SAKUNTALA NAHAK
SAURABH DEWANGAN
and
SOMNATH CHATTOPADHYAYA

Wearing mechanisms of picks used in continuous miner machine for coal cutting

Conical pick or point attack pick is an essential tool for cutting coals and rocks in mines. The abrasive parts of the mining tools are made of cemented carbide. An optimum combination of hardness, strength and wear resistance properties make the cemented carbide an essential material for tools in the field of excavation. The tool life gets limited by different wearing phenomena of the tool. It is critical to find out the wear mechanisms in order to facilitate the development of new and improved grade of cemented carbide and steel body. The present paper focuses different deterioration mechanisms in conical picks. All the picks under study have been used in coal cutting operation in an underground mine. The analysis through field emission scanning electron microscopy (FESEM) and energy dispersive X-ray spectroscopy (EDS) reveals mainly four types of deterioration mechanisms, such as, coal and rock penetration into the tip and the body part, coal cover formation, cracking of WC grains, scratches and plastic deformation.

Keywords: *Conical pick; cemented carbide; wearing mechanisms; FESEM; EDS*

I. Introduction

Conical pick is an essential tool for cutting coal in mines. Highly efficient machines, such as, continuous miner, roadheader, shearer, are fitted to conical picks. A continuous miner machine equipped with conical picks is shown in Fig.1(a). During the process of cutting with conical pick, it has been found that as the depth of cutting increases, the need for specific energy decreases [1]. The shape of conical pick remains sharp due to the symmetrical wearing during cutting [2]. The conical tool provides better efficiency because it needs the lowest specific energy for penetration [3]. They are made of steel body with inserted cemented carbide (CC) tip. The unique combination of hardness, toughness and wear resistance property accounts for the widespread use of CC in the field of coal/rock excavation. Tungsten carbide (WC) hard metals are glued together with Co material for making such a hard component. WC grains provide hardness, strength and wear resistance to CC, whereas Co is responsible for its toughness [4]. The hard phase (α-phase), i.e., WC, is the main part of the CC because it can weigh up to 70% - 90% of the whole material. The fractures on CC during coal/rock cutting operation limit their working life. The relative motion between the tool and rock/coal causes the wearing of the tool. A few distorted conical picks are shown in Fig.1(b). Conditions of both, the tip and the steel body, deteriorate in the worn out conical pick. Tip removal, tip crushing, body deformation and cracks are common wear phenomena in the tool surface, which can be seen with naked eyes. For observing internal distortion, high resolution microscopes are necessary. Wear mechanisms of CC are being studied for a long time. But till now, it has been difficult to explain the wearing process entirely. The highly heterogeneous nature of the coal/rock necessitates many variations in the cutting process. The wear mechanisms in the tool may vary according to condition of mines. However, it is assumed that under similar working conditions, similar types of tools undergo a similar nature of wearing phenomenon. Many researchers have studied the deterioration mechanisms of CC buttons in rock drillings. The literatures related to wear assessment of conical picks are few in number, although it may be assumed that the wear mechanism of CC tip will be same as CC buttons under similar working conditions. In this paper, the wear analysis of conical picks has been analysed. Along with the CC tip, the steel body part has also been observed critically by using SEM (scanning electron microscopy).

II. Previous studies

First, the performance and working life of the picks are substantially reduced by their process of wearing. Its effect depends upon rock/coal properties, quartz content, the structure and composition of the tool material and operational conditions, such as, cutting speed, bit orientation, cut distance and bit spacing. The drum design also considerably affects tool wear. One can observe the gradual wearing of picks under a process of normal cutting of coal/rock. This

Ms. Sakuntala Nahak, Department of Mechanical Engineering, Jaypee University of Engineering and Technology, Guna 473226, India, Messrs. Saurabh Dewangan, Department of Mechanical Engineering, Graphic Era University, Dehradun 248002, India and Somnath Chattopadhyaya, Department of Mechanical Engineering, Indian School of Mines, Dhanbad 826004, India

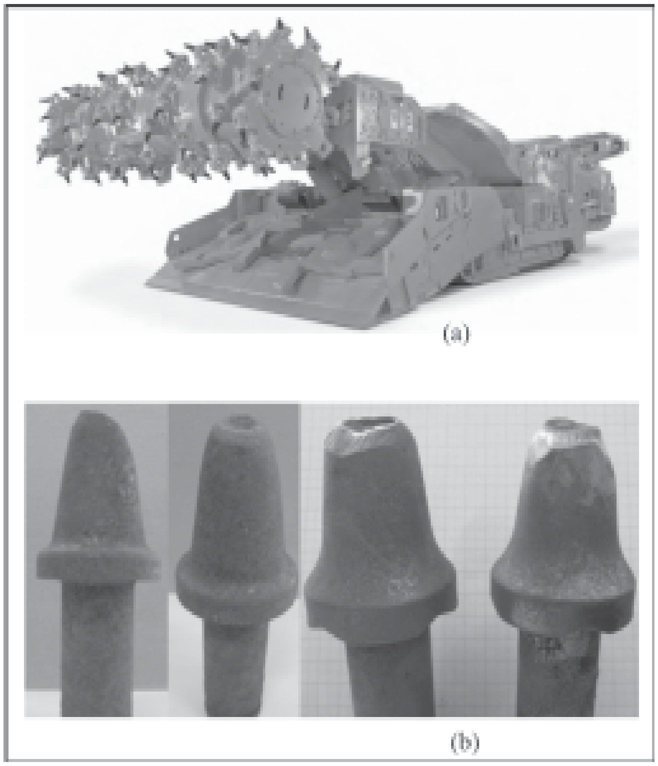

Fig.1 (a) 12 CM continuous miner machine (courtesy: Joyglobal) [5]; (b) Some worn out conical picks

process results in removal of the tungsten carbide grains from the CC structure. The fracture and detachment of the tip from the pick body can also be observed under severe cutting condition. The tools get heavy shocks during cutting of hard and sharp structure, which leads to severe damage. Most common types of wear mechanisms, which are encountered during cutting of coal/rock, are considered to be in the form of abrasive wear, microchipping, gross failure and thermal cracking [6].

