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Wear behavior in turning high hardness alloy steel by CBN tool

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Abstract

Tool wear mechanisms in turning of high hardness alloy steels by CBN tools under various speeds are investigated by experimental studies. In low speed cutting, the binder of the hard particles of the cutting tool is found to be removed from the substrate due to a high cutting force, resulting from low cutting temperature, and abrasion dominates tool wear. When the cutting speed is increased, a protective layer resulting from the diffusion of the bond material of the cutting tool starts to form on the chip-tool interface. This layer works as a diffusion barrier. Hence, tool wear rate is reduced and the usable life of the CBN tool is prolonged. However, when the cutting speed is further increased, cutting temperature becomes the dominant factor instead of the cutting force. The high cutting speed causes inhomogeneous shear strain, and a transition from continuous chip to saw-tooth chip occurs. The friction force is found to increase because of the very irregular chip-tool contact. This would remove the protective layer. In addition, the bond between tool particles is weakened due to serious diffusion between the work material and the cutting tool under high cutting temperature. Subsequently, hard particles are detached, and tool life is reduced. Hence, it is concluded that there exists an optimal cutting speed of CBN tool in turning of high hardness alloy steels.

Keywords: CBN; Tool life; Tool wear mechanism; High hardness alloy steel

1. Introduction

CBN tool material has been applied widely in the cutting of hardened steels, tool steels, difficult-to-cut materials, etc. due to its high temperature stability, hot hardness and low affinity to iron. In cutting hardened steels of different hardness by CBN tool, it was found that tool wear reduced first with the increase of the hardness of work material until a hardness of about HRc 50 where the wear started to increase abruptly. This phenomenon had been studied and unveiled by several investigators [1–4]. In cutting hardened steels, it was also noted that the life of CBN tools showed an increasing and then decreasing trend with increasing cutting speed [5–7]. This is quite different from that described by the traditional Taylor's tool life equation where tool life is inversely proportional to cutting speed. Regarding CBN tool wear mechanism, Zimmermann et al. [8] showed that wear of the tool in the crater region was primarily tribochemical, and most likely chemical in the flank region. Barry and ByrneT also suggested that the chemical wear was the dominant mechanism of CBN tools [9]. The works by Chou and Evans [10] and Poulachon et al. [11] indicated that the Tsize of carbide particles of the workpiece had significant effects on tool wear. TChou et al. noted that there was a transferred layer formed on the flank wear land, and it would lead to adhesive wear of the cutting tool [12]. All these studies provide more insight into CBN tool wear in cutting hardened steels. Nevertheless, the real mechanism governing the aforementioned peculiar increasing then decreasing tool life characteristic has not been clarified. Hence, the purposes of this paper are to study the cutting behaviors and tool wear mechanisms in the turning of high hardness alloy steels by CBN tools under various cutting speeds.

2. Experiments

Experiments were conducted on a lathe. The insert used in the turning experiments had a land of 0.2 mm width and 20° negative rake angle. It contains 50% and 45% of CBN, and TiC-based binder, respectively, and a small amount of Al (about 5%). The lathe-tool nomenclature denoted by the German system was $-6, -6, 6, 6, 30, 0, 0.8$. Work material was AISI 4340 alloy steel,

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and it was heat-treated to the hardness of HRc 50–59. Feed and depth of cut were fixed throughout the experiments, and they were 0.1 mm/rev and 0.2 mm, respectively. The cutting speed ranged from 58 m/min to 180 m/min. The infrared photography unit was mounted on the slide of the carriage so that the unit could move with the cutting tool, and temperature on the back of the chip could be measured. The cutting forces were measured by a Kistler dynamometer. Tool wear was examined by the use of SEM, and its quantity was measured under a toolmaker's microscope. Tool life was accessed by the flank wear since tool breakage does not occur in light cutting conditions. According to JIS B4011-1971, flank wear of 0.2 mm was used as the tool life criterion.

