

SAKUNTALA NAHAK*, SAURABH DEWANGAN**#, SOMNATH CHATTOPADHYAYA***,
GRZEGORZ KROLCZYK****, SERGEJ HLOCH*****

**DISCUSSION ON IMPORTANCE OF TUNGSTEN CARBIDE – COBALT (WC-Co) CEMENTED
CARBIDE AND ITS CRITICAL CHARACTERIZATION FOR WEAR MECHANISMS BASED
ON MINING APPLICATIONS**

**OMÓWIENIE ROLI WĘGLIKA SPIEKANEGO Z KOBALTEM WC-Co ORAZ OKREŚLENIE
JEGO KLUCZOWEJ CHARAKTERYSTYKI NIEZBĘDNEJ DO ROZPOZNANIA MECHANIZMÓW
ZUŻYCIA W KONTEKŚCIE ZASTOSOWAŃ W GÓRNICTWIE**

Cemented carbide (CC) is an important material for the mining tools. During mining applications, the service life of the CC gets highly reduced due to complex conditions offered by mines. In various applications, such as, rock drilling and coal cutting, the tools show different type of wear behaviour. Wear assessment has been an important area of research for a long time. In order to develop improved mechanical properties in the tools, it is necessary to know the characteristics and cause of wear mechanisms. For analyzing wear mechanisms in the CC, researchers have adopted mainly three different conditions. They are: rock drilling, coal cutting, and laboratory wear test methods. In the present work, an attempt has been made to review and summarize all those wear mechanisms found in the CC. The causes and effects of each mechanism are also explained comprehensively. In addition, various properties of recently developed cemented carbide have also been discussed.

Keywords: Cemented carbide; Rock drilling; Coal cutting; Laboratory wear test; Wear characterization; Recent development

Węglik spiekany (CC) jest znanym od dawna lecz wciąż powszechnie używanym twardym stopem metalu. Korzystne właściwości węgliku spiekanego sprawiają, że jest niezwykle pożądanym materiałem z którego wykonywane są narzędzia górnicze. W trakcie prowadzenia wierceń w skałach i urabiania skał, narzędzia pracują w bardzo złożonych warunkach i różnorodnych zastosowaniach, stąd też wykazują różne

* DEPARTMENT OF MECHANICAL ENGINEERING, JAYPEE UNIVERSITY OF ENGINEERING AND TECHNOLOGY, GUNA-473226, MADHYA PRADESH, INDIA

** MECHANICAL ENGINEERING, NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY, BERTHAMPUR

*** DEPARTMENT OF MECHANICAL ENGINEERING, INDIAN INSTITUTE OF TECHNOLOGY (ISM), DHANBAD-826004, JHARKHAND, INDIA

**** OPOLE UNIVERSITY OF TECHNOLOGY, 76 PROSZKOWSKA ST., 45-758 OPOLE, POLAND

***** TECHNICAL UNIVERSITIES OF KOŠICE WITH A SEAT IN PREŠOV, 080 01 PRESOV, SLOVAK REPUBLIC

Corresponding author: saurabh22490@gmail.com

oznaki zużycia zmęczeniowego. Ponieważ zużycie materiału skraca okres eksploatacji narzędzi, wielu badaczy podjęło się badań nad tym zagadnieniem. Kwestia oceny zużycia zmęczeniowego narzędzi wykonanych z węglików spiekanych badana jest od dłuższego czasu. Niezbędne jest poznanie charakterystyki procesu zużycia zmęczeniowego i jego przyczyn tak by można wyodrębnić do badania narzędzia nadające się do dłuższej eksploatacji, tym samym poprawiając opłacalność produkcji. Badano rozmaite mechanizmy zużycia zmęczeniowego węglików spiekanych związane z użytkowaniem narzędzi w wiertnictwie oraz urabianiu skał, opracowano także laboratoryjne metody jego badania. W artykule tym podjęto próbę zebrania i usystematyzowania wszystkich mechanizmów zużycia zmęczeniowego, jakiemu podlegają narzędzia wykonane z węglików spiekanych. Przyczyny i skutki każdego z procesów rozpatrywano w ujęciu całościowym. Ponadto, omówiono właściwości niedawno opracowanych węglików spiekanych.

Słowa kluczowe: węglik spiekany, wiercenie skał, urabianie skał, laboratoryjne badanie zużycia zmęczeniowego, charakterystyka zużycia zmęczeniowego, nowe rozwiązania

1. Introduction

The ideal combination of hardness, strength, toughness, and advanced chemical stability makes the cemented carbide excellent in performance. Therefore, it is widely used in the field of metal machining, mine excavation, oil drilling, geological exploration, and various industrial applications (Jiang, 2005; Dvoracek et al., 2017; Krolczyk et al., 2013a, 2013b; Maruda et al., 2015). The composite structure of the CC contains very hard (but relatively brittle) WC grains glued together with a ductile binder (like, Co, Ni, etc.) which is responsible for some plastic deformation to the hard metal alloy.

Rock and coal can be categorised under heterogeneous and brittle material. Rock drilling and coal cutting are basically carried out by breaking and fracturing techniques. With regard to rocks, there are mainly three techniques. First, rotary/ percussive drilling for very hard rock structure; second, rotary/crushing drilling for medium hard rock; third, cutting for soft rock types. These techniques are used to produce large hole without blasting (Beste, 2004). According to different applications, the machines and the tools are also different. For rotary percussive drilling, the drill bit, equipped with cemented carbide buttons at the head, is used. The drill head is advanced towards the rock so as to remove cut rock particles and to get a new surface of rock in each moment. For rotary crushing drilling, a tri-cone bit is used. It has three cones which can rotate at their own axis. Similar to drill bits, these cones are equipped with the cemented carbide buttons. In this way, rock is crushed when the tri-cone bit is advanced. For cutting, various shaped cutters, i.e., conical, radial, and forward attack picks are used. They are used for soft structure like coal, salt, concrete, etc.

With the continuous use, wearing of the cemented carbide happens and its service life gets reduced (Maidl et al., 2008). For a long time, there have been studies on identification of wear mechanisms in cemented carbide based tools. For different working conditions, such as, standard wear tests, drilling of rocks in laboratory, and in-situ mining operations, researchers have used the cemented carbide samples in various geometries and shapes. After certain period of application, worn out cemented carbide samples have been undergone through critical wear analysis by using high resolution microscopes, such as, scanning electron microscope (SEM), transmission electron microscope (TEM), X-ray diffraction analysis (XRD), etc. (Tong et al., 1991; Larsen-Basse, 1985; Beste et al., 2001, 2008; Beste & Jacobson, 2002, 2003, 2008; Pirso et al., 2004; Okamoto et al., 2005). In the present paper, a review on cemented carbide, its properties, and different modes of failure has been presented.

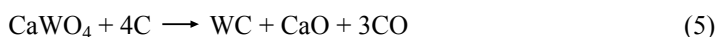
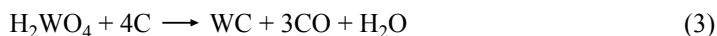
2. Cemented carbide: constituents and properties

Cemented carbide basically consists of two major phases: hard refractory phase WC and soft metal binder phase Co/Ni. The manufacturing of the hard metal alloys is done by the application of Powder Metallurgy (PM) process, which imparts the pressing and sintering of mixed powders of tungsten carbide and binder metal (Pastor, 1997).

Tungsten carbide is manufactured by mixing pure tungsten powder with pure carbon at a high temperature of around 1500°C in a vacuum or in presence of hydrogen (Tulhoff, 2000; Rajput, 2007).



