Research on the machinability when dry turning hardened steel with ceramic tool

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Abstract

The experiments of dry turning hardened steel with ceramic tool (CC6050) were carried out. The cutting forces of ceramic tool with different cutting parameters were measured by Kistler cutting force acquisition system, the prediction model of the surface roughness was built by Particle Swarm Optimization (PSO), the wear morphology of the tool and chip characteristics were observed by scanning electron microscope (SEM), analyzed the wear zone of the tool by the EDAXPV990(EDS). Results indicated that the cutting depth was the dominant factor affecting the cutting force, next was feed speed, the minimum was cutting speed. The feed speed was the dominant factor affecting the surface roughness, next was cutting depth, the minimum was cutting speed. The crater wear was shown on the rake face and the evenly distributed strip shaped wear was shown on the flank of the CC6050 tool, the main wear mechanism was abrasive wear, diffusion wear, adhesive wear and oxidation wear. The shape of chip was saw-tooth, the rough slice layers with periodic flow were shown on the upside of the chip and the streaks were evenly distributed on the underside of the chip. The cutting speed and feed speed were larger, the serrated level of the chip was higher and the angle of shear was larger.

Keywords: Ceramic Tool, Dry Turning, Hardened Steel, Machinability

1 Introduction

Hardened steel has been used in manufacturing all kinds of mechanical parts with high hardness and high wear resistance attribute to its excellent mechanical properties. Grinding was the most traditional processing technology on finishing hardened steel, however, it would cause lower production efficiency, high cost and heavy environmental pollution [1-3]. With the development of the super-hard tool materials, dry turning instead of grinding on finishing hardened steel is expected to become the new technology. However, hardened steel has high hardness and poor machinability, in order to achieve the technology by using dry turning instead of grinding, the tool material should have good resistance of thermic wear, tool edge and tool nose should have enough strength and low breakage rate of wear, all of above can ensure that the machining error is within the scope of the working accuracy.

Ceramic tool has high micro hardness and heat stability. It has good resistance of thermic wear when turning the hardened steel and the materials of ceramic tool are abundant, its price is not half of the CBN tool. The strength and fracture toughness would be increased greatly by advanced milling, sintering process and toughening technology. It has good comprehensive mechinablity and high cost performance [4]. So it is the ideal tool in dry turning hardened steel.

Xiaobin cui etc researched the evolution of the tool failure in intermittent turning hardened steel with ceramic tool, built the formulas of the tool life in the different failure stage of evolution under the condition of intermittent turning [5]. Professor Gabriel C. Benga in Romania did the research on the influence of tool life and surface roughness by cutting depth when turning 100Cr6 bearing steel with ceramic and PCBN cutting tools [6]. Xiaoguang Wang etc did the experiments on dry turning hardened steel by ceramic tool, researched the endurance, wear morphology and wear mechanism of the ceramic tool [7]. Xuhong Guo etc researched the wear morphology, wear properties and wear mechanism when turning GCr15 hardened steel with ceramic tool and PCBN tool [8]. Many scholars did the studies of dry turning hardened steel by ceramic tool, but most studies focused on the tool endurance and tool wear, it was lacked for intensive study on cutting force, surface quality, tool wear and chip characteristics in dry turning hardened steel, reports on these aspects at home and abroad were few.

The experiments of dry turning hardened steel by ceramic tool (CC6050) were carried out in this paper. Measured the values of cutting force in different cutting parameters, built the prediction model between cutting parameters and surface roughness by PSO, researched the impact of cutting parameters on the cutting force and surface roughness, micro analyzed the wear morphology of the CC6050 and the chip characteristics, researched their affects on dry turning hardened steel. We hope we can provide some experimental basis for popularization of the high hardened tool material.

2 Materials and Methods

The work material was GCr15 bearing steel，its chemical composition was shown in Table 1. It was provided by Suzhou Jingji Mech & Elec CO., LTD, which was φ40×300mm cylindrical specimen. The hardness of the

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workpiece quenched by machine oil at 840℃was 60HRC (58HRC~61HRC).

TABLE 1 Nominal chemical composition of GCr15 bearing steel (wt%)

C	Si	Mn	Cr	Mo	P	S
0.95~ 1.05	0.15~ 0.35	0.25~ 0.45	1.40~ 1.65	≤0.1	＜0.027	＜ 0.020

Dry turning experiments were carried out on the CA6140A lathe. The lathe was the product of Shenyang No.1 Machine Tool Plant. The ceramic cutting tool was the product of SANDVIK Company in Sweden. The type was SNGA120408S01525 6050. After clamping, the geometric parameters of the tool were shown in Table 2.

