

Experimental investigation on milling of hardened steel Cr12

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Abstract. Hardened steel Cr12 test piece with hardness HRC50 is designed with special shape by means of Buda method. The effect of cutting speed and feeding per tooth on chip deformation and shear angle can be investigated comprehensively. The shear angle increases significantly with the increasing of cutting speed. So that, chip deformation becomes less and less with the increasing of cutting speed. The cutting power becomes greater with increasing of cutting speed, cutting temperature rises, and then the friction coefficient between tool-chip becomes smaller, so the shear angle has a gradually increasing trend. The shear angle increases significantly with the increasing of feeding per tooth. As feeding rate increases, cutting force increases, cutting temperature rises, friction coefficient decreases, thus, the shear angle has the trend of increasing. The cutting force investigation has been done by means of multi-factor orthogonal test method with four factors and four levels. The calculation equations for cutting forces have been deduced by means of the mixed algorithm of least-square method fitting and Monte Carlo fitting. It follows from the significant test results of regression analysis of cutting force calculation equations and coefficients based on 99% confidence that the equations for cutting force calculation are of excellent significance. Cutting speed is minor factor to impact cutting forces. Feeding per tooth and axial depth of cut are the most important parameters to impact cutting forces.

1. Introduction

With the development of the science technology, mechanical products are developing with the trends of multi function, high function and miniaturization. Hardened steels, such as Cr12, are a kind of materials difficult to be processed, which has Martensite structure after quenching treatment, with high hardness and strength. Hardened steels have some cutting characteristics, such as high hardness, low thermal conductivity, high cutting temperature, bad machinability, built-up edge, blade is easy to break and wear, and so on[1-3]. So, large cutting force, high cutting temperature, quickly tools wear and periodically formed serration chips affect tool life spans and lead to premature tool failure [4-6]. Investigation on cutting of hardened steel is becoming a research hot spot. B. Wang et al. [7] proposed a method to predict the yield stress and fracture toughness for ductile metal materials through cutting process based on Williams' Model. Wang et al. [5] investigated the chip formation, chip flow and chip morphology of hardened steel. Buchkremer [8] proposed a modeling approach for the relationship between 3D chip geometry and the distribution of the stress triaxiality at the location of chip breakage based on the inverse identification of the Johnson–Cook constitutive equation. Liu and Su [9] validated the correlation between chip morphology and material mechanical properties by means of the cutting process of AerMet100. Dolinsek et al. [10] analyzed the chip segmentation frequency, chip shape and dimensions, size of deformed and un-deformed parts of chip segments in high-speed cutting of hardened steel. Ning et al. [11] investigated tool wear progress and chip formation in the process of dry



machining-hardened steel AISI H13 with nano-multilayered TiAlCrN/NbN coating ultra-fine-grained cemented carbide end mill. Chip formation during milling of hardened steel has been studied comprehensively [12-14]. Wang et al [15] modified the conventional empirical Johnson–Cook constitutive equation by employing stress–strain curves at high temperature and a high strain rate obtained using split Hopkinson pressure bar technology and considering the negative strain rate effect and temperature effect of the material, especially for hardened steel. Deformation of cutting closely contacts with cutting temperature, tool wear, cutting force and tool geometry angles. Most of the researches are aimed at the model of shear angle, equation of shear angle. Merchant, Shaw and other scholars, through long-term research, obtained the different shear angle modes. We have investigated the change of chip morphology, shear angle and chip thickness deformation coefficient with the increasing of cutting parameters as machining hardened steel Cr12 with coated cemented carbide mill.

2. Chip Deformation of Hardened Steel Milling

2.1. Test Piece

The shear angle is one of the factors influencing the cutting deformation and a important parameter of describing the deformation during cutting process. It not only affects the tool chip contact length, chip deformation, the stress distribution of rake face, but also affects quality of machined surface and cutting force. In order to obtain the chip root, test piece designed with special shape by means of Buda method is shown in Fig. 1.