There are several methods for manufacturing tungsten carbide (Tulhoff, 2000): tungsten oxides (WO_3), tungstic acid (H_2WO_4), ammonium paratungstate ($(NH_4)_{10}W_{12}O_{41} \times 5H_2O$) and scheelite ($CaWO_4$) can be carburised directly to get tungsten carbide:



Carburization of tungsten oxide can also be done by using gases like carbon monoxide or methane:



The newly formed product, WC, is then mixed homogeneously with a certain amount of cobalt. This is the cementation process for making CC. The homogeneous mixture is pressed into the required shapes under pressure from 100 to 420 MN/m² in presence of heat and vacuum. Sometimes hydrogenous environment is used in place of vacuum (Rajput, 2007). These specifically shaped products are sintered in a vacuum at a temperature around 1435°C so that the porosity can be minimized. The parameters, such as, WC grain size, Co content, porosity and carbon content, affect the performance of CC to a great extent (Bilgin et al., 2013).

The various grades of cemented carbide contain WC and Co as the main elements, although other elements like Cr, Ni, etc. are often added to optimize properties. The proportion of hard WC phase is normally 70-97% of the total weight of the composite and its grain size averages between 0.2 μm and 20 μm. With this variation, the CC has wide range of strength and toughness with a proper combination of wear resistance. On the basis of application, the CC can be categorised into three grades: (1) *Fine and Medium grades* with binder contents between 6-30% and WC grain sizes of 1-3 μm. This is used for the application which requires high strength and shock resisting properties. (2) *Medium Coarse, Coarse and Extra Coarse grades* with 6-15 wt% and > 3 μm of binder content and WC grain sizes respectively. They are used in oil drilling and other mining applications where resistance to impact as well as resistance to abrasive wear both are required. (3) *Corrosion resistant grades* are required where the CC undergoes to high chemical reactions. These grades are prepared by alloying Co with elements such as Nickel (Ni) and Chromium (Cr), or sometimes complete replacement of binder content (Courtesy: Sandvik,

2005). The tribological, mechanical and thermal properties of WC cemented carbide substantially depend on its composition and WC particle size (Tong et al., 1991; Larsen-Basse, 1985; Pirso et al., 2004; Dixon et al., 1983; Jia & Fischer, 1996). The different mechanical properties of the cemented carbide are listed in table 1.

TABLE 1

Some mechanical Properties of cemented carbide

S. No.	Parameters	Description
1.	Hardness	<ul style="list-style-type: none"> Varies with WC grain size and Co content. 92 Rockwell 'A' is typical for 6% of cobalt content (Courtesy: generalcarbide.com)
2.	Density	<ul style="list-style-type: none"> The density of a CC is about 13-15 g/cm³. The density of pure WC and pure Co are 15.7 g/cm³ and 8.9 g/cm³, respectively (Aylward & Friendly, 1994).
3.	Fracture toughness	<ul style="list-style-type: none"> Ability to resist fracture or energy required for mechanical failure Low carbide volume fraction and large grain size of WC increase toughness It is designated on the basis of critical stress intensity factor K_{IC} $K_{IC} = \sigma_F (a\pi c)^{1/2}$ where, K_{IC} is in [MPa], σ_F is the stress required to propagate an interior crack of length $2c$, a is a constant ~ 1 (Courtney, 2000). Fracture toughness is determined by palmqvist method. Typical values for CC:s lie between 5 Pam^{1/2} (for grain size below 0.5 μm and 3% Co) up to 26 Pam^{1/2} (for 2 μm grain size and 28 % Co) (Beste, 2004).
4.	Young's modulus	<ul style="list-style-type: none"> Young's modulus of CC is very high ranging from 400 to 650 GPa, i.e., 2 to 3 times higher than that of steel (Beste, 2004). It is highly dependent on grain size. For grain sizes of 3-20 μm, an approximate value is 577 GPa. Its value approaches 523 GPa when WC grain size becomes 30 μm. Also, it is inversely proportional to the Co content (Okamoto et al., 2005).

2.1. Binder phase and its effects

The binder material, Co, is used in the form of β -phase. The aim of the sintering process is to achieve FCC-structured Co binder because it has more ductility and thereby more fracture resistance than that of HCP-structure (Cha et al., 2001). To avoid the transition of Co from its high temperature ductile phase (FCC) to its low temperature brittle phase (HCP), it can be alloyed with Ni or Cr (Beste et al., 2001). It has been found that hardness of CC hardmetal alloy is greatly affected by the amount of Co present. If binder content is increased, the overall hardness of the CC decreases but toughness increases (Brookes, 1992). Transverse rupture strength increases with an increase in the cobalt content. Co may be increased up to 20%. A further increment of Co leads to the separation of carbide grains (Bilgin et al., 2013). In addition, it has also been found that high composition of Co-binder tends to increase the corrosivity of the CC. It becomes leached out under chemical reaction with leaving the original place empty. It results in disintegration of the CC (Exner, 1979; Voorhies, 1972). Therefore, some-times Co is removed totally to form binder-less carbides (almost pure WC), or small addition of TiC and TaNbC (with traces of Co) are carried out. This phenomenon results to form dense structure which is harder and more corrosion resistant than conventional CC (Beste et al., 2001).

2.2. Carbide phase and its effects

The WC hard phase (α -phase) constitutes the main part of cemented carbide. The amount of WC is much higher (70-97%) than the binder part (3-30%). The cemented carbide hard metal is very hard and brittle by the virtue of carbide phase only. WC has crystal orientation of non-centro symmetric hexagonal type. Variation in hardness of WC is dependent on its crystal system also. It varies from 1300 Vickers hardness (HV) on the crystal prism planes to 2300 Vickers hardness (HV) on the basal plane. Both the mechanical properties, i.e., hardness and toughness, can be controlled by WC grain size. After some abrasivity tests, it has been found that fine grains provide less toughness, high hardness and thereby high wear resisting properties (www.sandvik.com, 2005; Dixon et al., 1983; Milman et al., 1999). A detailed study has been done by the researchers towards the grain size estimation. The variations in sizes have been given as: very fine $<0.5 \mu\text{m}$, medium = $1.4\text{-}2.0 \mu\text{m}$, and coarse grains $\geq 5.0 \mu\text{m}$. The WC grain particles with sizes of less than $0.1 \mu\text{m}$ have been developed under the ultra-fine category. It provides extremely high wear resistance properties (Sheikh-Ahmad & Bailey, 1999; Oquigley et al., 1997).

2.3. Other factors and their effects

(1) Effect of porosity: Porosity may introduce at the time of sintering. It is a defect. The porous structure possesses less transverse rupture strength and hence the durability of the cemented carbide becomes low (Wood, 1970).

(2) Effect of carbon content: It has been observed that the presence of extra amount of carbon varies the mechanical properties of the cemented carbide. The WC grain growth and the amount of η phase are influenced by carbon content (Lee & Kang, 2006). During sintering of tungsten carbide, the entrenchment of carbon can decrease the rupture resistance property (Bilgin et al., 2013).

(3) Effect of heat: A high degree of heat is generated during excavation. Regarding hard rock drilling, Fish et al. (1959) have found that the temperature of the buttons gets increased due to high frictional heat generated by necessary high load of the machine. It results in tool material softening. After performing an experiment, Mari and Gonseth (1993) have concluded that fine grained sample exhibits better deformation resistance condition below 800°C but this phenomenon does not seem true at high temperature. Kindermann et al. (1999) have observed temperature-dependent fatigue effect for temperatures between 25° and 900°C . At low temperatures, the Co binder undergoes a phase transformation from FCC to HCP phase. The latter is more brittle and hard when subjected to cyclic loads.