The WC-Co material has wonderful proportion of hardness and strength for cutting coal/rock. It is important to understand the effect of components and operational parameters on the performance of WC-Co materials. The tribological, mechanical and thermal properties of WC cemented carbide substantially depend on its composition and WC particle size [7, 8, 9]. Grain size of carbide affects wear-resistance property of CC. The coarse-grained carbides usually have lower abrasive wear resistance than that of a fine or medium grain size [9, 10, 11]. Fracture toughness and wear resistance increase with an increase in the granule size. The grinding test has been carried out to check the performance of three types of CC, which contained coarse, fine, and ultrafine grains in the same cobalt content. It has been found that as the CC grains become coarser, the grinding force and energy consumption increase, provided all grinding parameters are unchanged [12]. Co is used as a binder material having $\hat{a}$-phase and it can be alloyed with Ni or Cr so that the transition of Co from its high temperature ductile phase (fcc) to its low temperature brittle phase (hcp) can be avoided [13]. In addition, it has also been found that the hardness of bulk composites decreases with an increase in the binder content [14].

For producing the WC-Co hard metal alloy, pure tungsten powder (W) is mixed with pure carbon (C) in the ratio of 94% to 6%, respectively at an increased temperature of around 1500^{o}C [15]. The new product WC is mixed homogeneously with small quantity of cobalt. This homogeneous mixture is compressed to the required shapes at a very high pressure of 100 to 420MN/m^2. After that, the sintering process is carried out in presence of hydrogen or in vacuum at a temperature of around 1435^{o}C. Sintering is necessary for minimizing the porosity [15, 16]. Porosity is an important factor which negatively affects the quality of WC. Transverse rupture strength and tool durability can be increased in the alloy by reducing porosity [17]. Daoush et al (2009) have concluded that porosity can be decreased by increasing the binder metal content [18]. Bilgin et al (2013) have explained that the addition of carbon content during sintering process can reduce the rupture resistance property [16]. A test was performed at the Colorado School of Mines for showing the relationship among hardness, cobalt content and grain size of WC (Fig.2).

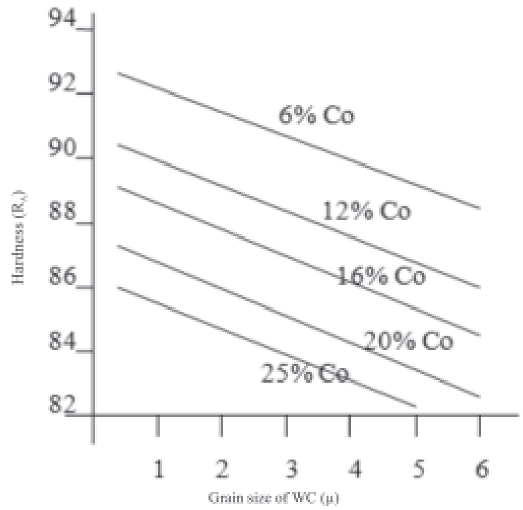

Fig.2 Variation of tungsten carbide hardness with cobalt content and grain size of WC [19]

The steel body is relatively soft and ductile as compared to the inserted tip. The condition of the tool body can deteriorate easily. However, ideally, it is assumed that the body part will not come in contact with rock materials. If hardness of the tool body material is increased, then the wear resistance increases but the fracture resistance decreases [20].

Wearing is a criterion that can be used for performance evaluation of coal cutting equipment. The tool life of bits is limited by their wear rate. The bits get worn out fast because of relative frictional motion between rock/coal and tool.

Wearing of the cutting tool is one of the most important process parameters for evaluating the economy of process and efficiency of the operation [21]. In general, wearing can be defined as the undesirable and continuous loss of material from a solid surface due to the mechanical interactions such as, contact and relative motion between two bodies [22]. The wear and frictional properties of a material are behavioural parameters, which are associated with the operational conditions. The damage of the tools can be explained as a combination of continuous wear of WC-Co and crack formation [23]. Kenny and Johnson (1976) have explained the phenomenon of wear flat generation due to the abrasive action between the flank/clearance surface of tool and rock material (Fig.3). This process makes the clearance surface smooth and parallel to the cutting direction. The wear flat changes the shape of tools. Sometimes more rubbing action leads to the inclination of flat surface. This inclination is in the opposite direction of cutting. This phenomenon is undesirable because it enhances the force value. It can be reduced by providing the clearance angle to the tool tip [20].

