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Critical Analysis of Wear Mechanisms in Cemented Carbide

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Wear phenomena of cemented carbide (94 wt.% WC, 6 wt.% Co) tip of conical picks have been observed by field emission scanning electron microscopy, energy dispersive x-ray spectroscopy (EDS), and x-ray diffraction analysis (XRD). The conical pick is one type of the cutters which are used to excavate soft structure like coal. It has a cone-shaped abrasive part made of cemented carbide (CC). The picks, under study, have been used for coal mining in an underground mine through a continuous miner machine. During the critical analysis of four picks, wear mechanisms are categorized into four parts, such as, *cracks, cavity formation in WC grains, grinding effect*, and *roughness of WC surface.* Through a careful examination, the cracking mechanism has been further divided into three parts. They are *cracks with overlapping surfaces, crack on a large surface of CC*, and *cracks in WC grains*. In addition, the severe *crushing* and *tearing* of WC grains have also been clearly examined. The possible causes of each wear phenomenon have been explained comprehensively. Crushing and corrosion are the two wearing processes which have severely deteriorated the condition of the CC. Corrosion has been easily identified by observing a number of pores and triangular notches in the WC surface. The oxidation of WC grains due to corrosion has been established by EDS and XRD.

Keywords CC, conical picks, EDS, FESEM, wear mechanisms, XRD

1. Introduction

Cemented carbide (CC) is an old material but still it has wide application in the field of metal and coal cutting. High hardness, strength, and wear resistance property make the CC absolutely fit for coal mining. The CC materials are not used as an entire tool. They are inserted in hardened steel body and fastened by brazing. For mining purpose, they have different shapes, such as, conical, radial, buttons, etc. According to the working conditions, particular types of tools are used. For soft structures, such as, coal and salt, cutters or picks are used. Mainly three types of picks, namely, conical pick, radial pick, and forward attack pick, are available. CC material is fitted in the form of cone in conical picks. Highly productive mechanical excavators, such as, continuous miner, roadheaders, and longwall shearers, are fitted with conical picks. The picks are arranged on the machine in such a manner that the CC parts can hit the coal mass properly. The sketch of a conical pick and the real picture of a continuous miner machine are shown in Fig. 1(a) and (b), respectively. Kenny and Johnson (1976) have explained that the steel body is relatively soft and ductile as compared to the inserted CC tip. The condition of the tool body can deteriorate easily. Ideally, it is assumed that the body part does not come in contact with rock materials (Ref 1). But practically, the tool body undergoes a severe microstructural deformation due to the penetration of uneven structured rocks/coals (Ref 2).

Nomenclature	
W	Tungsten
Co	Cobalt
WC	Tungsten carbide
CC	Cemented carbide
FESEM	Field emission scanning electron microscopy
EDS	Energy dispersive x-ray spectroscopy
SDD	Silicon drift detectors
nm	Nano-meter
kV	Kilo-volt
V	Volt
pA	Pico-ampere
nA	Nano-ampere
BSE	Back scattered electron
STEM	Scanning transmission electron microscopy
H	Hydrogen
S	Sulfur
O	Oxygen
Fe	Iron
Cu	Copper

At different wearing conditions, the wear behavior of the CC material has been investigated from many years. Coal/rock is highly heterogeneous substance and hence the wearing process of CC has so many variations. The wear phenomena of CC cannot be converged in a single domain. There must be further studies in this area. Wear assessment is necessary in order to enhance the required properties of the CC. It will help to develop better quality product and to reduce the wearing process. The development of

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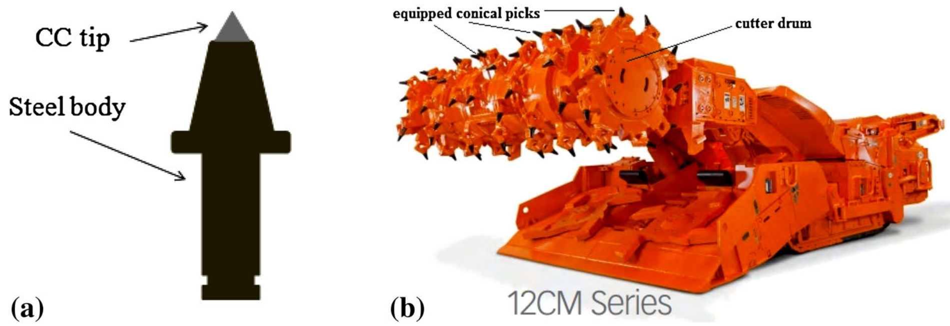


Fig. 1 (a) Sketch of a conical pick; (b) 12 CM series continuous miner (courtesy: joyglobal) (Ref 3)

wear-resistant coatings and binder-less carbide has dramatically improved the performance of the CC. A few literature are available regarding the wear analysis of conical picks. In the present study, the wear mechanisms in CC tip of conical picks have been critically observed. All the conical picks, under study, were used for coal cutting in a mine, and thus, they reached worn-out state after some period of tool-coal interaction.