3. Wearing process of cemented carbide

During *rock drilling*, cemented carbide buttons work under serious and complex conditions. These complex conditions are generated by the cumulative effect of variation in properties of rocks, its mineral contents, high heterogeneity, brittleness, other geological parameters, and various working techniques. These conditions greatly affect the physical and mechanical properties of the cemented carbide. The significant damage can be reported in cemented carbide drill button when hard and sharp rock penetrates into it (Beste et al., 2008; Beste & Jacobson, 2008; Larsen-Basse,

1973, 1983). A rock drill bit is shown in Fig. 1. The advancement of the CC button into sharp rock mass, brittle fracturing of rock, cracks generation and rock penetration in the CC is clearly demonstrated in Fig. 2. The failure process of the *coal cutting picks*, such as, conical pick, is similar to rock drill buttons. The continuous cutting operation tends to damage the cutters gradually. The interaction between pick and coal, cracks formation and gradual wearing of the cemented carbide tip are shown in Fig. 3 (a, b & c).

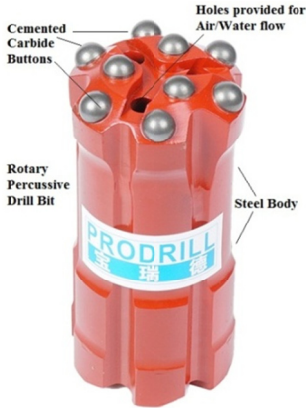


Fig. 1. Drill bit for rotary percussion drilling of hard rock (Courtesy: Prodrill)

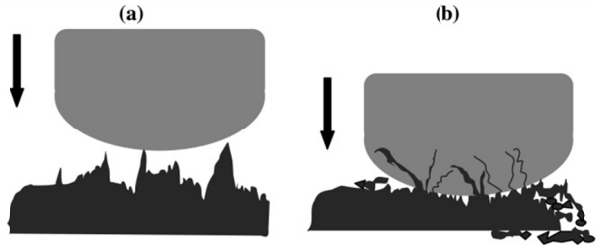


Fig. 2. (a) Advancement of the drill button towards hard rock; (b) Contact between button and rock resulting crushing of rocks; generation of cracks and penetration of rock into the CC

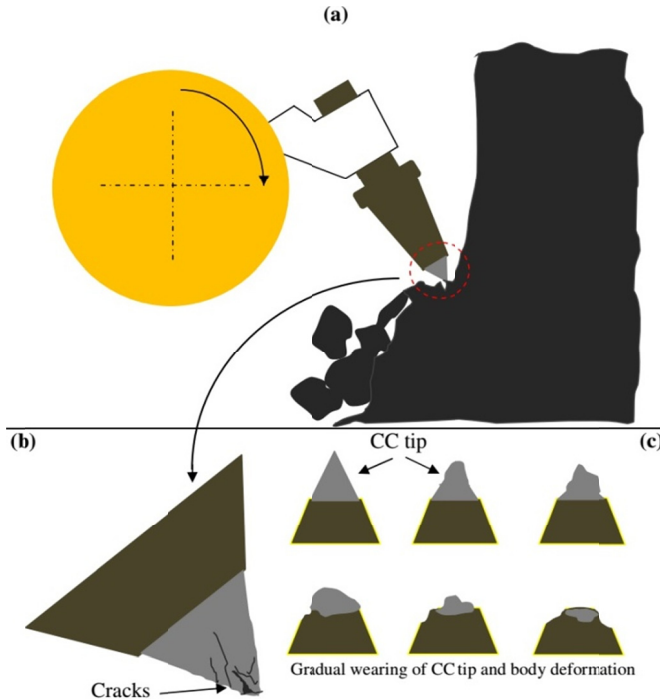


Fig. 3. (a) Interaction of the cemented carbide cone tip with coal by the rotating drum; (b) High impacts cause cracks in the cemented carbide tip; (c) One of the attributes of gradual wearing of the carbide tip and steel body

4. Wear mechanisms in cemented carbide

In all the wear test methods, in situ drilling or cutting and laboratory wear tests, worn out parts of the cemented carbide are prepared for wear analysis. For characterization purpose, high resolution microscopes, such as, scanning electron microscope (SEM), field emission scanning electron microscopy (FESEM), energy dispersive spectroscope (EDS), atomic emission spectroscopy (AES), electron backscatter diffraction (EBSD), transmission electron microscopy (TEM), energy filtered transmission electron microscopy (EFTEM), scanning transmission electron microscopy (STEM), focused ion beam scanning electron microscopy (FIB-SEM) are mainly used. A detailed list of wear mechanisms in cemented carbide and the steps involved in analyzing these mechanisms are given in Fig. 4.

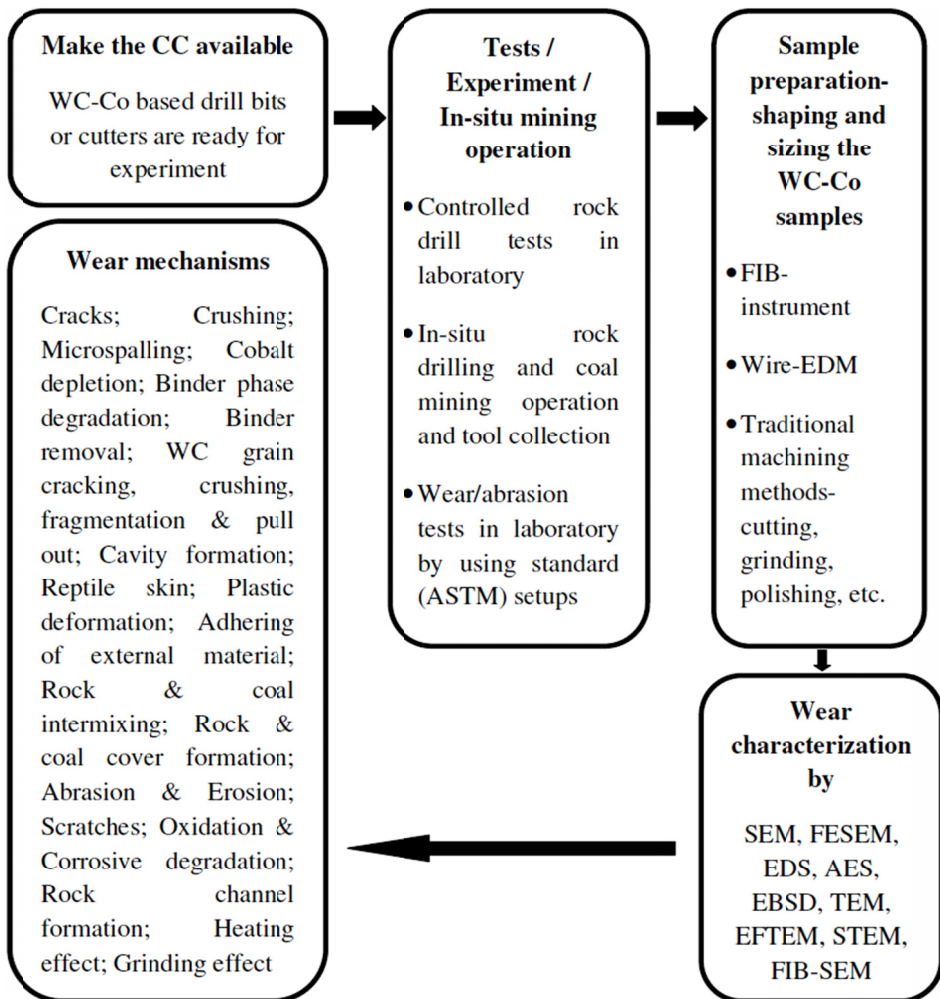


Fig. 4. Steps involved in wear analysis of cemented carbide

4.1. Wear analysis of the CC drill buttons

Wear analysis of the cemented carbide is not a new development. It has been done for a long time. Many researchers have reported about wear mechanisms of the CC tool by using SEM and FESEM. Most of the mechanisms are interrelated with each other. The main types of the damages are named as: Microspalling, Abrasion Wear, Cracks, WC grain pullout, Extrusion of binder metal and Reptile skin (Beste & Jacobson, 2003; Larsen-Basse, 1973, 1983, 1985).