TABLE 2 Geometric parameters of the tool after clamping

γ_o	α_o	λ_s	κ_r	r_ε	b_{rn}	γ_n
-6°	0°	-6°	75°	0.8 mm	0.15 mm	25°

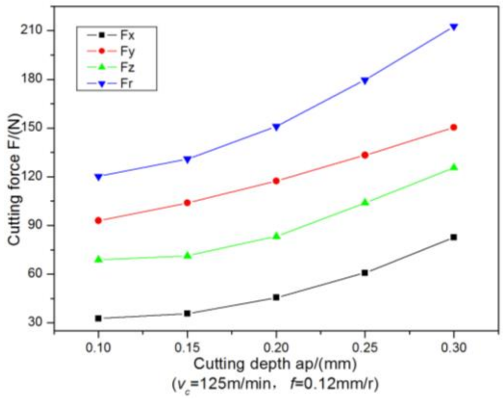
The values of the cutting force in different cutting parameters were measured by the cutting force data acquisition system, which was made up of Kistler9257B piezoelectric crystal sensor dynamometer, Kistler 507A10100 charge amplifier, Kistler9403 steel tool rack and computer. The surface roughness experiment based on $L_9(3^3)$ orthogonal, the factors of experiment were cutting speed, feed speed and cutting depth. The values of the surface roughness in different cutting parameters were measured by 2025 surface roughness tester. Enlarged photomicrograph of the wear morphology on the rake face and flank of CC6050 and chip characteristics were acquired by S-4700 scanning electron microscope (SEM), analysed the wear zone of CC6050 by EDAXPV9900 (EDS).

3 Results and Discussion

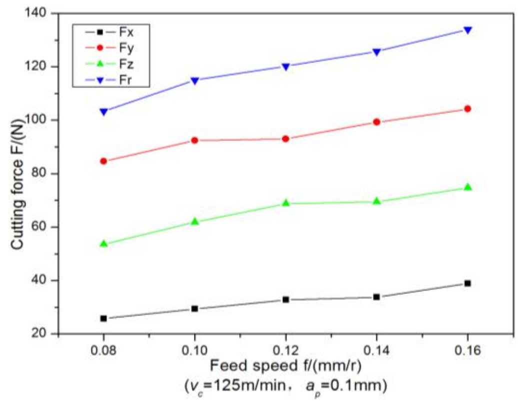
3.1 IMPACT OF CUTTING PARAMETERS ON CUTTING FORCE

The influence curves of cutting force in different cutting depth were shown in Figure 1(a) when cutting speed was 125m/min and feed speed was 0.12mm/r. The influence curves of cutting force in different feed speed were shown in Figure 1(b) when cutting speed was 125m/min and cutting depth was 0.1mm. The influence curves of cutting force in different cutting speed were shown in Figure 1(c) when feed speed was 0.12mm/r and cutting depth was 0.1mm. F_x was axial cutting force, F_y was radial cutting force, F_z was main cutting force and F_r was resultant tool force in three directions.

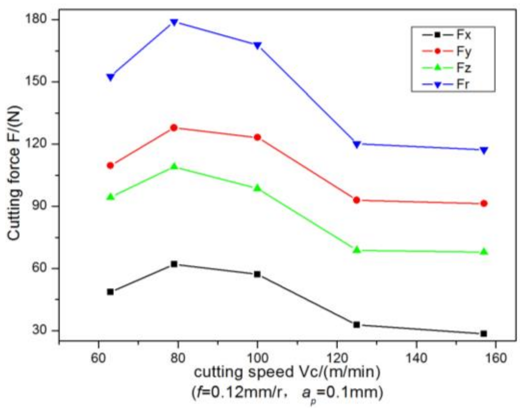
Figure 1(a) showed that the cutting forces in three directions of CC6050 increased gradually with cutting depth increasing when feed speed and cutting speed were certain and the relation was approximately linearity. When the cutting depth was less than 0.15mm, the trend of cutting force increasing was slow, when the cutting depth was larger than 0.15mm, the trend of cutting force increasing was fast. Figure 1(b) showed that the cutting forces in three directions of CC6050 also increased with feed speed increasing when cutting speed and cutting depth were certain, but the trend of cutting force increasing was not obviously, especially the cutting force in three directions keep basically stable when feed speed was within the scope of 0.12mm/r and 0.14mm/r. Figure1(c) showed that the cutting forces in three directions increased with cutting speed increasing when cutting speed was less than 80m/min and decreased when the cutting speed was larger than 80m/min. Especially the trend of cutting force decreasing was obviously when cutting speed was within the scope of 80m/min and 125m/min, the trend was slow when the cutting speed was larger than 125m/min. Compared with Figure 1(a), (b) and (c), the radial force was maximum, next was the main cutting force, the minimum was axial force when dry turning hardened steel by CC6050.