3. Results and discussions

3.1. Types of chips

The chips produced under various cutting speeds were collected and displayed in Fig. 1. At low speed cutting the chip is a continuous type (Fig. 1(a) and (b)). When the speed is increased, it is changed to saw-tooth type (Fig. 1(c) and (d)). It shows that the higher the cutting speed, the more noticeable the saw-tooth chip. This changing trend had also been reported by Komanduri et al. [13], Shaw [14] and others. Besides, the segment spacing (P_C) in Fig. 1(d) is larger than that in Fig. 1(c), a phenomenon in agreement with the finding of Davies et al. [15] that the mean spacing of segmentation increased with the increase of cutting speed. The mechanism involved in the formation of saw-tooth chip is very complex. It was reported to be attributed to the adiabatic shear on the shear plane [13,16] or cyclic cracks at the free surface of the chip [17,18]. A very detailed discussion had been given by Shaw [14]. There is no standard criterion to predict the onset of saw-tooth chip formation. In our case, the transition speed from continuous chip to saw-tooth chip is between about V = 80 m/min and 130 m/min. It is similar to the observation of Komanduri et al. [13] that the critical speed responsible for the formation of saw-tooth chips was found about 130 m/min in high-speed machining of AISI 4340 steel.

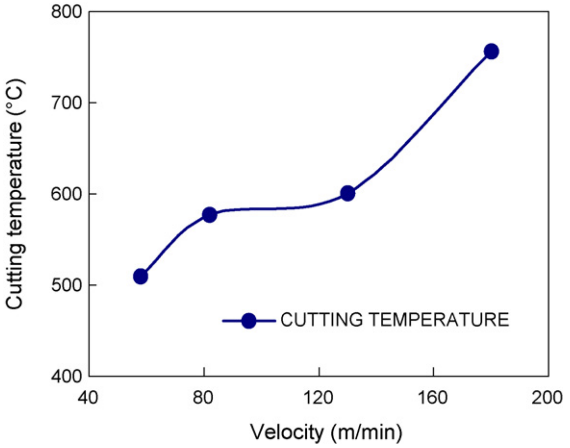

Fig. 2. Cutting temperature versus cutting speed for workpiece hardness of HRc 50.

3.2. Cutting temperature

Variation of cutting temperature with respect to cutting speed is shown in Fig. 2. It can be seen that cutting temperature increases with cutting speed, and the temperature curve can be divided into three stages. When cutting speed is comparatively small, the rate of temperature rise is larger. The curve becomes flatter in the middle part where cutting speed is in between about 80 m/min and 130 m/min. When the cutting speed is further increased, the rate of temperature change increases drastically again. It had been shown by others that the energy required to shear the work material is reduced once saw-tooth chip appears [1]. However, the heat flux in the shearing zones is increased