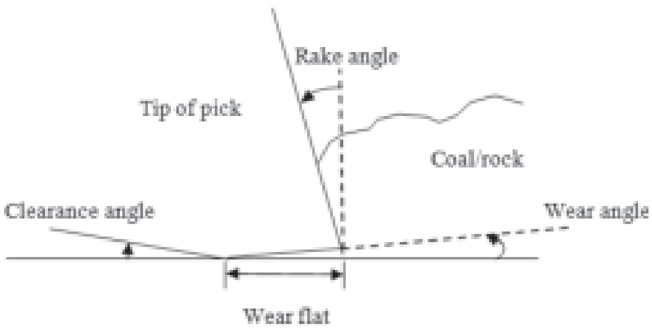

Fig.3 Formation of wear flat on the clearance surface [20]

High frictional resistance due to relative motion between tool and coal results in generation of high heat. The heat produced in the tools may exceed the critical range of the temperature. This results in the softening and rapid wear of tools [24, 25]. Conical bits are lashed at cutting drum in a manner so that they can rotate about their longitudinal axis during cutting and their shanks are inclined at 35Ú to 55Ú in the cutting direction. Rotation of bits around their axis increases the wear life of tools [24]. It has been observed that wearing is greater on the flank face than on the rake face. This is due to the fact that chipping of rock occurs at rake face which does not offer resistance against the latter [26]. Song-yong (2011) has developed a model to design the pick and its installation on cutting drum which is as follows:

$$\left[\frac{\cos\left\{\arctan\left(\frac{\cos\alpha_{w,x}}{\tan\theta_A}\right)\right\}}{\cos\alpha_{q,x}}\right]^2 + \left[\cos\alpha_{w,x}\sin\left\{\arctan\left(\frac{\cos\alpha_{w,x}}{\tan\theta_A}\right)\right\}\right]^2 = 1$$

Where θ_A is attack angle (impact angle), α_w, is skew angle and α_q, is inclination angle.

Range of tip angle $\theta \le 2\Psi_{\min} - 20_A$

And maximum clearance angle $\gamma_{\max} = \Psi_{\max} - \theta_A - \theta \ge 0$

Where θ_A = tip angle

ψ = Wearing angle

γ = Clearance angle.

It has been claimed that designing according to the above model will decrease wear and cutting load on the pick [27].

Mcgragor et al (1990) have compared the button picks and point attack picks by experiments. They have found that both the picks deteriorate in a similar manner. But buttons fail due to non-rotational wear. Buttons require comparatively higher average normal force than point attack picks. Progressive wear leads to an increase in the force value which is comparatively higher in case of button picks. Also, higher incidence of thermal cracks is observed in buttons [28].

Many researchers have used SEM and high resolution field emission gun SEM to characterize the wear mechanisms in rock drill buttons. Different mechanisms, such as, microspalling, abrasion wear, cracks, WC grain pullout, extrusion of binder metal and reptile skin, have been investigated [7, 29].

III. Experimental Work

Three damaged tools were collected from an underground mine for wear investigation. The condition of the tools had deteriorated due to coal excavation. The damaged tools were cleaned properly. All the tools were cut off from their tip portion so that the samples could be appropriate. The samples were cut according to the appropriate size by using electric discharge machining. For critical investigation of wear mechanisms, the samples were carefully observed by using FESEM and energy dispersive X-ray spectrography (EDS). The geological condition of underground mines varies due to temperature and pressure variation in presence of humidity. The underground mine under study had G4 grade of coal, which is known for its good quality. A very fine cutting line on the face of the mine could be observed. A little amount of rock materials were present in between the coals in the mine. Conical picks were used with the continuous miner machine for the coal cutting operation. The machine parameters were also noted down. The drum of continuous miner was rotating at 50 rpm. The velocity and bit attack angle of tools were 175 m/min and 50^o respectively. The combined effect of the geological conditions and machine parameters was the main reason behind wearing of picks. For getting good results, the samples were arranged properly. The wear descriptions of the samples are given in Table I.

IV. Investigation and analysis

On the basis of SEM images and EDS analysis, mainly four types of deterioration mechanisms, such as, coal and rock

Table I: Description of wear in tool samples

	Sample No.	Wear description	Working condition
1	Sample 'A'	WC-Co tip is removed, body is severely deformed	To cut G4 grade of coal in an underground mine
2	Sample 'B'	Small part of tip is remaining, body is deformed due to impact	To cut G4 grade of coal in an underground mine
3	Sample 'C'	Body and tip are not much affected	To cut G4 grade of coal in an underground mine

penetration into the tip and the body parts, coal cover formation, cracking of WC grains, scratches and plastic deformation, were observed. The reasons behind each type of wearing could be explained as follows:

A. Coal and rock penetration into the tip and the body part

It is a common process of deterioration which may be found in all types of coal and rock cutting equipment [29, 30]. In this, coal materials get entrapped in the internal structure of the tool materials. The sudden impacts created on the tool by irregular and sharp-edged coal mass causes penetration of coal particles into the tool. Further impacts facilitate the outer material to enter inside the microstructure. This phenomenon makes the tool useless as the Co binder phase is intermixed and degraded by the coal and rock material. The degraded binder phase has no proper capability for binding the WC grains. Hence, the WC grains can get removed easily. Also, the quality of steel body gets affected by coal penetration. The penetration of coal in between the WC-Co structure and the body part is shown in Figs.4 and 5, respectively.