Microspalling is a process in which small cracks are formed within the WC grains and thereafter chip removal phenomenon takes place (Swick et al., 1992). After percussive drilling of granite and limestone, Montgomery (1968) has found fatigue microspalling as main wear mechanism. It has been reported that rate of microspall increases with an increase in rock hardness. *Abrasion* is a common wearing attribute which can be referred as severe scratches imposed by harder body to soft surface. Due to various mineral contents, rock is very abrasive in nature. Perrot (1980) has observed that abrasion of the WC grains and Co-binder depends on the temperature and the sizes of the abrasive materials. Jia & Fischer (1996) have noted difference between abrasion effects of hard and soft abrasive particles. During abrasive wear of the cemented carbide, hard particles create plastic deformation and soft abrasive cause removal of binder material. *Cracks* may generate when harder particles slide over the CC surface with removing debris. The surface impacts, impact fatigue and thermal fatigue can also results in cracks. Sharp rock behaves like wedge and enhances the crack growth phenomenon. In addition to the overall surface crack, the individual WC grains have also been focused under detailed study of crack propagation by some researchers (Gee et al., 2007; Gant et al., 2005; Blomberry et al., 1974). *Extrusion of binder phase* occurs when drilling is performed at high impacts and high temperature. This condition vouches the plastic deformation and micro-abrasion between WC grains. The extruded binder accumulates at the surface the CC surface with leaving the original place binder-less. The high impacts facilitate relative motion among WC grains and thereby inter-granular fracture occurs. This phenomenon leads to fragmentation and removal of WC grains. In this way, it can be stated that WC grain pull out follows binder phase extrusion (Pirso et al., 2004; Larsen-Basse, 1985; Gee et al., 2007; Desai et al., 1984). *Reptile skin* is a common wear mechanism in the form of large number of cracks on the surface of the cemented carbide. It has been mainly found on the drills which are used for minerals, such as, magnetite, chromite and manganese (Beste, 2004; Larsen-Basse, 1973). Although the surface topography of the *reptile skin* is similar to normal cracks generated by high impacts, still both are different. Beste et al. (2001) have carried out drilling tests by using three different CC buttons (each possesses different hardness and grain size). The difference has been observed between long initial surface cracks and reptile skins. The surface crack advances like long straight line but the scale of the reptile skin is comparatively lesser.

Among all, two types of wear mechanism are typical in nature. They are: (a) rock cover formation & intermixed layer; (b) degradation of binder phase

(a) Rock cover formation and intermixed layer: When the CC buttons continuously come in contact with rock material, it causes formation of solid cover of rock material over a large part of buttons. It has been observed that fragmented rock particles become integral part (as a layer) of the button surface with replacing some of the binder content (Beste, 2004; Beste & Jacobson, 2008; Olovsjo et al., 2013).

(b) Embrittlement and degradation of the binder phase: Due to percussion drilling and rough contacts with rock, the binder phase experiences severe conditions. It results in micro-structural damage including fatigue induced degradation, plastic deformation, formation of twin and dislocation, etc. Finally damage occurs when Co transforms from FCC to HCP phase. In addition, the development of new binder phase in combination with cobalt, rock material and WC fragments has been reported. The new binder phase actually does not possess original binding quality. In other words, it can be referred as a degraded phase which is not desirable (Beste & Jacobson, 2008; Cha et al., 2001; Kindermann et al., 1999; Olovsjo et al., 2013; Rettenmayr et al., 1988; Schleinkofer et al., 1996).

4.2. Wear analysis of the CC coal mining picks

Cutters equipped with the CC tips are used to separate coal from the coal seam. Although literature on wear assessment of coal cutting equipment is less in number, the work of Dewangan et al. (2015a, 2015b), Dewangan & Chattopadhyaya (2015, 2016) and Nahak et al. (2015, 2016, 2017a, 2017b) towards wear characterization can be referred for further study. Two cutters, i.e., conical picks and radial picks have been taken for in-situ coal mining operation. In both the parts, i.e., the CC tip and the steel body, critical observation of wear mechanisms have been performed.

Wear mechanisms, such as, large cracks with depth, cracks with overlapping surfaces, grinding effect, adhesion of rock particle, and heating effect are found in the surface of the CC tip of the conical picks. These mechanisms have been categorised under the entire CC surface because they have been observed at comparatively lower magnification value of FESEM.

As the conical picks were used through continuous miner machine, they were rotated by cutting drum to the coal. Sudden impacts generate small cracks on the CC surface which get enlarged by subsequent impacts. As the crack gets enlarged, it allows the coal and rock material to lodge inside it. Therefore, it is named as *large crack with depth* (Dewangan et al., 2015b; Dewangan & Chattopadhyaya, 2016). *Cracks with overlapping surfaces* are typical type of wear phenomena and are not common. It has been noticed that one side of the crack tends to overlap on the other side by the influence of heavy impacts. As the name suggest, *grinding effect* is the result of continuous sliding of the particular part of the CC tip on a sharp and abrasive area of coal (Dewangan & Chattopadhyaya, 2015). *Adhesion of rock particle* is almost similar phenomenon as discussed in drill bits. It is an initiation of rock cover formation over the CC surface (Dewangan et al., 2015a). *Heating effect* has been established by observing the flow of brazing materials towards the CC microstructure under the influence of high heat. It has been concluded that the temperature of the tip reached $>450^{\circ}\text{C}$ (Dewangan & Chattopadhyaya, 2016).