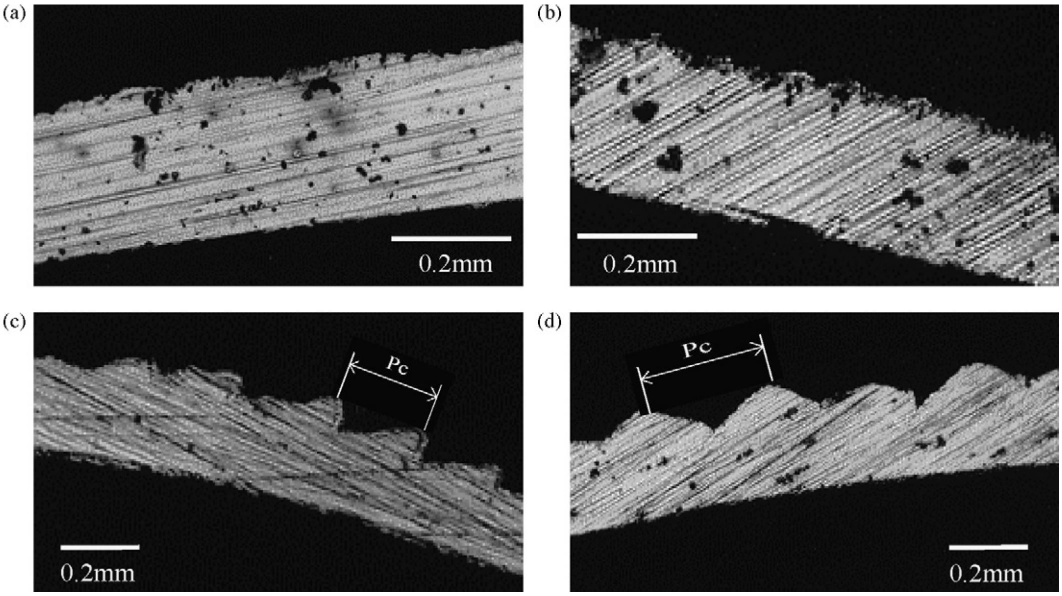

Fig. 1. Cross section of the chips for workpiece hardness of HRc 50 under (a) $V = 58$ m/min, (b) $V = 82$ m/min, (c) $V = 130$ m/min, and (d) $V = 180$ m/min.

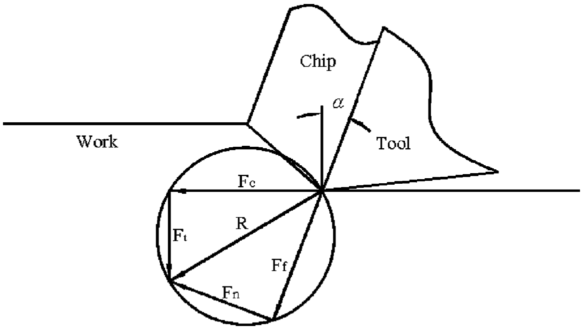

Fig. 3. Merchant's force circle.

with the increase of cutting speed. The cutting temperature is affected by these two factors. When the speed is in between about 80 m/min and 130 m/min, the rise of cutting temperature resulting from the increase of cutting speed is offset a little by the reduction of shear energy due to the appearance of saw-tooth chip. Hence, the rate of temperature rise is smaller in this region. When cutting speed is increased further, the increase of heat flux is far greater than the reduction of shear energy, and cancellation of cutting temperature becomes negligible, hence a drastic rise of cutting temperature at higher cutting speeds is observed.

3.3. Cutting forces and friction force

The well-known Merchant's force circle is drawn and given in Fig. 3 to illustrate the details of cutting forces at tool-chip interface; where in the figure F_C is the principal cutting force (tangential component), F_t is the feed force (along feed direction), F_f is the friction force (along tool face), R is the resultant force, and α is the back rake angle of the insert. The principal cutting force and feed force can be measured directly by a dynamometer. Their changes with cutting speed are shown in Fig. 4. With the increase of the cutting speed, the cutting temperature increases (referring to Fig. 2) and the hardness of workpiece material is decreased accordingly; As a result, both of the principal cutting force and feed force are reduced as depicted in the figure. To be more specific, the variation of principal cutting force is inversely proportional to the variation of cutting temperature. But the feed force does not decrease monotonically; it starts to increase at the cutting speed of 82 m/min. From the force circle given in Fig. 3, it can be readily shown [14] that the friction force is related to the measured forces and the rake angle by Eq. (1).

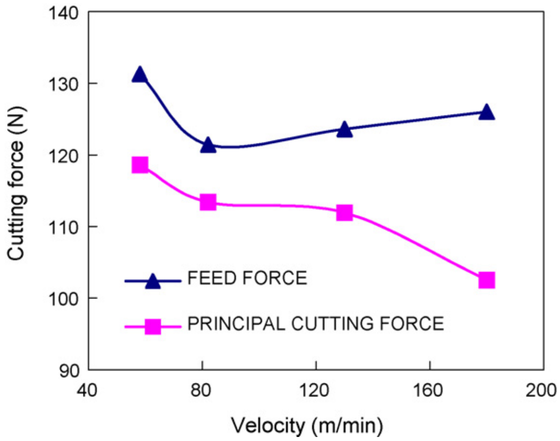

Fig. 4. Cutting forces vs. cutting speed for workpiece hardness of HRc 50.