(a) Impact of cutting depth



(b) Impact of feed speed



(c) Impact of cutting speed

FIGURE 1 Influence curves of cutting force in different cutting parameters

The reason was: cutting width a_w increased in direct proportion to cutting depth ($a_w=a_p/\sin K_r$), it caused cutting layer area, the deformation resistance and friction force increased, so cutting force increased. Cutting force increased with cutting power increasing when feed speed increased and cutting thickness a_c increased in direct proportion to feed speed ($a_c=f\sin K_r$), the deform coefficient ξ and friction coefficient μ decreased, so cutting force decreased. Therefore the trend of cutting force increasing was not obviously when feed speed increasing.

When the cutting temperature raised with cutting speed increasing, the metal softening effect was produced in the workpiece [9, 10], the friction coefficient μ decreased with cutting speed increasing, the angle of shear φ increased, it caused the deform coefficient ξ decreased, so the cutting force decreased.

3.2 IMPACT OF CUTTING PARAMETERS ON SURFACE ROUGHNESS

The values of the surface roughness after dry turning hardened steel by ceramic tool were shown in Table 3 based on L_9 (3^3) orthogonal experiment.

The theoretical prediction model of surface roughness was shown in Eq.1. The objective function built by Particle Swarm Optimization (PSO) was shown in Eq.2. Optimized the objective function with 1stOpt mathematical analysis software, the constraint expression was $x_{min} \leqslant x_i \leqslant x_{max}$ (x_{min} was the lower limit value of the variable and the x_{max} was the upper limit value of the variable) [11].

The each parameter in Particle Swarm Optimization was as follows: the populations size was 100, adjacent population was 2, the value of weighting factor was 0.1, learning factor was 2.05, the max speed was 2, the iterations was 5000. The model simulated with experiment results was shown in Eq.3.

TABLE 3 The measure results of surface roughness experiment

NO.	v_c(m/min)	f (mm/r)	a_p (mm)	R_a (um)
1	100	0.08	0.1	0.51
2	100	0.12	0.2	0.67
3	100	0.16	0.3	1.01
4	125	0.08	0.2	0.48
5	125	0.12	0.3	0.76
6	125	0.16	0.1	0.78
7	157	0.08	0.3	0.49
8	157	0.12	0.1	0.57
9	157	0.16	0.2	0.93

$$R_a = k a_p^x f^y v_c^z = e^{x_1} a_p^{x_2} f^{x_3} v_c^{x_4}, \quad (1)$$

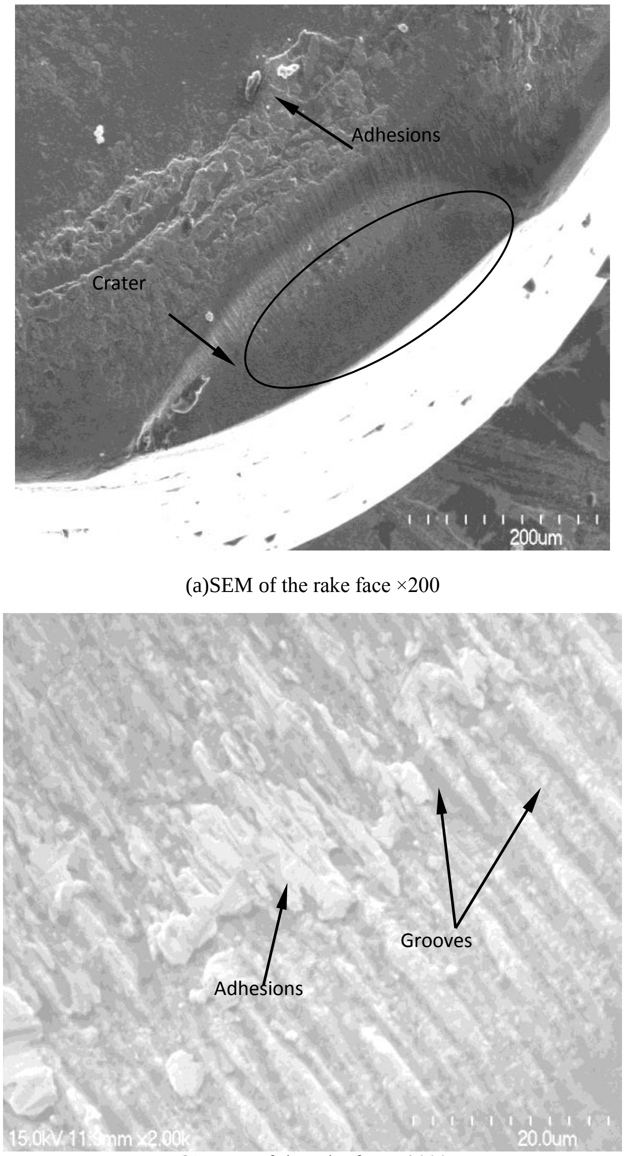
$$\min(f(x_1, x_2, x_3, x_4)) = \sum_{i=1}^{9} \left| e^{x_1} v_{ci}{}^{x_2} f_i^{x_3} a_{pi}{}^{x_4} - R_{ai} \right|, \quad (2)$$