In the WC grains, mainly five different types of wear mechanisms have been detected. These are: *cracking*, *crushing*, *cavity formation*, *corrosion in WC grains*, and, *abrasion in the individual grain*. For observing these mechanisms, FESEM images were taken under higher magnification. Being an extremely hard material, CC is very brittle. After being subject to repeated impacts, it begins to crack (Fig. 5) (Nahak et al., 2016). Prolonged impacts over a large area of the cracked CC result in the crushing of the WC grains. Crushing leads to grain fragmentation phenomenon. WC fragments displace or remove easily and leave the original place empty (Fig. 6) (Dewangan et al., 2015a). Wearing in the form of corrosive degradation is a serious problem in the cemented carbide. A number of research works has been conducted by many researchers to know the corrosion behaviour of the WC grains and Co content. According to Echtenkamp (1978), reduction in

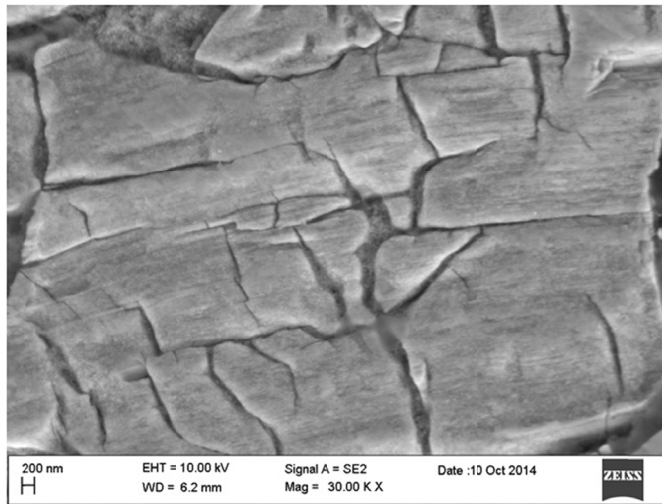


Fig. 5. Severe cracking in the WC grain (Nahak et al., 2016)

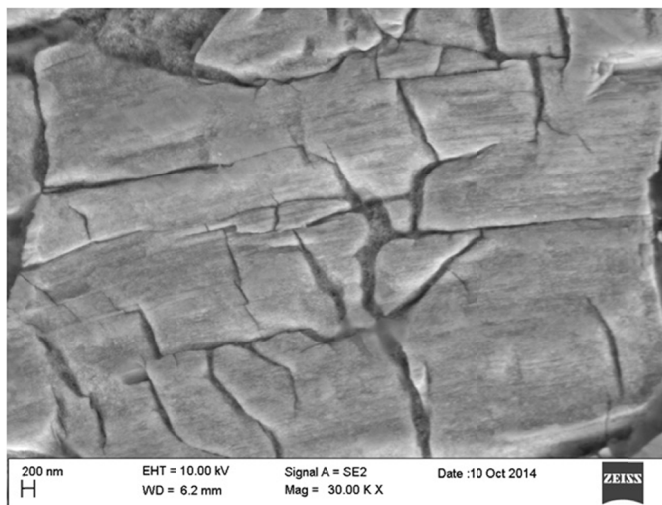


Fig. 6. Cavity formation in the WC grain (Dewangan et al., 2015a)

transverse rupture strength has been found after immersing the WC-12% Co in a ferric chloride solution. Also, it has been concluded that binder part removes from the original place and the chemical effect appears as a series of pores and triangular notches in the WC grains. In addition, Human & Exner (1996) have observed that the corrosion rate of binder part is faster than carbide. It has been concluded that high amount of cobalt enhance the corrosivity and vice-versa. Therefore, WC-Co with least amount of cobalt or binder-less carbide possesses high wear and corrosion resistance properties (Exner, 1979; Engqvist et al., 2000; Gee, 2010). With reference to the Indian mines, the corrosivity of water collected from different mines has been tested. Corrosion rates

are decided by the effects of Fe^{3+} , Cu^{2+} , SO_4^{2-} and Cl^- (Singh, 2006). Under the influence of corrosive mine water, the CC tip of coal mining picks have also been found corroded. Both the parts, WC grain and Co content, are affected by the mine water. The roughness of the WC grain surface appears in the form of pores and notches (Fig. 7). Also, the formation of tungsten oxide and binder phase removal due to corrosion has been reported (Dewangan & Chattopadhyaya, 2015, 2016). Also, a typical abrasion phenomenon in the individual WC grain has been reported by Nahak et al., (2017b) (Fig. 8).

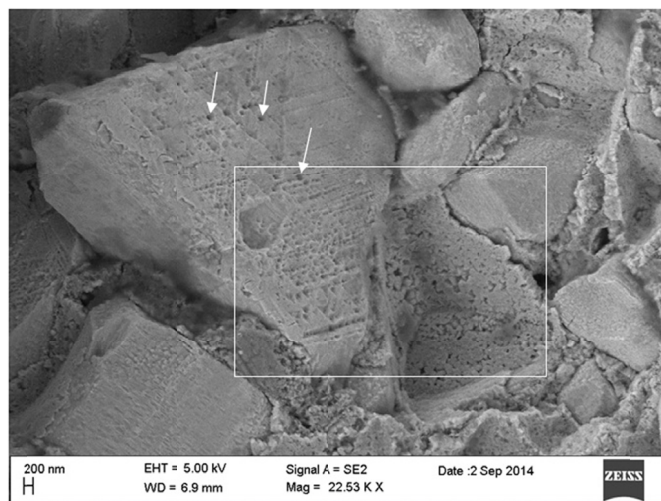


Fig. 7. Corrosive degradation of WC grains and binder content; white arrow marks show pores and down portion of the white rectangle shows removal of the cobalt binder (Dewangan & Chattopadhyaya, 2016)

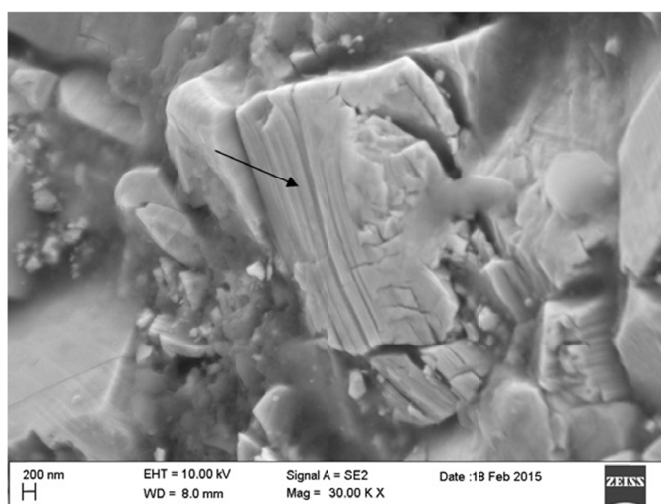


Fig. 8. Typical abrasion in an individual WC grain shown by a black arrow (Nahak et al., 2017b)

The cobalt content is found to be distorted mainly in two ways: (a) coal and rock intermixing; (b) corrosive degradation. The coal/rock intermixing into the binder content has been established by EDS. The external elements, such as, C, O, Mg, Al, and Ca have been predominantly observed. Here, C is an indication of coal material (Dewangan et al. 2015a, 2015b; Dewangan & Chattopadhyaya 2015, 2016; Nahak et al., 2015, 2016, 2017a, 2017b). With regard to *corrosive degradation*, the cobalt content completely washed out from the original place (Dewangan & Chattopadhyaya, 2015).

5. Laboratory wear test for cemented carbide

The laboratory wear test methods for cemented carbide generally possess different types of wheel which are rotated against the CC samples. Gant et al. (2005) have described two test setups: (a) the standard ASTM B611 system; (b) modified ASTM G65 test system. These two test methods are often utilized.

A schematic diagram of the ASTM B611 test system is shown in Fig. 9a. The sample is pressed against a steel wheel rotating in slurry with abrasive particles. The load between sample and rotating wheel is regulated by the weight attached in the lever.

In modified ASTM G65 test system, the sample is pressed against a rotating rubber rimmed steel wheel. Similarly, the contact load is regulated by a weight. Abrasive (sand) and fluid are supplied on the rubber rim through two different channels, as shown in Fig. 9b.