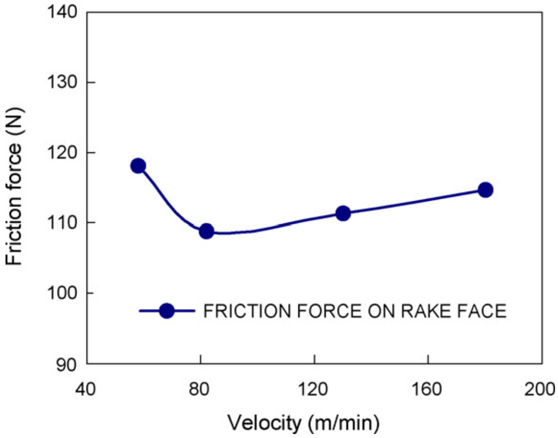

Fig. 5. Friction force vs. cutting speed for workpiece hardness of HRc 50.

$$F_f = F_C \sin\alpha + F_t \cos\alpha \tag{1}$$

The computed friction force is shown in Fig. 5. The high friction force at low speed cutting is attributed to the high hardness of workpiece material owing to low cutting temperature. As cutting speed is increased (up to 82 m/min), the friction force decreases because of the decrease of cutting forces with the increase of cutting speed. When the cutting speed is further increased the saw-tooth chip forms and the friction force rises. This fact confirms the finding of Matsumoto et al. [2] where the occurrence of saw-tooth chip caused friction force to increase. The rise of friction could be related to the tribological behavior between the tool and chip. This will be discussed in Section 3.4. Based on Eq. (1), the increase of feed force at the cutting speed beyond 82 m/min as that depicted in Fig. 4 is due to the increase of friction force.

3.4. Tool life and tool wear

Variations of tool life with cutting speed for the workpiece having hardness of HRc = 50 and 57 are shown in Fig. 6a and b, respectively. Both figures show that the CBN tool life is increased first with cutting speed. Once it reaches the highest tool life at a specific cutting speed (about 80 m/min), it starts to decrease thereafter. This trend is almost the opposite of the variation of friction force with cutting speed.

The flank wear at moderate cutting speed of $V = 82$ m/min is given in Fig. 7. It can be vaguely seen in the figure that there are scratched marks on the flank. This could be due to the abrasive action of hard carbide particles of the work material. It is well-known the wear is related to cutting temperature. Hence, abrasion is the main wear mechanism of flank wear at low cutting speed such as $V = 58$ m/min since it results in a lower temperature than that of $V = 82$ m/min. The wear on the rake face under various cutting speeds is shown in Fig. 8a–c. Referring to Fig. 8a,

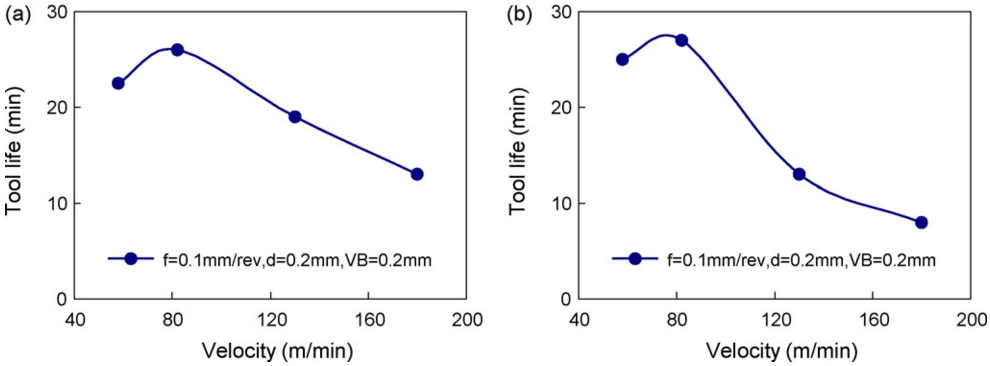

Fig. 6. Tool life vs. cutting speed for workpiece hardness of (a) HRc 50, and (b) HRc57.