$$R_a = e^{2.1599} v^{-0.0189} f^{0.9739} a_p{}^{0.2314}. \quad (3)$$

Eq.3 showed that the index of feed speed and cutting depth were positive value, so the surface roughness increased when feed speed and cutting depth uninterrupted increasing, the index of cutting speed was negative value, the surface roughness decreased when cutting speed uninterrupted increasing. It was apparent from the value of every index that the dominant influence factor of cutting parameters was feed speed, next was cutting depth, the minimum was cutting speed.

3.3 WEAR MORPHOLOGY ANALYSIS

The wear morphology of the rake face and flank were shown in Figure 2 and Figure 3 when dry turning hardened steel by ceramic tool (CC6050). The cutting parameters were v_c=125m/min, a_p=0.2mm, f=0.12mm/r, cutting time was 25min.

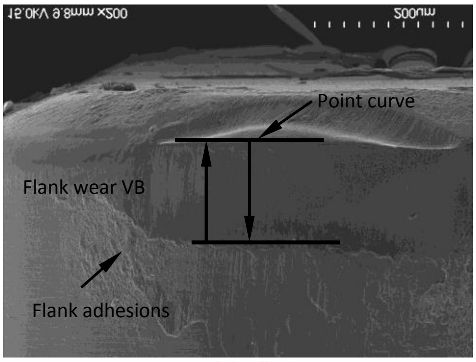


(a)SEM of the rake face ×200

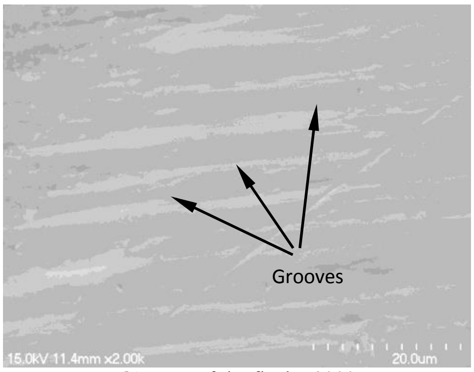
(b) SEM of the rake face ×2000

FIGURE 2 The Wear morphology of the rake face of CC6050 in later period of wear

Figure 2(a) showed that there was obviously crater wear on rake face of CC6050, wear zone was basically parallel to the rake face, it was wide at center and narrow at both sides. The wear area grouped mainly on the negative chamfering of the tool nose, it was directly connected with the tool edge, the depth of the crater was steady. Figure 2(b) showed that the groove like plowed covered on the wear area of the rake face, accompanied with more adhesions. The features of abrasive wear and adhesive wear were obviously showed in Figure 2.



(a)SEM of the flank ×200



(b) SEM of the flank ×2000

Figure 3 The wear morphology of the flank of CC6050 in later period of wear

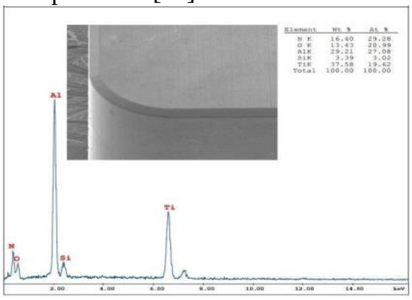
Figure 3(a) showed that there was strip shaped wear on the flank of CC6050 and its width was steady, the abrasion was relatively large on the arc chamfering of tool nose, accompanied with more adhesions near by the flank wear area, the wear marks was not obviously on the border of wear area, large slough was not exist. Figure 3(b) showed that the groove like plowed on the wear area of flank was steady. The steady feature of abrasive wear was showed in Figure 3.