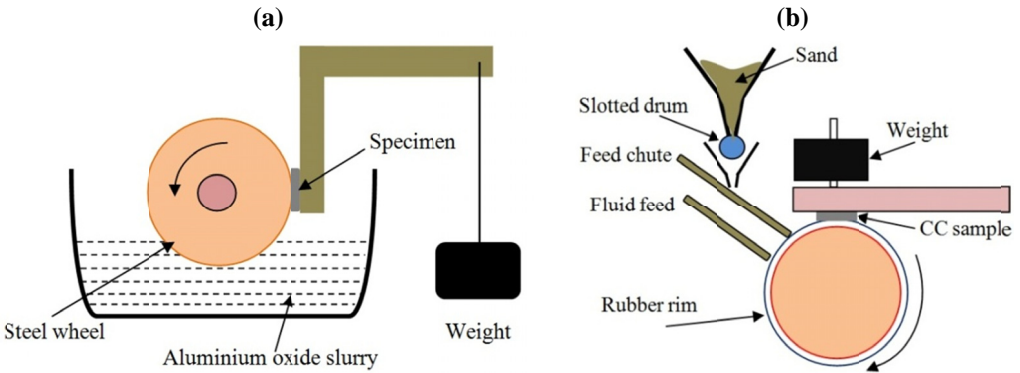


Fig. 9. (a) Schematic diagram of ISO 12962/ASTM B611 test system; (b) Schematic diagram of rotating wheel (modified ASTM G65) test system (Gant et al., 2005)

Gee et al. (2005) have compared the two test systems from wearing attribute point of view. They have found that both the methods provide very similar results for wearing of cemented carbide. Gant et al. (2005) and Gee et al. (2007) have used ASTM B611 test system with abrasives as alumina (size 660 μm) to investigate wear mechanisms in WC-Co hardmetal. By analysing through SEM images of worn out surfaces, they found various failure behaviour like deterioration of Co binder phase, WC grains fracture, fragmentation of WC into the binder phase, breakaway of material and sub-surface cracking.

6. Discussion

Different wear mechanisms are appeared in the cemented carbide at various working conditions and accordingly the proper selection of the best grades of the CC is done prior to use. For example, if the cemented carbide is to be used for hard and abrasive work-piece, then it should posses high wear and fracture resistance properties. These properties are achieved by minimizing both, the grain size and also the cobalt content. Similarly, if corrosion resistance is required, then Co content should be minimized or removed or replaced by some other corrosion resistant binding material. Therefore, for enhancing the desirable properties of the cemented carbide to the excellent level, some techniques have been developed recently. These techniques are: (a) development of nano-sized WC grains; (b) development of functionally graded cemented carbide; (c) development of binder-less cemented carbide.

- (a) Nano-sized cemented carbide contains powder of WC grains. It is a very dense structure. Although it does not possess cobalt as a binder, still it contains good fracture toughness (Mukhopadhyay & Basu, 2011; Zhang et al., 2003; Butler et al., 2007).
- (b) Development of functionally graded cemented carbide becomes vital when both the properties, i.e., fracture toughness and wear resistance are highly required. This combination is very useful in the field of metal cutting, rock drilling, coal mining, and oil drilling etc (Fischer et al., 1988, 1999; Hartzell et al., 1995; Ren et al. 2013). The CC is prepared with varying cobalt content from the surface to the core of the structure. If the surface is to be made highly tough, higher amount of cobalt is provided in the surface. This is usually used in normal cutting tools. Sometimes, the structure is divided into three zones due to cobalt distribution. In this situation, generally, the cobalt content is provided in fewer amounts at the surface and at the core and in higher amounts at between them. This structure possesses abrasion resistance at the surface and good toughness at the next layer of cobalt distribution. These properties are highly desirable for rock drilling tools (Fischer et al., 1989; Akerman et al., 1995; Liu et al., 2006; Zhang et al., 2008; Wang et al., 2013).
- (c) The binder-less cemented carbides are specially designed for increasing the corrosion and oxidation resistance properties. This consists of secondary carbides, such as, TiC, TaC or NbC. The resultant composite is very hard but the toughness is very low (Imasato et al., 1995; Raghunathan et al., 1996). It has also been noted that Co can be replaced by Ni/Ni-Cr/Ni-Co and sometimes can be alloyed with Cr_3C_2 to increase the corrosion resistance property (Tomlinson & Linzell, 1988; Human & Exner, 1996; Hochstrasser et al., 2007).

7. Conclusion

The learning and conclusion derived from this review is as follows:

- (a) WC-Co cemented carbide is a very important tool material. Due to an excellent combination of hardness, strength, wear resistance and fracture toughness, it is widely used in metal machining, rock drilling, coal cutting, metal mining and oil drilling etc. During mine excavation, the CC undergoes a complex condition created by varying geological condition, quartz content in hard rock, heat generation due to friction, and different

machining parameters. These conditions restrict the long service life of the CC by making it worn out during application. The CC gets damaged by different mechanisms. In the present paper, an attempt has been made to review all those mechanisms with their causes and effects. The analysis of wear mechanisms is an important technique to know the behaviour of the tool towards failure. After knowing the exact wear behaviour, the concentration of the tool material can be changed or modified to get the resisting properties against any particular wear mechanism. Therefore, some standard laboratory wear test methods are also developed by ASTM to observe the wear response of the cemented carbide.

- (b) Wear analysis of the cemented carbide has been mainly performed after three different applications: rock drilling through drill bits with the CC buttons; coal mining by using the CC based cutters like conical and radial picks; standard wear tests in laboratory by preparing exact size of the CC sample.
- (c) For characterization purpose, worn out CC samples are undergone through high resolution microscopes like SEM, FESEM, EDS, AES, EBSD, TEM, EFTEM, STEM, XRD, and FIB-SEM, etc. According to the characteristics and appearance, different types of wear mechanisms are reported.
- (d) Different types of wear mechanisms in the cemented carbide can be listed – *Cracks; Crushing; Microspalling; Cobalt depletion; Binder phase degradation; Binder removal; WC grain cracking, crushing, fragmentation & pull out; Cavity formation; Reptile skin; Plastic deformation; Adhering of external material; Rock & coal intermixing; Rock & coal cover formation; Abrasion & Erosion; Scratches; Oxidation & Corrosive degradation; Rock channel formation; Heating effect; Grinding effect.*
- (e) All types of wear mechanisms initiate from generation of minor cracks. Among them, rock intermixing, cobalt degradation, and corrosive degradation create severe condition for the cemented carbide. Through minor cracks, rock and coal particles get intermixed with cobalt content to form a mixture with undesirable properties. Unlike Co, this mixture does not possess binding quality. Cobalt gets degraded from FCC to HCP structure which further gives rise to WC grain removal and overall CC damage. Corrosive degradation is found in WC grains and Co both. It generally occurs when the CC comes into influence of any chemical or corrosive environment. Cobalt removal and porosity in the surface of WC are the common effects of corrosion. By the effect of corrosive mine water, high degree of corrosion is reported in coal mining picks.
- (f) Three wear mechanisms, such as, Co depletion, grinding effect, and typical abrasion in individual grain are rarely found but they are important because their effects are highly damage prone.
- (g) To predict, observe and establish any type of wear behaviour, an excellent laboratory set up and high quality instruments are needed. It will give a proper understanding of a critical stage.
- (h) The wear analysis of the cemented carbide must be carried out in future so that new directions of the research can be implemented.

As rock drilling and coal cutting are difficult to be done in the laboratory, wear testing methods are useful in the workshop practice. Therefore, the development of new wear testing machines or modification of the standard wear test apparatus may be an important area of research in this field.