2. Literature Survey

CC has wonderful proportion of strength and hardness for coal and rock excavation. It has hard WC phase and soft Co/Ni binder phase. The presence of WC grains impact hardness, strength, and wear resistance to cemented carbide, whereas binder phase Co/Ni is responsible for the toughness and ductility of such hard-metal alloys (Ref 4, 5). The density of CC is about 13-15 g/cm^3, and the densities of pure WC and pure Co are 15.7 and 8.9 g/cm^3, respectively (Ref 6). Tungsten carbide is manufactured by powder metallurgy process. Pure tungsten (W) is mixed with the pure carbon (C) at a high temperature of around 1500 °C in vacuum or sometimes in the presence of hydrogen (Ref 7, 8).The new product (WC) is then homogeneously mixed with the cobalt in the high pressure of 100-420 MN/m^2 under high heat and vacuum for cementation of WC into Co (Ref 7). The sintering process is carried out at the temperature of 1435 °C. The required shapes of the WC-Co are made under the influence of high pressure. The parameters, such as, WC grain size, Co content, porosity, and carbon content, affect the performance of CC to a great extent (Ref 9).

2.1 Effect of WC Grain Size

The tribological, mechanical, and thermal properties of WC cemented carbide substantially depend on its composition and WC particle size (Ref 10-12). It has been concluded that the fine grains provide high hardness and high wear abrasivity to the hard-metal alloy (Ref 13). The grinding test has been carried out to check the performance on three types of cemented carbides, which contained coarse, fine, and ultrafine grains of the same cobalt content. With keeping all the grinding parameters unchanged, it has been found that as the cemented carbide grains become coarser, the grinding force and energy consumption increase (Ref 14).

2.2 Effect of Binder (Co) Content

Brookes has concluded that the hardness of bulk composite decreases with an increase in binder content (Ref 15). Transverse rupture strength increases with an increase in cobalt content. The increase in Co may be up to 20%. The further increment of Co leads to the separation of carbide grains (Ref 9).

2.3 Effect of Porosity

Porosity is a defect introduces during sintering. It can reduce the transverse rupture strength and hence the durability of CC (Ref 16). The porosity can be minimized by increasing the cobalt content in the CC (Ref 17).

2.4 Effect of Carbon Content

It has been concluded that the carbon content affects the mechanical properties of the CC. It influences the WC grain growth and the amount of η phase (Ref 18). The entrance of carbon content during sintering can reduce the rupture resistance property (Ref 9).

In addition, *heat generated* during excavation greatly affects the tool durability. Some literatures are available related to CC drill bits. Regarding hard rock drilling, Fish et al. have found that there is a process of tool material softening due to high button temperature and the necessary high load generates high frictional heat (Ref 19). According to Beste et al., the actual surface temperature on the drill button is unknown and it is very difficult to measure, although a common estimation is that the rock drill button exhibits the temperature on an average between 300 and 400 °C (Ref 20). Kindermann et al. have found temperature-dependent fatigue effect for temperatures between 25 and 900°C. It has been investigated that at low temperatures, the Co binder undergoes a phase transformation from FCC to HCP phase which is more brittle and hard when subjected to cyclic loads. Also, oxidation of Co takes place near crack tips at higher temperature, which leads to brittle-ductile transitions (Ref 21). Lagerquist has studied the thermal fatigue crack propagation in WC-Co and its relation to the width of the Co layers between adjacent WC grains (Ref 22).

Stolarski has explained that wear and frictional properties of a material are behavioral parameters which are associated with the operational conditions. The damage can be assumed as the combination of continuous wear of WC-Co and crack formation (Ref 23). Maidl et al. have explained that wear analysis is used for performance evaluation of coal mining equipment. Wearing of tools is an undesirable parameter as it limits the tool life. It occurs because of relative frictional motion between rock/coal and tool. Wear of the cutting tools is one of the most important process parameters for evaluating the economy of process and efficiency of the operation (Ref 24). According to Zum Gahr, wear can be defined as the undesirable and continuous loss of the material from a solid surface due to mechanical interactions such as, contact and relative motion between two bodies (Ref 25).

A few literature are available describing wear analysis of the conical picks. Wear investigations of CC buttons of drill bits have been carried out significantly. Many researchers have investigated wear mechanisms of CC tool by using SEM and high-resolution field emission gun SEM. The wear mechanisms, such as, Microspalling, Abrasion Wear, Cracks, WC grain pullout, Extrusion of binder metal, and Reptile skin, have been mainly found in CC buttons (Ref 10, 26-31). In a review, Larsen-Basse has explained the wearing process of rock drill bit by the following mechanisms: Surface impact spalling, Surface impact fatigue spalling, Thermal fatigue, and Abrasion (Ref 32). Olovsjo et al. have concluded that main controlling parameters of CC wear are plastic deformation, cracking and crushing of individual WC grains, Co depletion, and rock material penetration (Ref 33).