The coal/rock intermixed part was investigated through EDS analysis to verify the material concentration on the binder part of WC-Co structure. For this, a SEM image of deteriorated WC-Co surface was taken for comparing the two different points. The first point (spectrum 1) was selected on

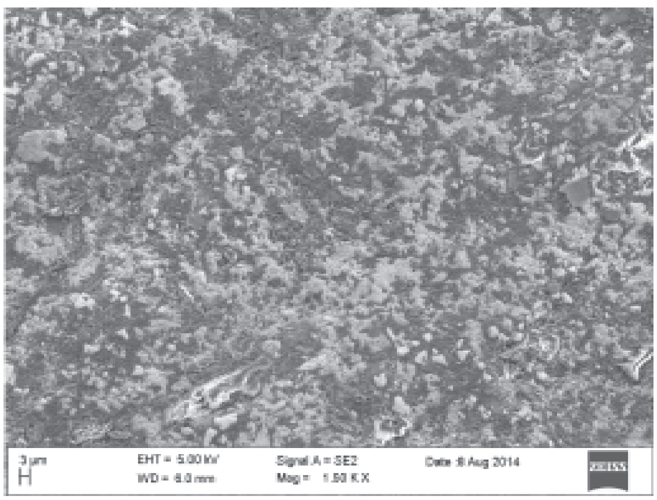

Fig.4 Coal penetration (black parts) into WC-Co structure

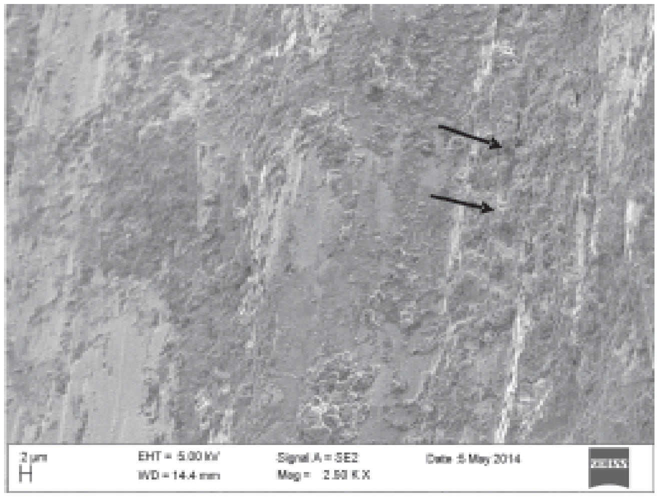

Fig.5 Coal materials adhere in the tool body (arrow sign)

the binder part, which is supposed to degrade by coal/rock material. The second point (spectrum 2) was selected on a WC grain. The following images were taken into consideration. Spectrum 1 and spectrum 2 are shown in Figs.6 and 7, respectively.

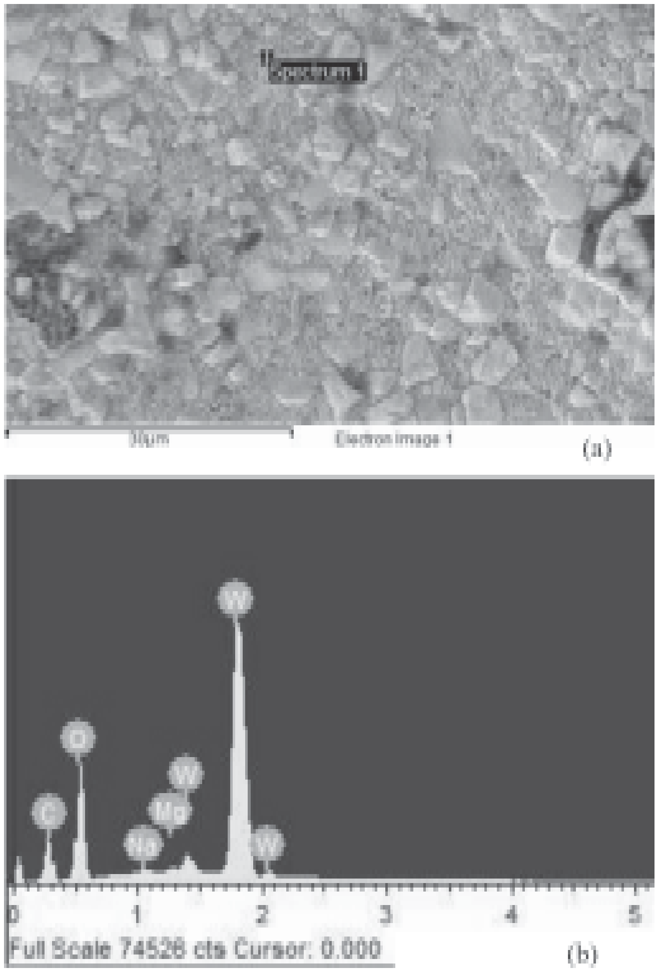

Fig.6(a) SEM image of a deteriorated part of cemented carbide; (b) EDS of spectrum 1