Reference

- Akerman J.G.H., Fischer U.K.R., Hartzell E.T., 1995. *Cemented carbide body with extra tough behavior*. US Patent 5, 453, 241.
- Aylward G., Friendly T., 1994. *SI Chemical Data*. ed. P. Storer. John Wiley & Sons, Sydney.
- Beste U. et al., 2001. *Particle erosion of cemented carbides with low Co content*. Wear, **250**, 809-817.
- Beste U. et al., 2001. *Surface damage on cemented carbide rock drill buttons*. Wear, **249**, 324-329.
- Beste U., 2004. *On the Nature of Cemented Carbide Wear in Rock Drilling*. Acta Universitatis Upsaliensis. Comprehensive summary of Uppasala dissertations from the faculty of Sc. and Tech. 964.
- Beste U., Jacobson S., 2002. *Friction between a cemented carbide rock drill button and different rock types*. Wear, **253**, 1219-1221.
- Beste U., Jacobson S., 2003. *Micro scale hardness distribution of rock types related to rock drill wear*. Wear, **254**, 1147-1154.
- Beste U., Jacobson S., 2008. *A new view of the deterioration and wear of WC/Co cemented carbide rock drill buttons*. Wear, **264**, 1129-1141.
- Beste U., Jacobson S., Hogmark S., 2008. *Rock penetration into cemented carbide drill buttons during rock drilling*. Wear, **264**, 1142-51.
- Bilgin N., Copur H., Balci C., 2013. *Mechanical excavation in mining and civil industries*. CRC Press, Boca Raton, 103-123
- Blomberry R.I., Perrot C.M., Robinson P.M., 1974. *Abrasive wear of tungsten carbide-cobalt composites. I. Wear mechanisms*. Materials Science and Engineering, **13**, 93-100.
- Brookes K.J.A., 1992. *Hardmetals and Other Hard Materials*. International Carbide Data.
- Butler B.G., Lu J., Fang Z.Z., Rajamani R.K., 2007. *Production of nanometric tungsten carbide powders by planetary milling*. Int. J. Powder Metall., **43**, 35-43.
- Cemented Carbide, Sandvik new developments and applications. Ref no. H-9116 ENG. (Edited 2005), www.hardmaterials.sandvik.com
- Cha S.I. et al., 2001. *Mechanical properties of WC-10Co cemented carbides sintered from nanocrystalline spray conversion processed powders*. Int. J. Refract. Met. Hard. Mater., **19**, 397-403.
- Chiaia B., Borri- Brunetto M., Carpinteri A., 2013. *Mathematical modelling of the mechanics of core drilling in geomaterials*. Machining Sc. and Tech, **17**, 1-25.
- Clark G.B., 1982. *Principles of rock drilling and bit wear*. Colorado School of Mines, Quarterly, Golden, **77**, 91.
- Courtney T.H., 2000. *Mechanical behaviour of materials*. 2nd edition, McGraw-Hill.
- Desai V.M., Rao C.M., Kosel T.H., Fiore N.F., 1984. *Effect of carbide size on the abrasion of cobalt-phase powder metallurgy alloys*. Wear, **94**, 89-101.
- Dewangan S., Chattopadhyaya S., 2015. *Critical analysis of wear mechanisms in cemented carbide*. Journal of materials engineering and performance, **24**, 2628-2636.
- Dewangan S., Chattopadhyaya S., 2016. *Characterization of wear mechanisms in distorted conical picks after coal cutting*. Rock Mech. Rock Eng., **49**, 225-242
- Dewangan S., Chattopadhyaya S., Hloch S., 2015a. *Critical damage analysis of WC-Co tip of conical pick due to coal excavation in mines*. Advances in materials science and engineering, **2015**, 7.
- Dewangan S., Chattopadhyaya S., Hloch S., 2015b. *Wear assessment of conical pick used in coal cutting operation*. Rock Mech. Rock Eng., **48**, 2129-2139.
- Dixon G., Wright R.N., Lee M., 1983. *Processes involved in the wear of cemented carbide tools*. Proc. Int. Conf. Wear Mater., 218-226.
- Dvoracek J., Sousedikova R., Vratny T., Jurekova Z., 2017. *Global tungsten demand and supply forecast*. Arch. Min. Sci., **62**, 3-12.
- Echtenkamp A.L., 1978. *Combating corrosion/wear with the hard carbide alloys*. Proc. of the ASLE/ASME lubrication conf., Oct 24-26, Minneapolis.

- Engqvist H., Beste U., Axen N., 2000. *The influence of pH on sliding wear of WC-based materials*. International Journal of Refractory Metals and Hard Materials, **18**, 103-109.
- Exner H.E., 1979. *Physical and chemical nature of cemented carbides*. International Materials Reviews, **24**, 149-173
- Fischer U.K.R., Hartzell E.T., Akerman J.G.H., 1988. *Cemented carbide body used preferably for rock drilling and mineral cutting*. US Patent No. 4,743,515.
- Fischer U.K.R., Hartzell E.T., Akerman J.G.H., 1989. *Cemented carbide body with a binder phase gradient and method of making the same*. US Patent No. 4, 820, 482.
- Fischer U.K.R., Waldenstrom M., Hartzell E.T., 1999. *Cemented carbide body with increased wear resistance*. US Patent No. 5,856,626.
- Fish B.G., Guppy G.A., Ruben J.T., 1959. *Abrasive wear effects in rotary rock drilling*. Trans. Inst. Min. Met., **68**, 357-383.
- Gant A.J., Gee M.G., Roebuck B., 2005. *Rotating wheel abrasion of WC/Co hardmetals*. Wear, **258**, 178-188.
- Gee M.G., 2010. *Model scratch corrosion studies for WC/Co hardmetals*. Wear, **268**, 1170-1177.
- Gee M.G., Gant A., Roebuck B., 2007. *Wear mechanisms in abrasion and erosion of WC/Co and related hardmetals*. Wear, **263**, 137-148
- Hartzell E.T., Akerman J.G.H., Fischer U.K.R., 1995. *Cemented carbide body used preferably for abrasive rock drilling and mineral cutting*. US Patent No. 5, 401, 461.
- Hochstrasser (-Kurz) S., Mueller Y., Latkoczy C., Virtanen S., Schmutz P., 2007. *Analytical characterization of the corrosion mechanisms of WC-Co by electrochemical methods and inductively coupled plasma mass spectroscopy*. Corrosion sc., **49**, 2002-2020.
- Human A.M., Exner H.E., 1996. *Electrochemical behaviour of tungsten-carbide hardmetals*. Material science and engineering A, **209**, 180-191.
- Imasato S., Tokumoto K., Kitada T., Sakuguchi S., 1995. *Propertiers of ultrafine grain binderless cemented carbide RCCFN*. Int J Refract Met Hard Mater, **13**, 305-312.
- Jia K., Fischer T.E., 1996. *Abrasion resistance of nanostructured and conventional cemented carbides*. Wear, **200**, 206-214.
- Jiang X., 2005. *The study on the preparation and microstructure of ultrafine cemented carbide*. Master Thesis, Chong Qing University, China.
- Kindermann et al., 1999. *High-temperature fatigue of cemented carbides under cyclic loads*. Int. J. Refract. Met. Hard Mater., **17**, 55-68.
- Krolczyk G., Legutko S., Raos P., 2013a. *Cutting wedge wear examination during turning of duplex stainless steel*. Tehnicki Vjesnik-Technical Gazette, **20**, 413-418.
- Krolczyk G., Legutko S., Stoic A., 2013b. *Influence of cutting parameters and conditions onto surface hardness of duplex stainless steel after turning process*. Tehnicki Vjesnik-Technical Gazette, **20**, 1077-1080.
- Larsen-Basse J., 1973. *Wear of hard-metals in rock drilling: a survey of the literature*. Powder Metall., **16**, 1-32.
- Larsen-Basse J., 1983. *Effect of composition, microstructure, and service conditions on the wear of cemented carbides*. J. Met., **35**, 35-42.
- Larsen-Basse J., 1985. *Binder extrusion in sliding wear of WC-Co alloys*. Wear, **105**, 247-256.
- Lee G.H., Kang S., 2006. *Sintering of nano-sized WC-Co powder produced by a gas reduction-carburization process*. Journal of alloys and compounds, **419**, 281-289.
- Liu Y., Wang H., Long Z., Liaw P., Yang J., Huang B., 2006. *Microstructural evolution and mechanical behaviors of graded cemented carbides*. Mater. Sci. Eng. A, **426**, 346-54.
- Maidl B., Schmid L., Ritz W., Herrenknecht M., 2008. *Hard rock tunnel boring machines*. Ernst & Sohn, Berlin.
- Mari D., Gonseth D.R., 1993. *A new look at carbide tool life*. Wear, **165**, 9-17.
- Maruda R., Legutko S., Krolczyk G., Raos P., 2015. *Influence of cooling conditions on the machining process under MQCL and MQL conditions*. Tehnicki Vjesnik-Technical Gazette, **22**, 965-970.
- Milman Yu.V., Luyckx S., Northrop I.T., 1999. *Influence of temperature, grain size and cobalt content on the hardness of WC-Co alloys*. Int. J. Refract. Met. Hard Mater., **17**, 39-44.