Corrosion is a serious problem in hard-metal alloys. A considerable research work has been carried out to test the corrosivity of cemented carbide. Echtenkamp has immersed the WC-12%Co alloy in a ferric chloride solution. After 2 h, a 40% reduction in the transverse rupture strength has been reported in alloy. It has been observed that the binder part has been removed to a depth of approximately 80 µm, and the hard phase of WC has a series of pores and notches (Ref 34). Human and Exner (1996) have explained that binder part corrodes in faster rate. In spite of having porous structure as WC, binder is leached out (Ref 35). Machio et al. have investigated the effect of varying VC content on the corrosion behavior of WC-10 wt.% Co hard-metals in sodium chloride (NaCl) and synthetic mine water (SMW). After using anodic polarization scans and surface analytical methods, it has been concluded that (Ref 1) In NaCl, the corrosion resistance is poorer and independent of VC content, (Ref 2) In synthetic mine water, high amount of VC in hard-metal indicates the high corrosion resistance (Ref 36).Singh has analyzed the various physico-chemical characteristics with the corrosivity of different water samples of Indian mines. The mine water has been categorized into neutral, alkaline, low acidic, and extremely acidic in nature. The corrosivity has been found to be varied from low to high. The corrosion rates have been checked on the basis of the effect of Fe^{3+}, Cu^{2+}, SO_4^{2-}, and Cl^- (Ref 37).Engquist et al. have investigated the tribological properties of different CC (Co bonded, NiCo bonded, and binder-less) in the presence of different pH solutions. It has been observed that Co and NiCo have dissolved in aqueous solutions of very low pH. There is a heavy attack on the WC grains and the drop in Co-bonded material at high pH. The binder-less carbide shows a very high and a very low wear rate in alkaline and acidic solutions, respectively (Ref 38). Yeo and Park have investigated the corrosion properties of SiC-coated WC-Co by using the potentio-dynamic electrochemical test under various conditions. It has been concluded that corrosion current density decreases with an increase in SiC coating thickness (Ref 39). Gee has performed an experiment to check the difference in wear of WC-Co hard-metals. Wear tests have been carried out in the presence and absence of corrosive fluid. In the presence of corrosive fluid (HCl), Co has been removed, and the surface has been fractured leading to the removal of WC grains. In the absence of corrosive fluids, generation of a layer of binder phase with adhered nano-sized fragments of WC, plastic deformation, and fracture of grains have been observed (Ref 40). Several attempts have been put to minimize the corrosion of WC-Co by many researchers. It has been found that using Ni/Ni-Cr/Ni-Co as a binder material with replacing Co or alloying the Cr_3C_2 in the binder material increases the corrosion resistance property (Ref 41-44). Binder-less CC has been developed for using in corrosive environment. This consists of secondary carbides, such as, TiC, TaC, or NbC. The resultant composite is very hard but the toughness is very low (Ref 45, 46).

3. Experimental

The present study is focussed on the critical examination of CC tip (proportion of WC-6%Co) of worn-out conical picks.