the scratched marks on the tool face can be seen under low speed cutting ($V = 58$ m/min). This speed would result in high cutting forces due to the less degree of the softening of work material. The high cutting forces, in particular the friction force, will lead to severe abrasion of rake face by the hard carbide particles of work material; and thereby removes the binder of CBN. Since cutting temperature is not high enough, there is no or only slight diffusion between the chip and tool. Hence, tool wear is mainly by abrasion. As cutting speed is increased ($V = 82$ m/min), a layer generated on the tool face is found as shown in Fig. 8b. The EDAX analysis of this layer given in Fig. 9 reveals that, besides oxygen, this layer is basically composed of the elements of Fe, Mn, Ni, and Si which are the constituents of the workpiece material, and the elements of Ti and Al which came from the binder of CBN tool. Concerning the formation of this layer, a hydrodynamic model was proposed by Shaw [14] that a wedge-shaped semi-liquid layer could generate between chip and tool interface resulting from thermal softening of the chip due to a high cutting temperature, subsequently leading to a squeeze-film action. Bossom [19] also clarified that the lower thermal conductivity of CBN tool would result in the thermal softening of workpiece materials in the shear zone. When the cutting speed is too low (such as 58 m/min), it is found that no oxide layer deposited. This may be because of insufficient energy to induce thermal softening of chips. As cutting speed is increased (such as 82 m/min), the cutting temperature is raised accordingly. Since the melting point of ternary eutectic FeO–SiO_2–Al_2O_3 could be reduced to 1083 °C [20]. It is expected that the complex oxides in this study would exhibit an even lower melting point than 1083 °C, which is in accordance with the suggestion outlined by Klimenko et al. [21] that the compounds on the wear surface would possess a lower melting point than that of the chip. It is deduced that the oxides are readily melted and thereby lead to the wetting of tool surface. The layer thus generated may result in adhesion of the binder compound [12] and hence it would adhere on the tool simultaneously. It is noted that this layer is semi-liquid rather than in mobile state [14], hence it may not wet the tool face completely. Instead, the oxides are deposited on the tool surface as suggested by Barry and Byrne [9], and hence the layer in Fig. 8(b) is seen not very smooth. This layer could work as diffusion and thermal barriers, and it is beneficial to tool life. The same proposition had been suggested by others as well [9,14], and this protective effect is similar to that of the oxide layer formed on P-type carbide tools in the machining of Ca-treated steels [22]. When the speed is further increased, the adhesive layer could increase the friction force. At very high cutting speed such as V = 130 m/min, the layer cannot withstand the high friction force any more, and it is apt to be worn away from the tool face. Since at this moment the temperature increases significantly which weakens the bond between the hard particles of the cutting tool, the hard particles would be plucked out of the tool face via adhesion (Fig. 7c). Similar viewpoint was proposed by Chou et al. [12]. Detachment of hard particles on tool face can be seen more clearly in Fig. 10 where certain part of Fig. 8c is magnified. The rough tool surface could contribute further increase of friction force.