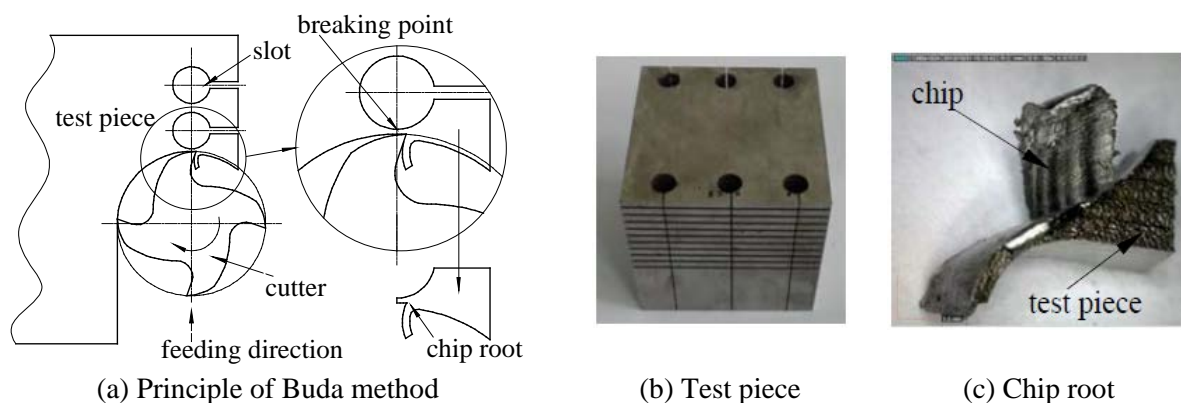


Figure 1. Buda method and test piece

The designed geometric structure of test piece can make chip root rapidly broken down when the tool feeding into the area above the circular groove. Chip root breaks down because it cannot withstand the cutting force. The chips root collected are made into metallographic specimen to measure the cutting and plastic deformation area. The test piece is made up of hardened steel Cr12 with hardness HRC50.

2.2. Test Condition

Milling experiments were conducted on a machining center YCM-V116B as shown in Fig. 2. TiAlSiN coated KMG5515 carbide cutter HMX-4E-D12.0 was used to mill hardened steel Cr12. Its diameter is 12mm. HMX-4E-D12.0 is of four cutting teeth each of them consisting of a cylindrical edge (with helical angle of 45°) and an end edge. The rake angle of cylindrical edge is -3° and that of end edge is -2° . The clearance angle of cylindrical edge is 9° and that of end edge is 7° . The cylindrical edges are actual cutting edges and the end edges do not carry out cutting duty. Cutting fluid is diesel oil.



Figure 2. Pictures of machining center and cutter

In order to look for the regulation of cutting deformation, experiments have been done by means of a series of cutting parameters as shown in Table 1. So that, the effect of cutting speed v or feeding per tooth f on chip deformation and shear angle can be investigated comprehensively.

Table 1. Parameter's list

Cutting speed v (m/min)	Feeding rate f (mm/tooth)	Axial depth of cut a_p (mm)	Radial depth of cut a_e (mm)
30	0.05	1	11
36	0.03-0.05, step0.005	1	11
42	0.05	1	11
48	0.05	1	11

2.3. Test Results

Shear angle is the angle between cutting direction and shear plane. The value of shear angle is opposite to the extent of chip deformation, that is, the less the shear angle, the greater the chip deformation is. The states of chip deformation corresponding to different cutting speeds are shown in Fig. 3. The shear angle can be measured according to pictures in Fig.3. The change trend of shear angle with the increase of cutting speed is shown in Fig.4.