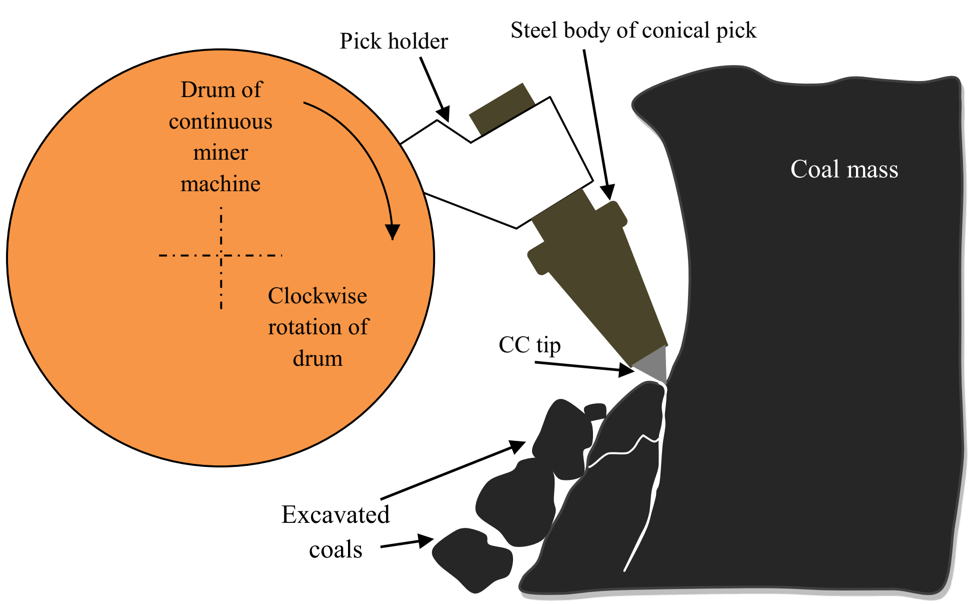


Fig. 2 Coal excavation by conical pick through a continuous miner machine

All the picks were used for in situ coal cutting operation in an underground mine. For the purpose, picks were equipped into a 12CM15 continuous miner machine. The continuous miner is one of the mechanical excavators used in the mining operation. It has a drum which rotates along with a number of conical picks. A sketch of coal excavation process by a conical pick through the continuous miner machine is shown in Fig. 2. For the current work, the rotational speed of the drum of miner was adjusted at 50 rpm. Hence, the tangential velocity of the picks was 175 m/min. The picks were arranged in 50° of attack angle in the drum. The machine specification affects the tool life to a great extent. During the continuous use, the picks undergo a gradual wearing process which leads to the complete removal of the CC tip. A sketch of gradual wearing of the CC tip of conical pick is shown in Fig. 3. The mine, under study, had W-II grade of coal. Inside the mines, coal mass may contain hard rock materials, gangues, and chemically affected mine water. As all the picks were used at once for cutting coals, they underwent through the same environmental conditions. The conical picks were used for 15 h per day. After 10 days, the picks were removed out from the miner. Hence, the period of usage of conical picks is 150 h. Four conical picks, namely, sample 1, sample 2, sample 3, and sample 4, have been taken for critical investigation. Generally, the CC tip removes out from the tool body during excavation. We have selected such picks which have their distorted CC part remained. For the wear investigation, selected worn-out picks are shown in Fig. 4. Proper cleaning is necessary to remove dust and rust from outer surface of the tools. Small- and appropriate-sized samples are primary requirements for observation in FESEM and EDS. Hence, the conical picks have been cut from the upper part so that required areas can be examined. The critical analysis has been done through FE-SEM Supra 55 (Carl Zeiss, Germany) which is attached with Energy Dispersive Microanalysis (Oxford Liquid Nitrogen free SDD X MAX 50 EDS). The specification of FESEM is given in Table 1.

Fig. 3 Sketch of gradual wearing of conical picks used in continuous miner machine

4. Observation

All observations of wear mechanisms have been carried out in FESEM images of selected samples. On the basis of present observation and considering previously found results (Ref 2, 20, 27, 33, 49), the wearing mechanisms have been divided into four types: cracks; cavity formation in WC grains; grinding effect; and roughness of WC surface. Cracks have been further divided into three subtypes. All the wear mechanisms are listed in Table 2.

4.1 Cracks

These are the common wearing mechanisms, which can be found in any type of tool in any cutting operation, i.e., metal cutting (Ref 47, 48) and coal mining (Ref 33, 49), which is subjected to shocks. High impacts and sudden shocks are responsible for generation of cracks. In case of coal mining, the conical picks continuously hit the coal mass to excavate it. Coal is a heterogeneous material. There is a great uncertainty in its composition. Sometimes hard rock particles entrap inside the coals in mines. They are main cause of the tool failure. The

Table 1 Specification of FESEM

S. No.	Specification	Parameters
1	Resolution	0.8 nm at 15 kV, 1.6 nm at 1 kV
2	Magnification	12-1000000×
3	Acceleration voltage	100 V to 30 kV
4	Gun type	Schottky Field Emission Electron Gun
5	Maximum probe current	12 pA to 100 nA
6	Detectors	SE, in-lens, BSE, retractable STEM with bright and dark field

Table 2 Types of observed wear mechanisms in conical picks

S. No.	Observed wear mechanisms in CC
1	Cracks Cracks with overlapping surfaces Crack on a large surface of CC Cracks in WC grains
2	Cavity formation in WC grains
3	Grinding effect
4	Roughness of WC surface

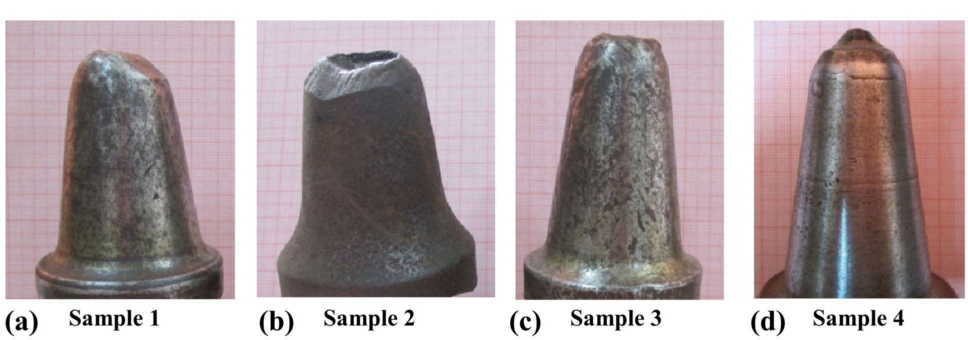


Fig. 4 Worn-out conical picks used for critical examination

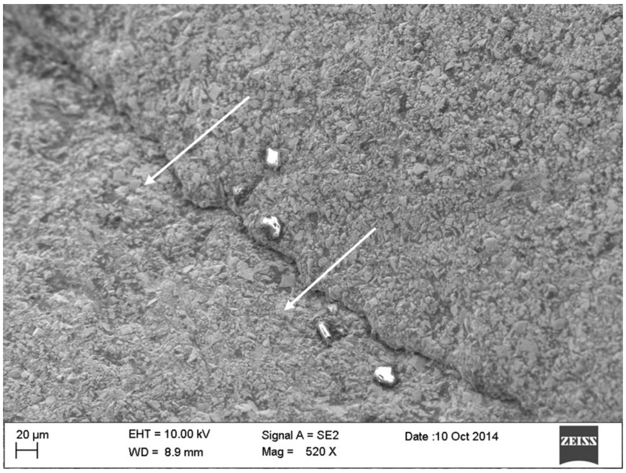


Fig. 5 Overlapping of the cracked surface in magnification of ×520; white arrow shows the overlapping direction (sample 1) (scale of image = 20 μm)