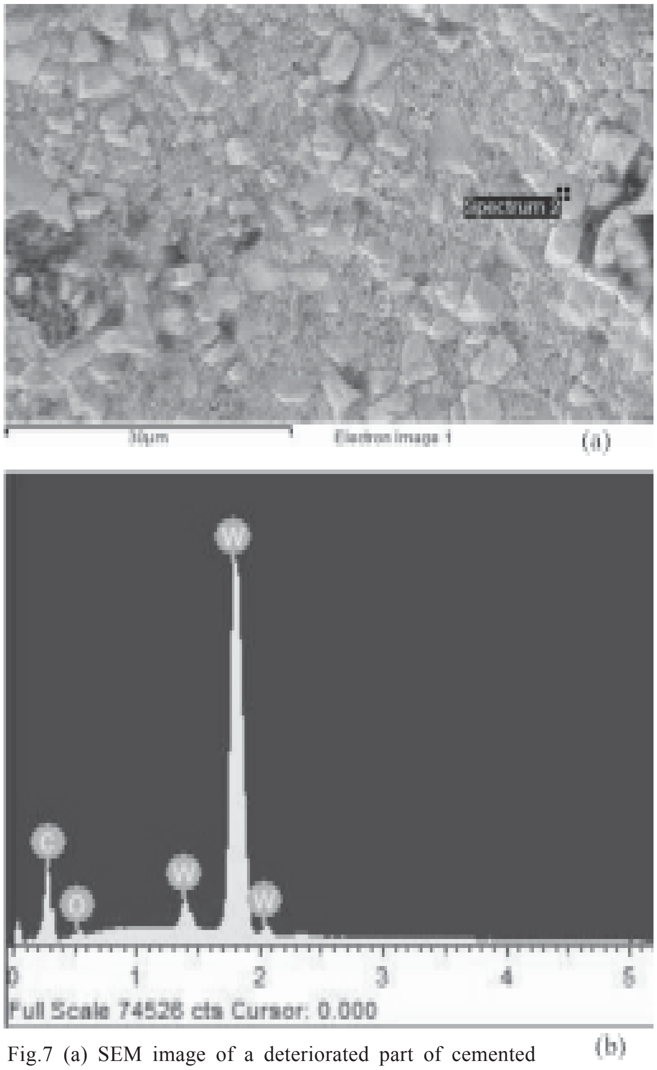

Fig.7 (a) SEM image of a deteriorated part of cemented carbide; (b) EDS of spectrum 2

The weight percentage of material, which was found in the EDS spectrograph 1, is as follows: CK = 9.78%; OK = 19.18%; Na K = 0.22%; Mg K = 0.30%; W M = 70.51%

On the basis of weight percentage of material, found in spectrograph 1, it can be concluded that oxygen and carbon are the two elements which are available significantly other than tungsten. Carbon signifies the coal particles penetration and oxygen is an indication of intermixed earth rocks. Sodium and magnesium are also present as the sign of rock material, although their quantity is very small.

The weight percentage of materials, which were found in spectrograph 2, is as: CK=14.91%; OK=1.24 %; WM=83.85%

Considering the point selected on the WC grain, it can be observed that the main constituents are W and C only. Both the elements are the basic contents of tungsten carbide. The extra and unwanted substance is oxygen, which is present in a very small quantity (1.24%). It is the deteriorated surface of the CC which helps some rock particles to get entrapped in it.

The comparative study of both the spectrographs proves the presence of coal/rock material in the CC microstructure. The quantity of mixed material may vary at different parts of worn out CC surface. In a highly interrupted area, usually a small part of the coal intermixed CC detaches from the original part. In other words, coal/rock penetration may be assumed to be primarily responsible for causing other types of deterioration.

B. Coal cover formation

This phenomenon is almost the same as the coal penetration. In this, a lump of coal particles enters into the WC-Co structure and the steel body part. A comparatively large part of WC grains is covered by coal material, which has a degree of thickness. The coal cover formation in WC-Co tip of tool is shown in Fig.8. Also, a thin layer of coal materials enters into the steel body and adheres to it. The coal cover formation in the tool body is shown in Fig.9. The original steel body, which is cracked, is indicated by a white arrow. This phenomenon is similar to rock penetration into the CC surface of drill bits as reported by Beste and Jacobson (2008) [31] and Olovsjo et al (2014) [32].

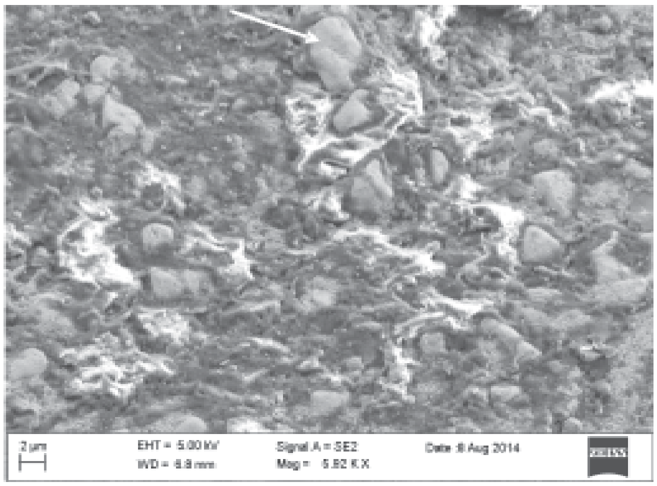

Fig.8 Coal cover formation into WC-Co structure (white arrow is indicating a WC grain)

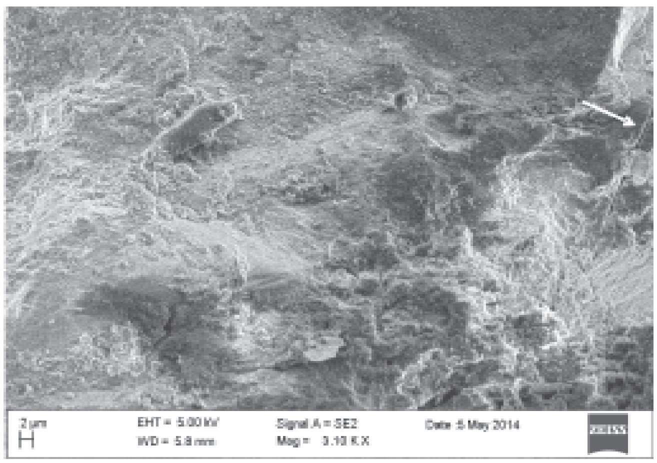

Fig.9 Coal cover formation on the tool body material (white arrow is indicating cracked steel body)

C. Cracking of WC grains

This is a severe damage phenomenon in which hard WC grains get cracked and crushed. Sometimes WC grains may get removed from crushed zone. This is because of high impacts and shocks that the tools have to endure due to continuous running of the drum of machine during coal cutting. The coals may have some hard rock particles in them which are the main cause of WC grain cracking. During the present study, the CC part of the samples B and sample C were critically examined by the SEM analysis. Sample 'C' had a few cracks (Fig. 10) whereas a severe cracking in the WC grains was reported in sample 'B' (Fig.11).