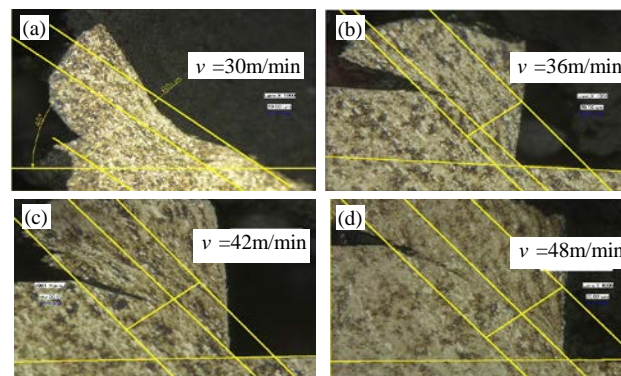


Figure 3. Relationship between chip deformation and cutting speed as $f=0.05\text{mm/tooth}$

It is found that the shear angle increases significantly with the increasing of cutting speed. So that, chip deformation becomes less and less with the increasing of cutting speed. The increasing of cutting speed makes cutting power become greater, cutting temperature rise, and then the friction coefficient between tool-chip become smaller, so the shear angle has a gradually increasing trend. The states of chip deformation corresponding to different feeding rates are illustrated in Fig. 5. The change trend of shear angle with the increase of feeding rate is shown in Fig.6. It is found that the shear angle increases significantly with the increasing of feeding per tooth. As feeding rate increases, cutting force increases, cutting temperature rises, friction coefficient decreases, thus, the shear angle has the trend of increasing.

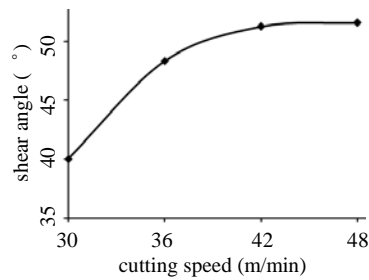


Figure 4. Effect of cutting speed on shear angle

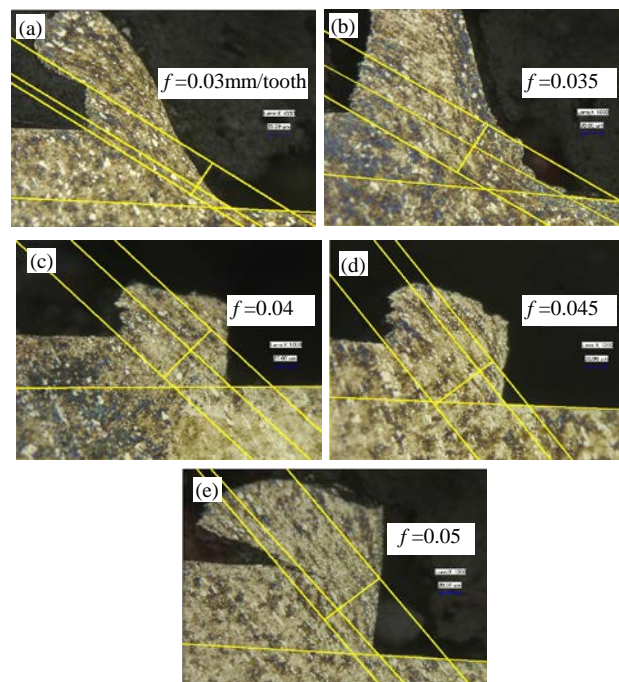


Figure 5. Relationship between chip deformation and feeding rate as $v=36\text{m/min}$

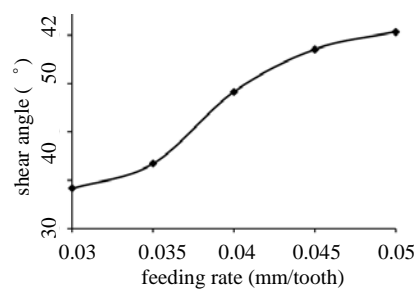


Figure 6. Effect of feeding rate on shear angle

3. Cutting Force as Milling Hardened Steel

Machining center and cutter used in this section are as same as those used in the investigation of cutting deformation. Test piece is a $200\text{mm} \times 200\text{mm} \times 100\text{mm}$ block of hardened steel Cr12 with hardness HRC50. Kistler9257B dynamometer was used to measure the cutting forces during milling process. DEWETRON amplifier was used to amplify the output signals acquired by the dynamometer. The data acquisition system was set with a 24 kHz frequency rate allowing acquiring simultaneously all the signals without any post-synchronize needed. Systematic error and intercept of the force signals were corrected.