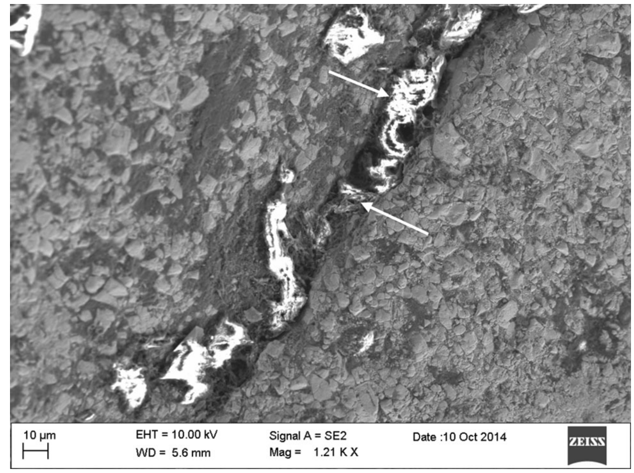


Fig. 6 Crack on a large surface of CC surface (image magnification: ×1.21 K); white arrow is showing the filled rock/coal particles (sample 2) (scale of image = 10 μm)

tools undergo hammering action of hard rocks. Minor cracks generate in the microstructure of CC after a few impacts. After a certain period of cutting, cracks may be observed over a large area of the CC surface which can be seen by naked eyes. Of course, we need to go up to micro level for understanding the wear pattern. In the present study, the cracks are divided into three categories. All the phenomena are explained as follows:

4.1.1 Cracks with Overlapping Surfaces. This phenomenon has been observed in a lower magnification of 520× in the sample 1. A large crack can be observed on the CC surface. Due to the hammering action of coal/entrapped rock, one side of the crack tends to overlap on the other side. But this process does not happen for a long time. After a period, there can be disintegration of CC into various parts. The direction of overlapping has been shown by white arrows in Fig. 5. This type of wear mechanism has not been reported in previous literature.

4.1.2 Crack on a Large Surface of CC. A large and deep crack on the CC surface can be observed in sample 2 (Fig. 6). The crack is filled with rock and coal particles. The pattern of crack can be compared with that of presented by Beste et al. (Ref 50). Under the topic of "composite scale crack formation," they explained the formation of 'shallow valley' which is a form of reptile skin. In our study, the crack seems to have comparatively greater depth and length. The rock/coal materials are looking bright. They are indicated by white arrows.

4.1.3 Cracks in WC Grains. Severe cracking in WC grains has been observed in sample 3. A clear view of the WC grain cracking is shown in Fig. 7 and 8. Comparatively higher magnification is needed to observe it. The grains get separated into different parts due to the cracks. In this condition, the tool becomes absolutely useless.

Researchers have investigated severe cracking and crushing in CC drill buttons used for rock drilling (Ref 20, 32, 49-51). Similar pattern of cracking has been observed for the CC tip of conical picks which were used in coal cutting through continuous miner machine. The drum of miner has been continuously rotated at 50 rpm. The structure of coal mass is highly uneven. Hence, the combined effect of sudden shocks and abrasive action of coal/rock further make the crushing

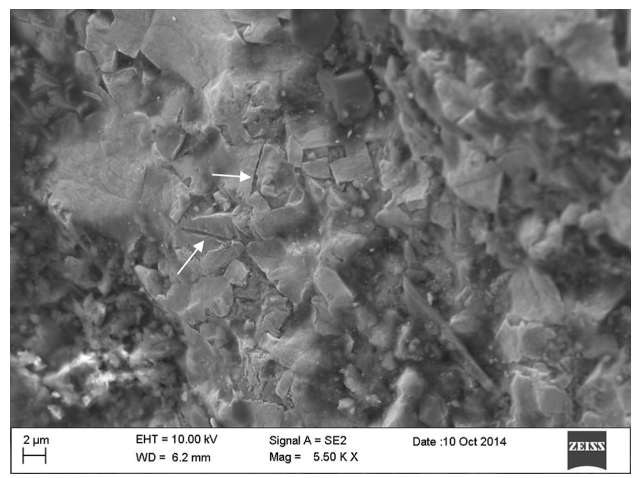


Fig. 7 Cracking of WC grains in sample 3 (magnification of image: ×5.50 K) (scale of image = 2 μm)

action in the cracked WC grains. Severe crushing phenomenon is observed in Fig. 8. In addition, little cracked grains (white circle), fragmented grain particles (black arrow), and surface deterioration of grain (yellow rectangle) have also been reported. In crushing, grains are disintegrated into a number of parts. The binder part has no longer capability to bind the fragmented grains properly. Hence, they easily remove out.