The main reason to produce the wear morphology of the above was: in the cutting progress, the acutely friction was produced by high stress contact between the rake face of tool and chips, the average temperature measured in these cutting areas was higher than 1000°C according to work-tool thermocouple principle, adhesive, diffusion and oxidation wear were intensified, the high temperature zone of the tool was close to the tool edge and the cutting force was also focused on the near to the tool edge, the softened tool edge with heat deformed and collapsed [12]. Elastic and plastic deformation were produced because the contact force between the flank and surface of the workpiece was very large, the contact area between flank and workpiece was small, the strength of tool nose was lower and the cooling condition was poor, so the wear was serious.

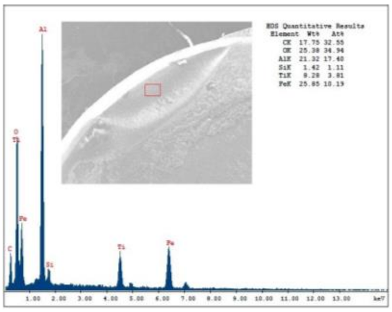
3.4 WEAR MECHANISM

The EDS spectra of the tool face on CC6050 before and after dry turning were shown in Figure 4.

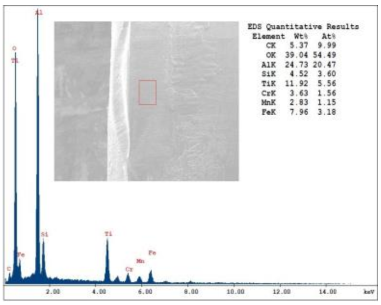
Compared with Figure 4(a), (b) and (c), the mass fraction of oxygen in the rake face and frank of CC6050 was improved from 13.43% to 25.38% (in the rake face) and 39.04% (in the flank), it proved that the oxidation wear was produced. The mass fraction of Ti was decreased from 37.58% to 8.28% (in the rake face) and 11.92% (in the flank), it proved that Ti in the tool had been diffused to the material and chip, the diffusing phenomenon in the rake face was more obviously. The mass fraction of Si and Al had little change, it proved the chemical affinity between Si, Al and material was small, it was hard to adhere in turning. Otherwise, the Fe, C and Cr was added in the flank of the tool, the mass fraction was 7.96%, 5.37% and 3.63% respectively, the three elements of the material were separated out because of the high temperature in turning and diffused to the flank of the tool. There had no Cr element in the rake face, but the content of the Fe and C in the rake face was higher than flank, its mass fraction was 25.85% and 17.75% respectively, the chemical affinity between the tool and material was improved with the content of the Fe and C improved, it caused the adhesive wear of the tool was produced [13].



(a) The EDS spectra of the tool before dry turning



(b) The EDS spectra of the rake face after dry turning



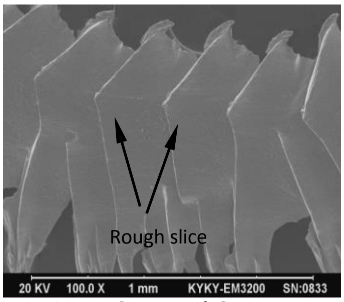
(c) The EDS spectra of the flank after dry turning

FIGURE 4 The EDS spectra of CC6050 before and after dry turning

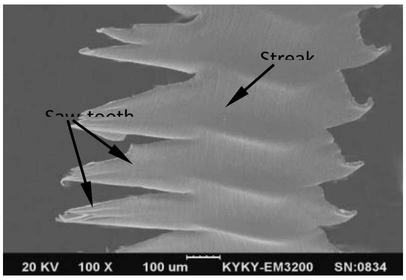
3.5 CHIP CHARACTERISTICS ANALYSIS

The shape of chips was shown in Figure 5 when dry tuning hardened steel by CC6050. Figure 5(a), (b), (c) showed the shape of chips when the cutting parameters were v_c=157m/min, f=0.2mm/r, a_p=0.3mm. The values of three cutting forces measured in these cutting parameters by Kistler cutting force acquisition system were F_z=262.95N, F_x=142.44N, F_y=371.04N. Figure 5(d),(e),(f) showed the shape of chips when the cutting parameters were v_c=125m/min, f=0.12mm/r, a_p=0.4mm. The values of three cutting forces were F_z=213.06N, F_x=145.67N, F_y=259.61N.