3.1. Orthogonal Test Variable Setting and Test Results

The cutting force investigation has been done by means of multi-factor orthogonal test method with four factors and four levels. Cutting parameters, that is, cutting speed, feeding per tooth, axial depth of cut and radial depth of cut, are variable factors. The variable list and cutting force test results are illustrated in Table 2.

Table 2. List of variable factors and test results

v (m/min)	f (mm/tooth)	a_p (mm)	a_e (mm)	$F_{x\max}$ (N)	$F_{y\max}$ (N)	$F_{z\max}$ (N)	Resultant cutting force F_{\max} (N)
80	0.02	3	0.2	301.7674	418.0554	170.2783	542.9812
80	0.04	4	0.3	519.6561	608.4622	246.7735	837.3565
80	0.06	5	0.4	748.1346	782.8478	312.9969	1127.175
80	0.08	6	0.5	988.2975	949.5576	373.5376	1420.536
100	0.02	4	0.4	412.1146	490.6663	216.5674	676.3825
100	0.04	3	0.5	460.7640	504.5967	279.4366	738.2453
100	0.06	6	0.2	760.2661	885.8473	263.2347	1196.671
100	0.08	5	0.3	801.1039	857.0736	318.1853	1215.559
120	0.02	5	0.5	499.0396	559.0370	238.3024	786.3529
120	0.04	6	0.4	721.8854	772.6598	284.4880	1095.014
120	0.06	4	0.3	610.4508	685.3285	284.9777	961.0086
120	0.08	3	0.2	524.8008	631.9600	269.1421	864.4228
140	0.02	6	0.3	522.2462	630.5742	210.7877	845.4563
140	0.04	5	0.2	568.4415	700.2716	229.2971	930.6359
140	0.06	4	0.5	662.1489	677.6726	332.2693	1004.034
140	0.08	3	0.4	586.0956	622.6258	330.8441	916.8581

3.2. Test Result's Data Processing

The model of cutting force calculation for milling is shown as equation (1).

$$F_{\max} = K v^a f^b a_p^c a_e^d \quad (1)$$

Where K, a, b, c and d are coefficient.

Cutting parameters and test results listed in Table 2 have been processed by means of the mixed algorithm of least-square method fitting and Monte Carlo in order to get coefficient K, a, b, c and d.

According to data processing results, equation (2), (3) (4) and (5) for milling force calculation can be shown as following.

$$F_{x\max} = 876.03 v^{-0.0028} f^{0.4000} a_p^{0.7000} a_e^{0.1600} \quad (2)$$

$$F_{y\max} = 689.39 v^{-0.0066} f^{0.3000} a_p^{0.6100} a_e^{-0.0200} \quad (3)$$

$$F_{z\max} = 721.84 v^{0.0350} f^{0.3200} a_p^{0.1100} a_e^{0.2900} \quad (4)$$

$$F_{\max} = 1230.90v^{-0.0044}f^{0.3419}a_p^{0.6008}a_e^{0.0782} \quad (5)$$

Significant test of regression analysis. Table 3 shows the significant test results of regression analysis of cutting force calculation equations and coefficients based on 99% confidence. It follows from Table 3 that F's value for cutting force $F_{x\max}$, $F_{y\max}$, $F_{z\max}$ or F_{\max} is great larger than the critical value $F_{(0.01)}(4,15)=4.89$. The critical value of linearly dependent coefficient for 99% confidence with 16 degrees of freedom totally in 4 groups $R_{(0.01)}(4,11)$ is 0.8211. The value of R for cutting force $F_{x\max}$, $F_{y\max}$, $F_{z\max}$ or F_{\max} is larger than critical value $R_{(0.01)}(4, 11)$. Therefore, the equations (2), (3), (4) and (5) for cutting force calculation are of excellent significance.