4.2 Cavity Formation in WC Grains

It happens due to the removal of a small part of the individual WC grain with leaving the original place empty. In fact, it can be assumed under the mechanism of crushing. Sometimes a sudden hitting on the already cracked grain surface causes the local crushing of the specific part of grain. A little amount of crushed grains removes out from the original place. By observing, it looks like a cave (Fig. 9). It is highly undesirable as it provides an easy path to the coal particles to get inside for further degradation. In the binder material, sharp rock/coal particles easily penetrate and get intermixed with it. Mixing of coal/rock into the binder (Co) content in the presence

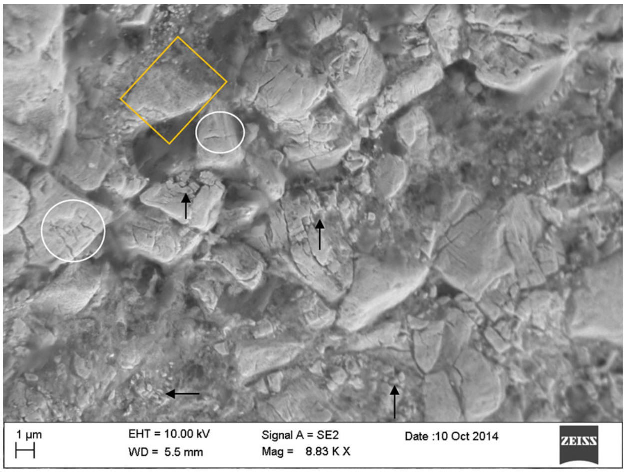


Fig. 8 Fully cracked and crushed WC grains observed in magnification of ×8.83 K (sample 3) (scale of image = 1 μm)

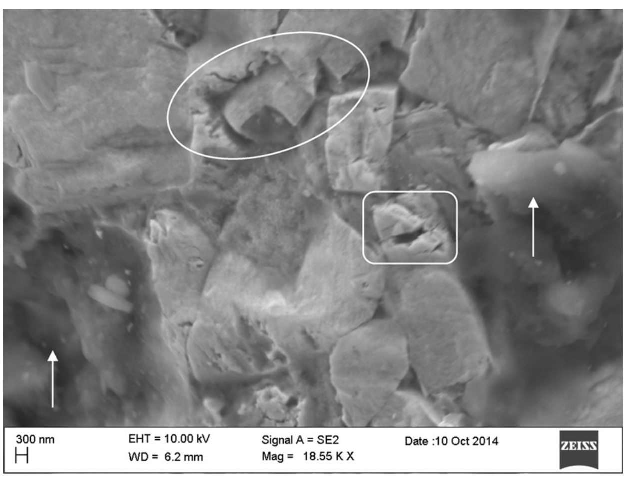


Fig. 9 Localized crushing of grain to form a cave-like structure (inside rounded rectangle); arrow indicates the rock/coal mixing into binder content; tearing of WC grains has been shown inside oval sketch (sample1). (Magnification of image: ×18.55 K) (scale of image = 300 nm)

of mine water, heat, and high pressure facilitates the formation of a complex structure inside the WC grains. In Fig. 9, the penetration of coal/rock materials into the CC structure has been observed (indicated by white arrow mark). This phenomenon is similar to rock penetration and adhesion into the CC structure as reported by Beste and Jacobson (Ref 49), and Olovsjo et al. (Ref 33). In addition, we have reported severe tearing of the WC grains (indicated inside white oval in Fig. 9). The reason behind tearing is abrasion at a high temperature. Olovsjo et al. have demonstrated this type of mechanism as severe plastic deformation (Ref 33).

4.3 Grinding Effect

Some hard and sharp-edged coal particles are very abrasive. They impose high degree of abrasion on the CC surface. This phenomenon is enhanced by entrapped hard rock particles. A large part of CC is affected. From Fig. 10, this wear phenomenon can be called as the grinding effects on the CC surface. In the magnification of 2.00 K×, the severity of grinding effect has been observed in sample 4. In Fig. 10, bright structures are WC grains, whereas the dark part indicates the binder content intermixed with coal particles. Also, the polished surface of WC grains can be reported. Probably, one single part of the CC tip would have come into contact with the single abrasive substance for a number of times.

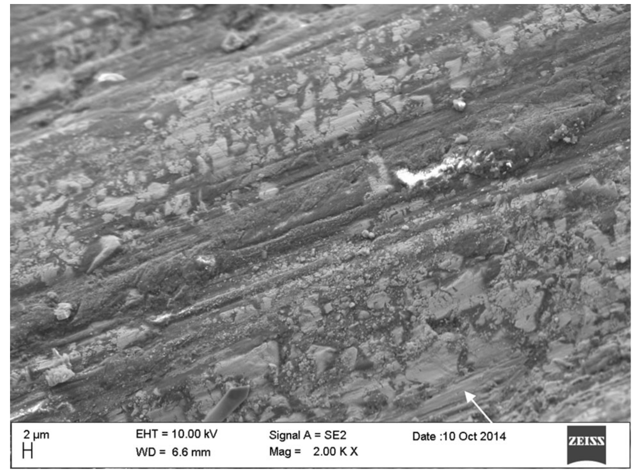


Fig. 10 Grinding effects in the CC surface (observed at the magnification of ×2.00 K); white arrow indicates polished surface of WC (sample 4) (scale of image = 2 μm)