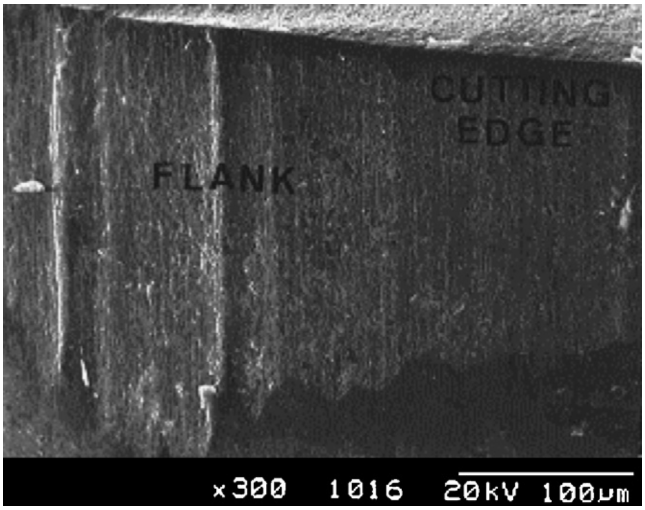

Fig. 7. Wear on the flank face for workpiece hardness of HRc 50 under $V = 82$ m/min.

4. Tool wear mechanisms

Based on the discussion given above, it is found that the form of wear of CBN tool in cutting hardened AISI 4340 alloy steels varies with cutting speed. Its wear mechanisms can be summarized as follows:

(1) When the cutting temperature is comparatively low (i.e. at low speed cutting), there are high cutting forces because the

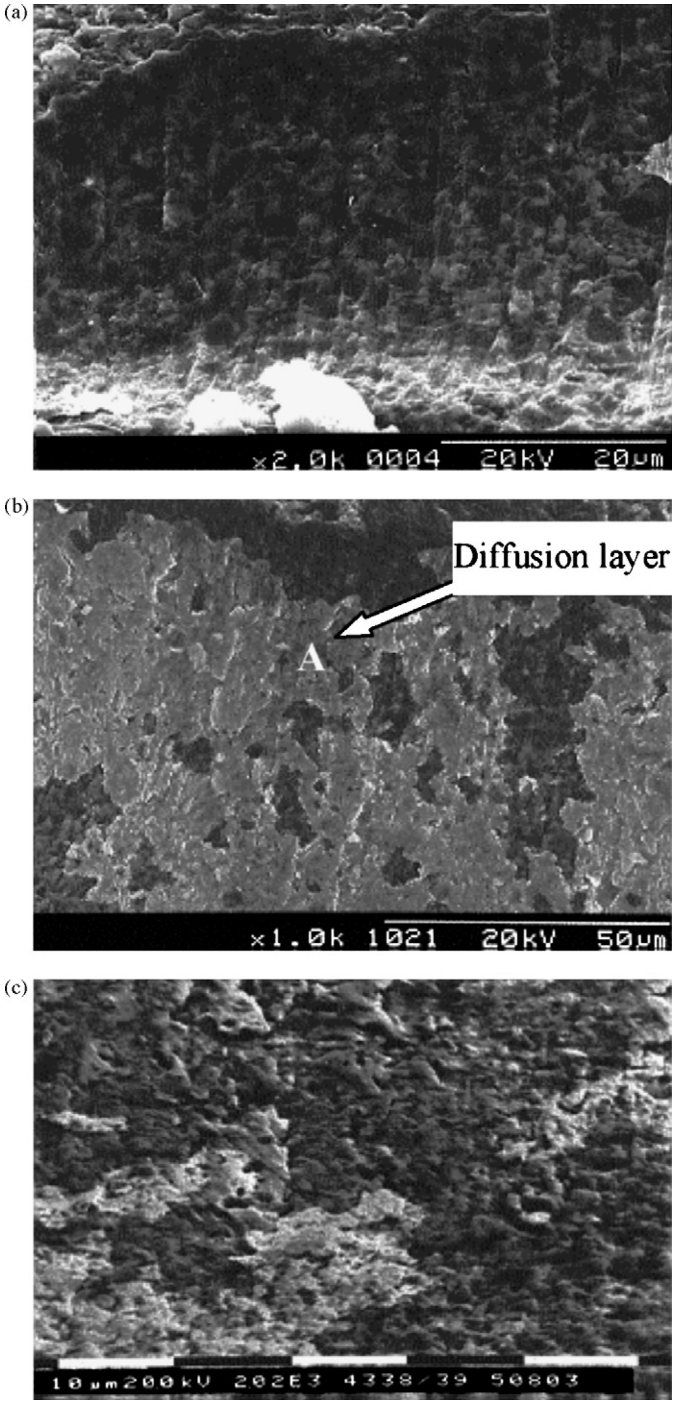

Fig. 8. Wear on the rake face for workpiece hardness of HRc 50 under (a) $V = 58$ m/min, (b) $V = 82$ m/min, and (c) $V = 130$ m/min.