- Mishnaevsky L.L., 1995. *Mathematical modeling of wear of cemented carbide tools in cutting brittle materials*. Int. J. Machine Tools and Manufac., **35**, 717-724.
- Montgomery R.S., 1968. *The mechanism of percussive wear of tungsten carbide composites*. Wear, **12**, 309-329.
- Mukhopadhyay A., Basu B., 2011. *Recent developments on WC-based bulk composites*. J. Mater. Sci., **46**, 571-89.
- Nahak S., Chattopadhyaya S., Dewangan S., Hloch S., Krolczyk G., Legutko S., 2017a. *Microstructural study of failure phenomena in WC 94%-Co 6% hard metal alloy tips of radial picks*. Advances in Science and Technology Research Journal, **11**, 36-47
- Nahak S., Dewangan S., Chattopadhyaya S., 2015. *Discussion on wear phenomena in cemented carbide*. Procedia Earth and Planetary Science, **11**, 284-294
- Nahak S., Dewangan S., Chattopadhyaya S., 2016. *Wearing mechanisms of picks used in continuous miner machine for coal cutting*. Journal of Mines, Metals & Fuels, **64**, 128-135
- Nahak S., Dewangan S., Chattopadhyaya S., Hloch S., 2017b. *Characterization of failure behaviour in distorted WC-Co tip of coal mining picks*. Journal of Failure Analysis and Prevention, **17**, 136-143
- O'quigley D.G.F., Luyckx S., James M.N., 1997. *An empirical ranking of a wide range of WC-Co grades in terms of their abrasion resistance measured by the ASTM standard B 611-85 test*. Int. J. Refract. Met. Hard Mater., **15**, 73-79.
- Okamoto S., Nakazono Y., Otsuka K., Shimoitani Y., Takada J., 2005. *Mechanical properties of WC/Co cemented carbide with larger WC grain size*. Materials Characterization, **55**, 281-287.
- Olovsjo S., Johanson R., Falsafi F., Bexell U., Olsson M., 2013. *Surface failure and wear of cemented carbide rock drill buttons – The importance of sample preparation and optimized microscopy settings*. Wear, **302**, 1546-1554.
- Pastor H., 1997. Centenaire de la découverte du carbure de tungstène par Henri Moissan. historique du développement de ce matériau. La Revue de Métallurgie-CIT/Science et Génie des Matériaux. 1537-1552.
- Perrot C.M., 1980. Abrasive wear of hard metal rock bits, in: Proceedings of the Conference on Lubrication Friction and Wear in Engineering, Melbourne.
- Pirso J., Letunovič S., Viljus M., 2004. *Friction and wear behaviour of cemented carbides*. Wear, **257**, 257-265.
- Prodrill. www.rock-drill-bits.com/t38/Threaded-Button-Bit-02.html
- Raghunathan S., Caron R., Friederichs J., Sandell P., 1996. *Tungsten carbides technologies*. Advanced materials and processes, **4**, 21-23
- Rajput R.K., 2007. A text book of Manufacturing technology: Manufacturing processes. Firewall Media, India.
- Ren X., Miao H., Peng Z., 2013. *A review of cemented carbides for rock drilling: An old but still tough challenge in geo-engineering*. Int. Journal of Refractory Metals and Hard Materials, **39**, 61-77.
- Rettenmayr M., Exner H.E., Mader W., 1988. *Electron microscopy of binder phase deformation in WC-Co alloys*. Mater. Sci. Technol., **4**, 984-90.
- Schleinkofer U. et al., 1996. *Microstructural processes during subcritical crack growth in hard metals and cermets under cyclic loads*. Mater. Sci. Eng. A, **209**, 103-10.
- Sheikh-Ahmad J.Y., Bailey J.A., 1999. *The wear characteristics of some cemented tungsten carbides in machining particleboard*. Wear, **225-229**, 256-266.
- Singh G., 2006. *A survey of corrosivity of underground mine waters from Indian coal mines*. Int J. of mine water, International mine water association 2006/www.imwa.info.
- Swick K.J., Stachowiak G.W., Batchelor A.W., 1992., *Mechanism of wear of rotary-percussive drilling bits and the effect of rock type on wear*. Tribol. Int., **25**, 83-8.
- The designer's guide to tungsten carbide, www.generalcarbide.com
- Tomlinson W.J., Linzell C.R., 1988. *Anodic polarization and corrosion of cemented carbides with cobalt and nickel binders*. J. Mater. Sc., **23**, 914-918.
- Tong Z., Ding C., Yan D., 1991. *Size and shape characteristics of wear debris of WC + Co coating sliding against 45 steel*. Chin. J. Met. Sci. Technol. **7**, 282-287.
- Tulhoff H., 2000. Carbides. Metal like carbides of industrial importance. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VHC. doi: 10.1002/14356007.a05_061

- Voorhies J.D., 1972. *Electrochemical and chemical corrosion of tungsten carbide (WC)*. J. Electrochem. Soc., **119**, 219-222.
- Wang X., Hwang K.S., Koopman M., Fang Z.Z., Zhang L., 2013. *Mechanical properties and wear resistance of functionally graded WC-Co*. Int. J. Refract. Met. Hard Mater., **36**, 46-51.
- Wood G.A., 1970. *Quality control in the hard metal industry*. Powder Metallurgy, **13**, s. 338-368.
- Zhang F.L., Wang C.Y., Zhu M., 2003. *Nanostructured WC/Co composite powder prepared by high energy ball milling*. Scr. Mater., **49**, 1123-8.
- Zhang L., Wang Y.J., Yu X.W., Chen S., Xiong X.J., 2008. *Crack propagation characteristic and toughness of functionally graded WC-Co cemented carbide*. Int. J. Refract. Met. Hard Mater., **26**, 295-300.