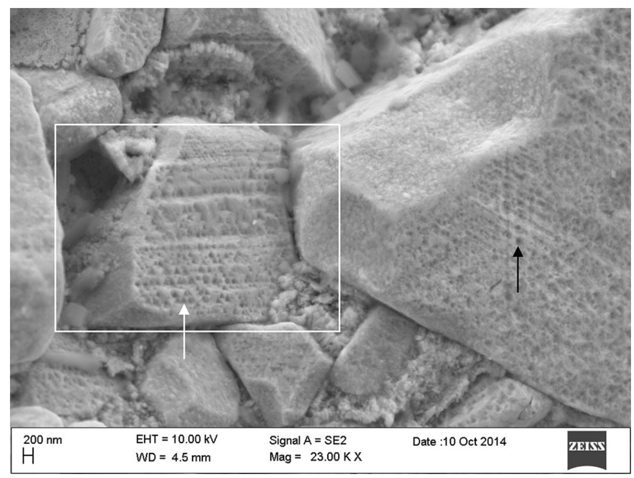


Fig. 11 Surface roughness of WC grains due to corrosion (observed at magnification of ×23.00 K); black arrow is indicating pores; white arrow is indicating triangular notches (sample 3) (scale of image = 200 nm)

4.4 Roughness of WC Surface

Although the WC is a high wear-resistant material, the corrosion resistance property is not up to the mark. In the presence of corrosive environment, CC structure gets degraded. The corrosive degradation has been observed in the WC grains of the CC part of conical pick. The reason behind degradation is reaction of chemically activated mine water with the WC-Co in the presence of high heat. In Fig. 11, it can be observed that corroded surface of WC has a number of inline pores and notches. Black and white arrows are indicating pores and triangular notches, respectively (Fig. 11). As a result, surface of the WC

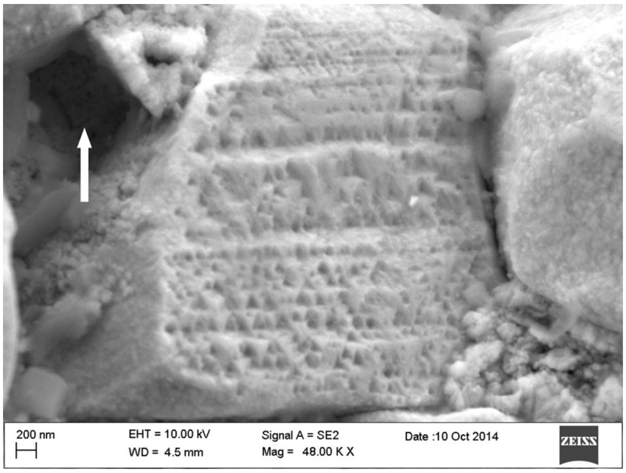


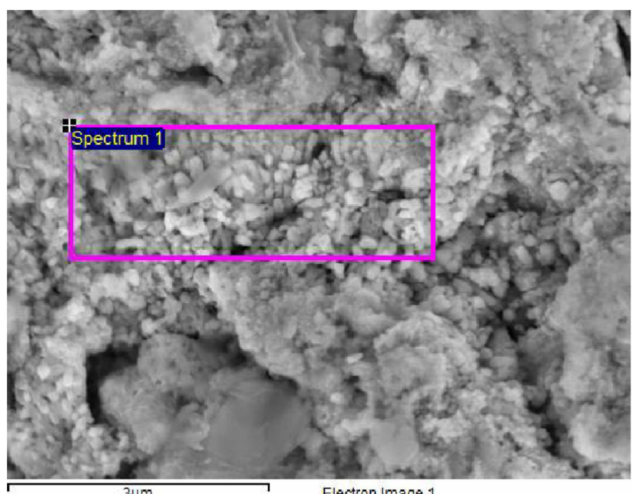
Fig. 12 Enlarged view of corroded WC surface with notches; arrow indicates the absence of Co (sample 3) (magnification of image = ×48.00 K) (scale of image = 200 nm)

grains becomes rough. This phenomenon is similar to the results discussed by Echtenkamp (1978). He has tested the WC-Co sample inside the ferric chloride solution for a certain period and found the roughness in WC surface in the form of pores and notches (Ref 34). Beste and Jacobson (2008) have also reported corrosive decay in CC drill buttons after rock drilling (Ref 49).

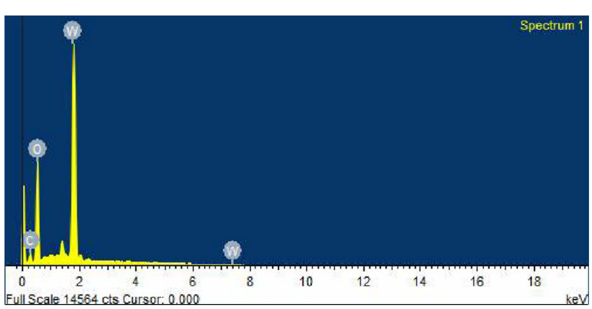
WC is more corrosion-resistant than Co. Hence, if the amount of tungsten is increased in CC, the process of corrosion decreases. Also, if the carbon content decreases in WC, then the amount of W increases proportionally. This increment in the amount of W makes the hard-metal alloy highly corrosion-resistant (Ref 52). Voorhies (1972) has explained the corrosion of tungsten carbide in a 2N H_2SO_4 solution (Ref 53). The oxidation reaction of WC has been given by

$$WC + 5H_2O \rightarrow WO_3 + CO_2 + 10H^+ + 10e^-$$

Literature prove that cobalt is more corrosion susceptible than WC grains (Ref 35). In the SEM image, it can be seen that cobalt binder has separated from the WC grains (Fig. 11). In