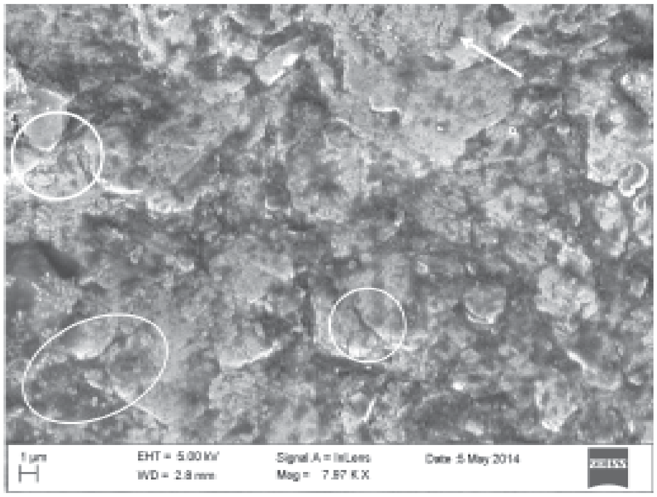

Fig.10 Cracks on WC grains indicated by circle and arrow (sample 'C')

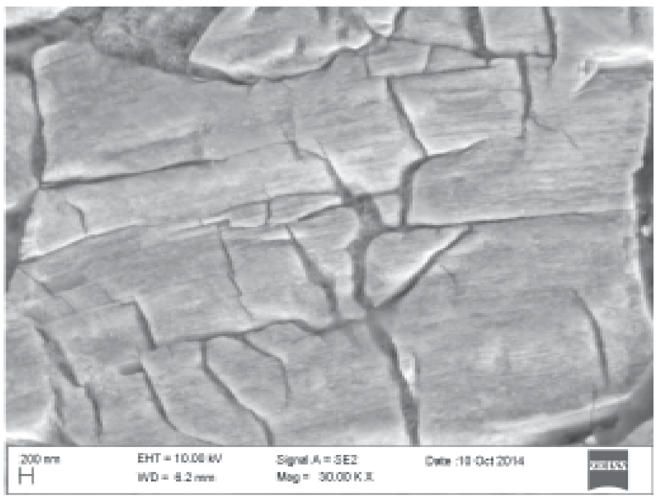

Fig.11 A severe cracking of WC grain in sample 'B'

D. Scratches and Plastic deformation

Rocks and coals have highly unpredictable characteristics. They may have heterogeneous character even in same types of samples. The hard rock materials are always present along with coals in the mines. When some hard and sharp edges of coal along with abrasive rock materials come into contact with tool, scratches develop on the body material. These scratches grow due to continuous rotation of the drum. It creates high degree of friction leading to generation of high degree of heat. As a result, the tool materials get softened. At this stage, the scratches further enlarge and transform into long passage that has a certain degree of depth as well. This is called plastic deformation of the tool body materials. Some coal particles may get entrenched in the passage. Fig. 12 is showing plastic deformation of the tool body.

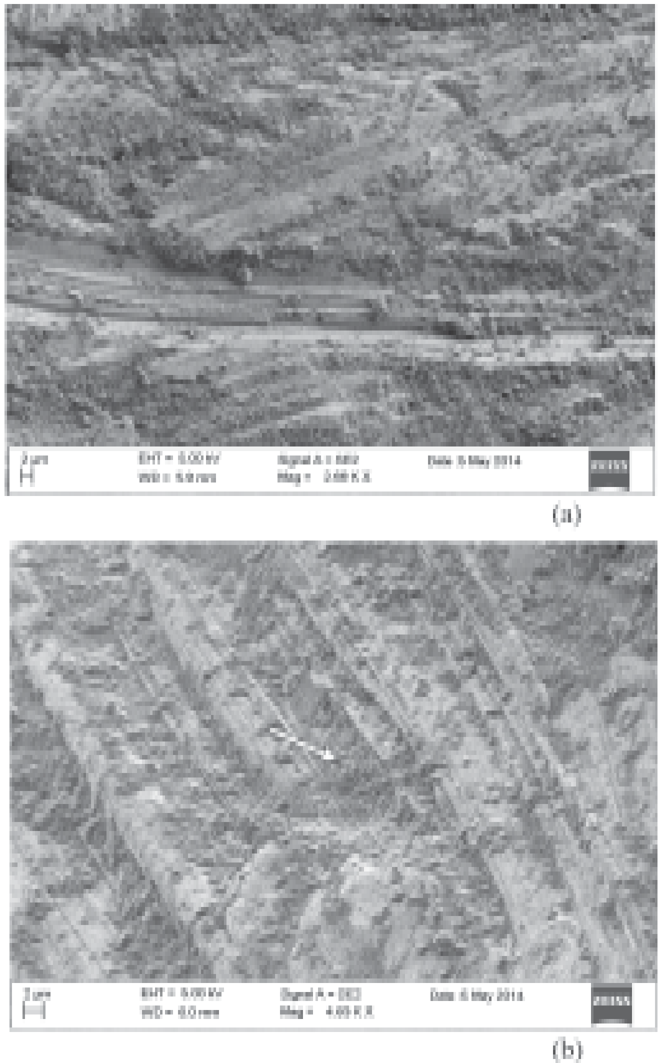

Fig.12 Plastic deformation; (a) initiation of scratches enlargement; (b) plastic deformation with the formation of passage (coal particles are indicated by arrow sign)