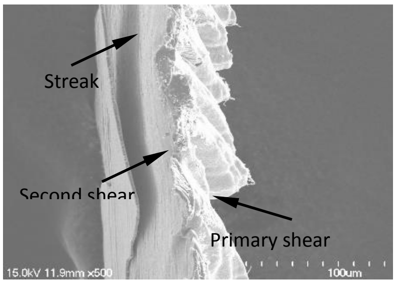
Figure 5 showed that the chip characteristic was obviously saw-tooth when dry turning hardened steel by CC6050. The extrusion plasticity shear of the chip was produced in the primary and second shear zone [14]. The severe plastic deformation was produced under extreme stress in the primary shear zone, so the rough slice layers with periodic flow was shown on the upside of the chip and the underside of the chip was smooth, the streak was evident as a result of the extrusion and friction of the chip against the rake face of tool.



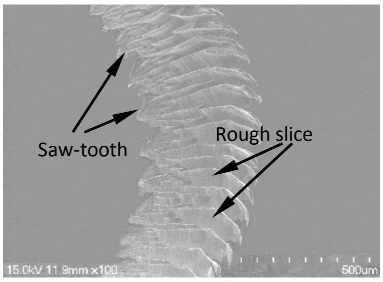
(a)Upside SEM of chip×100
(vc=157m/min, f=0.20mm/r, ap=0.3mm)



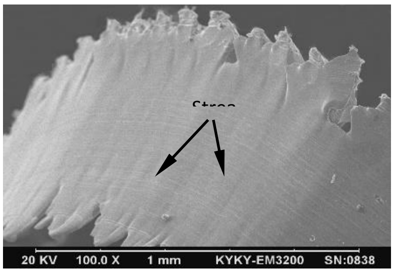
(b) Underside SEM of chip×100
(v_c=157m/min, f=0.20mm/r, a_p=0.3mm)



(c)SEM of the chip in profile×500
(v_c=157m/min, f=0.20mm/r, a_p=0.3mm)



(d)Upside SEM of chip×100
(v_c=125m/min, f=0.12mm/r, a_p=0.4mm)



(e) Underside SEM of chip×100
(v_c=125m/min, f=0.12mm/r, a_p=0.4mm)

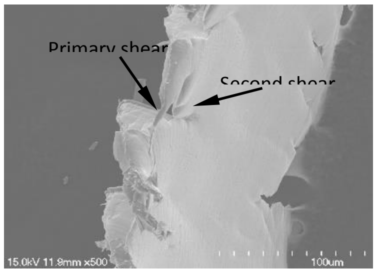

(f)SEM of the chip in profile×500
(v_c=125m/min, f=0.12mm/r, a_p=0.4mm)

FIGURE 5 The shape of chip

Compared with the Figure 5(a),(b),(c) and (d),(e),(f), when the values of the cutting speed and feed speed were larger, the serrate level was higher, the spacing of rough slice layers was wider and the angle of shear was larger[15]. The reason was: the strain rate was increased when the cutting speed increased, moreover the metal removal in unit time was increased when the feed speed increased, the power consumption and the cutting heat was increased, the deformation time of the chip was shorten, it caused that the cutting heat was produced more fast and diffused more harder. These changes all of the above caused the adiabatic shear was aggravated, improved the deformational degree of the chip [16]. The saw-tooth chip caused the cutting force fluctuated and then influenced the machining precision, surface roughness and the tool wear [17].

4 Conclusion

1. The dominant factor affecting the cutting force is cutting depth, next is feed speed and the minimum is cutting speed when dry turning hardened steel by CC6050, the radial cutting force is maximum, next is main cutting force and the minimum is the axial cutting force.

2. The dominant factor affecting surface roughness is feed speed, next is cutting depth and the minimum is cutting speed.

3. There is obviously crater wear on the rake face and steady strip shaped wear on the flank of CC6050. The mainly wear mechanism is abrasive, diffusion, adhesive and oxidation wear.

4. The chip characteristics is saw-tooth when dry turning hardened steel with ceramic tool, the cutting speed and feed speed are larger, the serrated level of the chip is higher, the spacing of the rough slice layers on the upside of the chip is wider and the angle of shear is larger.

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