(a)



Element	Weight %	Atomic %
C K	2.42	10.50
O K	20.81	67.75
W M	76.77	21.75
Totals	100.00	

(b)

Fig. 13 (a) A SEM image of corroded surface of WC (scale of image = 3 µm); (b) spectrograph of selected area spectrum1

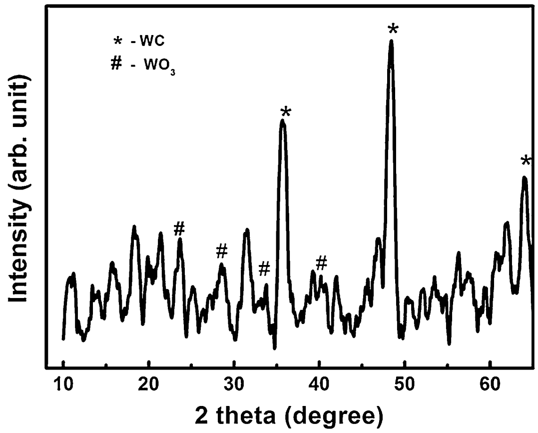


Fig. 14 Establishment of tungsten oxide (WO3) in CC through XRD

this case, if the CC part is subjected to heavy impacts, easy removal of WC grains takes place. Corrosion is responsible for reducing hardness of the WC grains.

An enlarged view of rectangular part, selected from Fig. 11, is shown in Fig. 12. The WC grain, with high amount of roughness, has been exposed in a high magnification value of 48×10^3. White arrow is indicating a void area from where the cobalt binder has been leached out due to high degree of corrosion.

The oxidation of WC grains has been established by EDS and XRD. A corroded area with small WC fragments has been considered for checking the materials concentration. In Fig. 13(a), a rectangular area *spectrum1* has been selected in the corroded surface of WC. The spectrograph and the materials concentration corresponding to *spectrum1* have been shown in Fig. 13(b). We can see that tungsten and oxygen have weight percentage of 76.77 and 20.81%, respectively. Such a high amount of *O* is indicating the oxidation of WC surface. Generally, rocks also possess oxygen and other elements. Due to the absence of other elements in spectrograph, it can be concluded that the presence of whole oxygen is completely because of the oxidized surface. Also, carbon is present in a small amount (2.42 wt.%) because it is one of the basic constituents of tungsten carbide.

The CC sample has been undergone through XRD analysis. In Fig. 14, some peaks (indicated by #) show the presence of tungsten oxide (WO_3). These peaks have been observed at $2\theta = 23.67^{\circ}$, 28.64°, 33.73°, and 40.21°.

5. Conclusion

Wearing process limits the service life of tools to a great extent. It is necessary to understand the wear mechanisms in order to develop better quality of product. Hence, for a given working condition, the modified tool can be used for a longer time. It is highly heterogeneous behavior of coal/rock for the tools, which does not converge the wearing mechanisms in a single domain. In the present study, an attempt has been made to find out the critical wearing phenomenon in the CC tip of the four conical picks. Critical observation has been carried out by using FESEM, EDS, and XRD. All the picks, under study, were used for in situ operation of coal mining through a continuous miner machine. The careful examination of appropriate samples has revealed very clear and highly magnified images. After observing the images, wear mechanisms are categorized into four parts:

(1) Cracks have been predominantly found. Observed results have been analyzed and compared with previous literature. Cracks have been categorized into three parts, such as, cracks with overlapping surfaces, crack on a large surface of CC, and cracks in WC grains. In addition, we have reported a different type of mechanism i.e., crack with overlapping surfaces. The sudden shocks and high impacts on the tool imposed by brittle coal/rock material are the main causes of crack generation. Continuous impacts make severe crushing action on the cracked parts. It facilitates the grain fragmentation.

(2) Cavity or a hole-like structure in the WC grain has been found to be a part of crushing. The localized crushing removes a little amount of fragmented grains with making the original grain empty. It can be an easy path for coal/rock materials to enter inside the hole.

(3) Sometimes tool comes into contact with highly abrasive part of coal. As a result, the surface of CC undergoes grinding process. The entrapped hard rock particles between coals are also responsible for severe abrasion of CC.

(4) The surface of the WC grains becomes rough due to corrosive degradation. Corrosion is mainly caused by the reaction of the CC with chemically activated mine water in the presence of high heat. A number of pores and notches have been observed on the surface of WC. Also, the cobalt removal due to high corrosion has been reported. In addition, the establishment of oxide formation (WO_3) of WC grains has been reported through XRD. It can be concluded that the corrosion reduces the hardness of WC grains significantly.

All the wearing mechanisms have been analyzed and compared with the previously found results. Cracks, crushing, and corrosion have been discussed earlier in case of rock drill buttons, although the mechanisms like overlapping cracks and grinding process indicate that wearing behavior of CC is not limited. There is a possibility of existence of more wear mechanisms in the same conical picks which have been selected for present study. It depends on the knowledge and skill of the researchers to characterize the mechanisms properly. Hence, the ongoing research is necessary in future also.

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