V. Conclusion

A wear analysis of conical picks was done for understanding the mechanisms responsible for such development. It was found that the conical picks get distorted after being used with continuous miner machine in coal cutting operations in underground mines. The worn out surfaces of samples were critically observed by using field emission scanning electron microscopy (FESEM) and energy dispersive X-ray spectroscopy (EDS). Primarily, four types of deterioration mechanisms could be pointed out, namely, coal and rock penetration into the tip and the body part, coal cover formation, cracking and crushing of WC grains and scratches and plastic deformation. The presence of hard rock materials along with coals was found to be the deciding factors in wear mechanisms. In addition, temperature, pressure and humidity variations in mines also result in various distortion mechanisms. Coal/rock penetration was concluded to be a common wear phenomenon which can be observed in any coal cutting equipment. The presence of coal/rock particles, which entered into the microstructure of CC, was established by EDS spectrographs. Mainly two elements, carbon and oxygen, were found to be the main constituents in the degraded binder part. It was found that due to sudden shocks, the tool cracks after coming into contact with sharp and hard edges of coal/rock. A lump of coal materials gets entrenched into the tool surface. Further impacts on the tool due to continuous rotation of the drum cause the lump of coal to enter into microstructure and form a cover on the surface. Scratches develop due to the interaction of tool with the hard rocks. The continuous relative motion and high frictional heat enlarge the scratches leading plastic deformation of tool. Plastic deformation could be observed mainly in the steel body.

It is, therefore, essential to develop new grades of CC with high efficiency and high wear-resistance property. In addition, the properties of steel body would also have to be improved in order to avoid severe plastic deformation.

References

[1] Bilgin N., Demircin M.A., Copur H., C. Balci, Tuncdemir H., and N. Akcin, (2006): "Dominant rock properties affecting the performance of conical picks and the comparison of some experimental and theoretical results", *International Journal of Rock Mechanics & Mining Sciences*, vol. 43, pp. 139–156.

[2] Khair A.W., "Research and Innovations for Continuous Miner's Cutting Head for Efficient Cutting process of rock/coal", 17* International Mining Congress and Exhibition of Turkey- IMCET 2001, ISBN 975-395-417-4.

[3] Miller M.H., and Sikarskie D.L., (1968): "On the penetration of rock by three-dimensional indentors", *International Journal of Rock Mechanics and Mining Sciences,* vol. 5, pp. 375-398.

[4] Upadhyaya G.S., (2001): "Materials science of cemented carbides – an overview", *Mater Des,* vol. 22, pp. 483–489,.

[5] 12CM series continuous miner product overview, www.joyglobal.com

[6] Hurt K.G., and Evans I., (1981): "Point Attack Tools, An Evaluation of Function and Use for Rock Cutting", *The Mining Engineer.*

[7] Larsen-basse J., (1985): "Binder extrusion of sliding wear of WC–Co alloys", Proc. Int. Conf. Wear Mater, vol. 5, pp. 39–44.

[8] Jia K., and Fischer T.E., (1996): "Abrasion resistance of nanostructured and conventional cemented carbides". *Wear*, vol. 200, pp. 206–214.

[9] Pirso J., Letunovits S., and Viljus M., (2004): "Friction and wear behaviour of cemented carbides", *Wear*, vol. 257, pp. 257–265.

[10] Kagnaya T., Boher C., Lambert L., Lazard M., and Cutard T., (2009): "Wear mechanisms of WC-Co cutting tools from high-speed tribological tests", *Wear*, vol. 267, pp. 890-897.

[11] Deng J.X., Zhou J.T., Zhang H., and Yan P., (2011): "Wear mechanisms of cemented carbide tools in dry cutting of precipitation hardening semi-austenitic stainless steels", *Wear*, vol. 270, pp. 520-527.

[12] Ding C., Zhao Y., and Ding Y., (2009): "The study on the grinding performance of the different grain carbide", *Diamond and Abrasives Engineering*, vol. 173, pp. 67-70, [in Chinese].

[13] Beste U., Hartzell T., Engqvist H., and Axen N., (2001): "Surface damage on cemented carbide rock drill buttons", *Wear* vol. 249, pp. 324-329.

[14] Brookes K.J.A., (1992): "Hardmetals and Other Hard Materials", *International Carbide Data.*

[15] Rajput R.K., (2007): A text book of Manufacturing technology: (Manufacturing processes), firewall media, pp. 407,.

[16] Bilgin N., Copur H., and Balci C., (2013) "Mechanical excavation in mining and civil industries", CRC Press, pp. 103-123.

[17] Wood G.A., (1970): "Quality control in the hard metal industry", *Powder metallurgy*, vol. 13, pp. 338-368.

[18] Daoush W.M., Lee K.H., Park H.S., and Hong S.H., (2009): "Effect of liquid phase composition on the microstructure and properties of (W, Ti) C Cemented carbide cutting tools", *Int journal of ref. Metals and hard materials*, vol. 27, pp. 83-89.

[19] Clark G.B., (1982): "Principles of rock drilling and bit wear", *Colorado School of Mines*, Quarterly, vol. 77, pp.91.