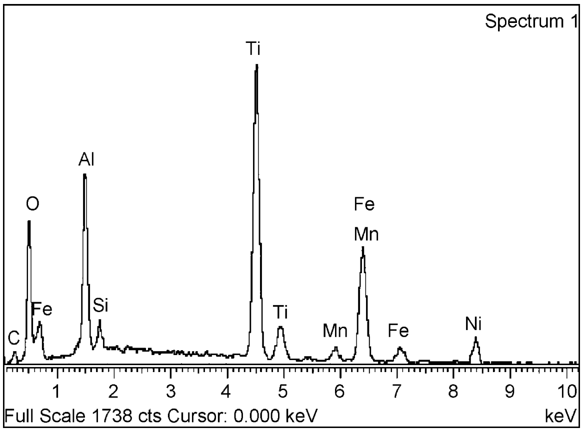

Fig. 9. EDAX analysis on site A in Fig. 8(b).

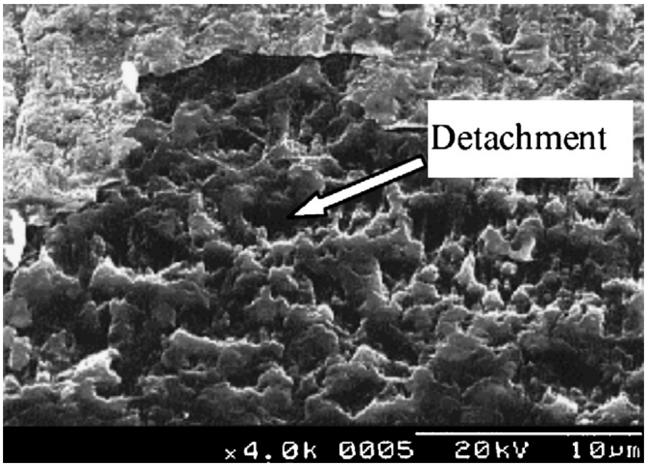

Fig. 10. Magnification of certain part of Fig. 8(c).

degree of the softening of work material is not significant. Hence, the tool face would be scratched by the hard carbide particles of work material and the binder of the CBN is removed. The main type of wear is abrasion, and there are scratched marks on tool face.

(2) The softening of work material becomes significant as cutting speed is increased. This, in turn, causes cutting forces to reduce. Abrasion is not important any more. The diffusion and oxidation would be more pronounced due to higher cutting temperature. A layer with oxidized compounds exhibiting a lower melting point is generated. This layer can protect cutting tool from wear. Hence, tool wear is reduced and tool life is prolonged.

(3) When there is very high cutting temperature, the sticking layer is worn away due to a great friction force. In addition, the bond between the CBN particles of the cutting tool is weakened owing to severe diffusion of work and tool materials. Hence, CBN particles are plucked out of the tool face. Subsequently, cutting edge is weakened, and flank wear is increased.

5. Conclusions

Wear behavior of CBN tool in cutting hardened steels is studied. It is found that tool life rises with the increase of cutting speed until a maximum is reached where it starts to decrease. In low speed cutting, abrasion is the main form of wear. When cutting speed is increased, a sticking layer is formed and remained on the tool face which protects tool face from wearing. At high cutting speed, the chip is transformed from continuous type to saw-tooth type. Friction force is increased accordingly, and the layer on tool face is abraded gradually. Since diffusion between work and tool materials becomes more severe at high cutting speed, the bond between the hard particles is weakened, and wear on the rake face is increased drastically. Together with the increase of crater wear, flank wear is increased.

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