Table 3. Significant test results of regression analysis

Coefficient significant test						Eq. significant test
	Model	Std. coeff.	Std. error	t	Sig.	R, F, Sig.
$F_{x\max}$	K	6.7754	2.791E-7	24279040.7420	7.2694E-77	
	lnv	-.0028	5.538E-8	-51463.0842	1.8732E-47	R=1.0000
	lnf	.4000	2.223E-8	17996403.6522	1.9589E-75	F=1.457E14
	lna _p	.7000	4.487E-8	15601966.8034	9.4205E-75	Sig.=2.1386E-75
	lna _e	.1600	3.387E-8	4724409.0990	4.800E-69	
$F_{y\max}$	K	6.5358	2.647E-7	24692232.4107	6.0379E-77	
	lnv	-.0066	5.253 E-8	-125654.6338	1.0188E-51	R=1.0000
	lnf	.3000	2.108 E-8	14230306.3468	2.5923E-74	F=9.8293E13
	lna _p	.6100	4.256 E-8	14334364.8467	2.3927E-74	Sig.=1.8637E-74
	lna _e	-.0200	3.212 E-8	-622623.2999	2.3045E-59	
$F_{z\max}$	K	6.5818	6.070 E-7	10844034.7861	5.1517E-73	
	lnv	0.0350	1.204 E-7	290588.4157	1.0069E-55	R=0.9998
	lnf	0.3200	4.834 E-8	6619535.3915	1.1747E-70	F=1.9872E4
	lna _p	0.1100	9.758 E-8	1127263.3199	3.3633E-62	Sig.=5.2561E-70
	lna _e	0.2900	7.366 E-8	3937108.6632	3.5653E-68	
F_{\max}	K	7.1155	2.010E-2	354.0201	1.1470E-23	
	lnv	-0.0044	3.989E-3	-1.1071	0.2919	R=0.9998
	lnf	0.3419	1.601 E-3	213.5461	2.9792E-21	F=1.9872E4
	lna _p	0.6008	3.231 E-3	185.9389	1.3654E-20	Sig.=3.8768E-21
	lna _e	0.0782	2.439 E-3	32.0566	3.2395E-12	

The greater the absolute value of t, the more significant the corresponding parameter is during t test for partial regression coefficient. That is, the corresponding parameter is more important to influence on cutting force. According to Table 3, the parameters are arranged as $f > a_p > a_e > v$ in the order of effect importance on cutting force $F_{x\max}$. So, Feeding per tooth is the most important cutting parameter to influence on cutting force in x-axial. For $F_{y\max}$, $F_{z\max}$ or F_{\max} , the order of effect importance on cutting force can be illustrated as $a_p > f > a_e > v$, $f > a_e > a_p > v$, $f > a_p > a_e > v$ respectively. Generally speaking, cutting speed v is minor factor to impact cutting forces, feeding per tooth and axial depth of cut are the most important parameters to impact cutting forces.

4. Conclusion

Test piece, made up of hardened steel Cr12 with hardness HRC50, is designed with special shape by means of Buda method. The effect of cutting speed and feeding per tooth on chip deformation and shear angle can be investigated comprehensively. The shear angle increases significantly with the increasing of cutting speed. So that, chip deformation becomes less and less with the increasing of cutting speed. Cutting power becomes greater as cutting speed increasing, cutting temperature rises, and then the friction coefficient between tool-chip becomes smaller, so the shear angle has a gradually increasing trend. The shear angle increases significantly with the increasing of feeding per tooth. As feeding rate increases, cutting force increases, cutting temperature rises, friction coefficient decreases, thus, the shear angle has the trend of increasing.

The cutting force investigation has been done by means of multi-factor orthogonal test method with four factors and four levels. The calculation equations for cutting forces have been deduced by means of the mixed algorithm of least-square method fitting and Monte Carlo fitting. It follows from the significant test results of regression analysis of cutting force calculation equations and coefficients based on 99% confidence that the equations for cutting force calculation are of excellent significance. Cutting speed v is minor factor to impact cutting forces. Feeding per tooth and axial depth of cut are the most important parameters to impact cutting forces. For $F_{x\max}$, $F_{y\max}$, $F_{z\max}$ or F_{\max} , the order of effect importance on cutting force can be illustrated as $f > a_p > a_e > v$, $a_p > f > a_e > v$, $f > a_e > a_p > v$, $f > a_p > a_e > v$ respectively.

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