[20] Kenny P., and Johnson S.N., (1976): "The Effect of Wear on the Performance of Mineral-Cutting Tools", *Colliery Guardian,* vol. 224, pp. 246-251.

[21] Maidl B., Schmid L., Ritz W., and Herrenknecht M., "Hard rock tunnel boring machines", Ernst & Sohn, Berlin, 2008.

[22] ZumGahr K.H., (1987): Microstructure and wear of materials, Elsevier, Amsterdam.

[23] Stolarski T.A., (2000): Tribology in machine design, Butterworth–Heinemann, Oxford.

[24] Plis M.N., Wingquist C.F., and Roepke W.W., (1988): "Preliminary Evaluation of the Relationship of Bit Wear to Cutting Distance, Forces and Dust Using Selected Commercial and Experimental Coal and Rock Cutting Tools". USBM, RI-9193, 63.

[25] Martin J.A., and Fowell R.J., (1997): "Factors governing the onset of severe drag tool wear in rock cutting", *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, pp. 59-69.

[26] Loui J.P., and Rao Karanam U.M., (2005): "Heat transfer simulation in drag-pick cutting of rocks", *Tunnelling and underground space technology,* vol. 20, pp. 263-270.

[27] Song-yong L., (2011): "Method to determine installing angle of conical point attack pick", J. *Cent. South Univ. Technol*., vol. 18, pp. 1994-2000.

[28] MacGregor I.M., Baker R.H., and Luyckx S.B., (1990): "A comparison between the wear of continuous miner button picks and the wear of pointed picks used in South African Collieries", *Mining sc. and tech,* vol. 11, pp. 213-222.

[29] Beste U., and Jacobson S., (2002): "Friction between a cemented carbide rock drill button and different rock types", *Wear*, vol. 253, pp. 1219-1221.

[30] Dewangan S., Chattopadhayaya S., and Hloch S., (2015): "Wear assessment of conical pick used in coal cutting operation", *Rock Mechanics and Rock Engineering,* vol. 48, pp. 2129-2139.

[31] Beste U. and Jacobson S., (2008): "A new view of the deterioration and wear of WC/CO cemented carbide rock drill buttons", *Wear*, 264, pp. 1129–1141.

[32] Olovsjo S., Johanson R., Falsaû F., Bexell U., and Olsson M., (2013): "Surface failure and wear of cemented carbide rock drill buttons—The importance of sample preparation and optimized microscopy settings", *Wear*, 302, pp. 1546-1554.

ROADHEADER PERFORMANCE DURING DEVELOPMENT OF A COAL DRIVE

(Continued from page 104)

[8] Bilgin, N., Seyrek, T., Shahriar, K. (1988): "Roadheader performance in Istanbul", Golden Horn clean-up contributes valuable data. *Tunnels and Tunnelling*, June, pp: 41–44.

[9] Gehring, K. H., (1989): A cutting comparison, *Tunnels & Tunnelling*, pp: 27-30.

[10] Bilgin, N., Seyrek, T., Erdinc, E., Shahriar, K., (1990): Roadheaders glean valuable tips for Istanbul Metro. *Tunnels and Tunnelling*, October, pp: 29–32.

[11] Fowell, R.J. and Johnson, S.T. (1991): "Cuttability Assessment Applied to Drag Tool Tunnelling Machines", Proc. 7thInt. Congress Rock Mechanics. ISRM ed. Wittke, A.A. Balkema, Achen, pp :985-990.

[12] Rostami, J., Ozdemir, L., Neil, D.M. (1994): Performance prediction: a key issue in mechanical hard rock mining. *Mining Engineering*, pp:1263–1267.

[13] J. Rostami, L. Ozdemir, D.M. Neil (1994): Performance prediction: a key issue in mechanical hard rock mining, *Mining Engineering* (November), pp. 1263–1267.

[14] Copur, H., Ozdemir, L., Rostami, J. (1998): "Roadheader applications in mining and tunnelling industries", *The Mining Engineer*, March, pp:38-42.

[15] Copur, H., Rostami, J., Ozdemir, L., Bilgin, N. (1997): Studies on performance prediction of roadheaders. In: Proceedings of the 4th International Symposium on Mine Mechanization and Automation, Brisbane, Qld., Australia, pp: A4-1–A4-7.

[16] Thuro, K., Plinninger, R.J. (1998): "Geological limits in roadheader excavation – four case studies", 8th International IAEG Congress, Balkema, Rotterdam, pp: 21-25.

[17] Thuro, K., Plinninger, R.J. (1999): "Roadheader excavation performance-geological and geotechnical influences", 9th ISRM Congress Paris, Theme 3: Rock dynamics and tectonophysics/rock cutting and drilling, pp:25-28.

[18] Thuro, K.Plinninger, R.J. (1999): "Predicting roadheader advance rates". *Tunnels and Tunnelling International*, June, pp: 36–39.

[19] Ebrahimabadi A., Goshtasbi, K. Shahriar, M. CheraghiSeifabad, (2010, 2011): "Predictive Models for Roadheaders Cutting Performance in Coal Measure Rocks", *Bulletin of the Earth Sciences Application and Research Centre of Hacettepe University*, 32 (2), pp: 89-104.

[20] Torabi, S. R. (2005): "Reliability of the application of Schmidt hammer in determination of the UCS", Final project report, in Persian, Shahrood University of Technology, and Shahrood, Iran.

[21] Brown, E.T. (1981): ISRM suggested methods – rock characterization, testing and monitoring, Pergamon Press, Oxford.