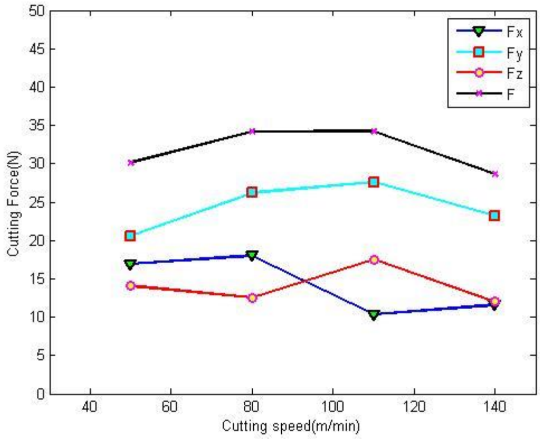

Figure 4. Influence of VC on Cutting Force

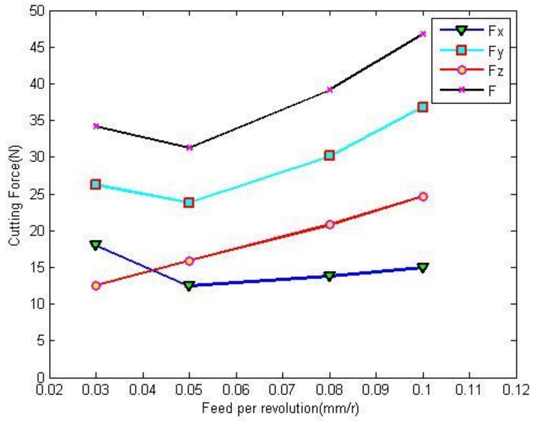

Figure 5. Influence of FZ on Cutting Force

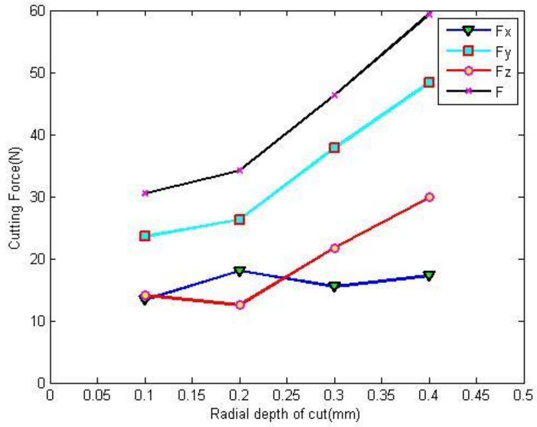

Figure 6. Influence of AE on Cutting Force

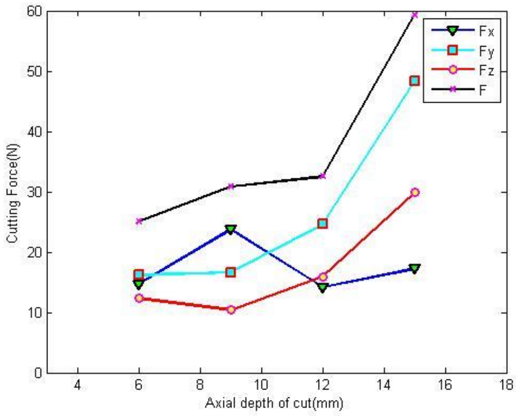

Figure 7. Influence of AP on Cutting Force

4. Conclusions

In this paper, flank milling of TC4 is conducted with carbide tools on CNC machining center. Acquired cutting force signals are analyzed in time domain and frequency domain based on Matlab software to obtain the distribution of cutting force energy. The flank milling force experimental formulas are established by means of regression analysis. The influence of cutting parameters is studied. The curves between cutting parameters and cutting force are obtained which verified the accuracy of the above experimental formula.

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