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# Abrasion in Tunneling and Mining

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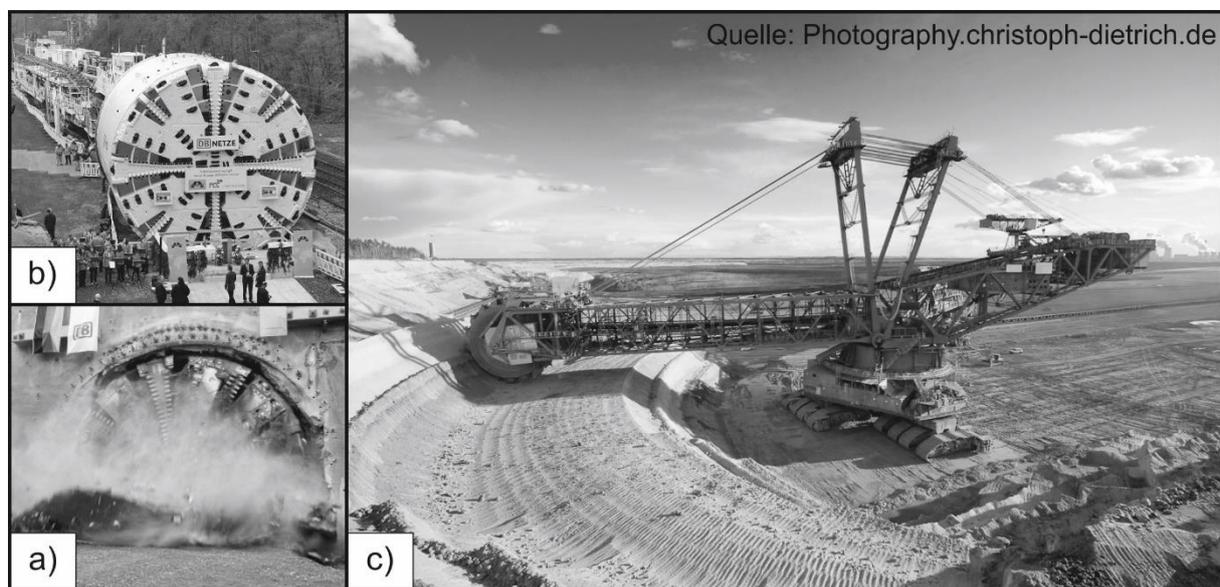
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**Abstract.** In future, tunneling and mining will play a major role due to the opening of new resources and living environment, as an irreversible consequence of the growing world population. To improve the efficiency of a tunneling or mining project, an increased durability of the used tools and the knowledge about the remaining service life constituent a key instrument in this context. It is the aim of this work to illustrate the different tribological systems which are present during a tunneling or mining process, depending on the soil or rather the material to be mined. In addition, different tool concepts, a description of the respectively tool-mineral interaction and common material concepts will be described, basically.

**Keywords:** Tunneling, Mining, hard face alloys, abrasive wear, metal matrix composites, hard phases

**Introduction:** Due to the increase in the world population from 7.28 mrd. people in 2015 to 9.6 mrd. people in 2050, more resources like energy, food, materials for consumer goods and more living space are required in the future [1]. To provide these demands, new technological solutions have to be developed, enabling a saving of limited resources by an improved efficiency of machines/plants or allowing the use of global available materials as substitution candidates. Independently of the respectively increase of the plants efficiency, there is no doubt that more resources are required, thus representing the continuing relevance of mining processes in the future. Beside more resources, more living space and the associated infrastructure is mandatory by an increase of the world population. Keeping in mind that megacities like Tokyo, Jakarta, Delhi or Shanghai are still overpopulated today, new living space and transport networks for example can only be developed by build upwards or into the ground. Especially, the height of skyscrapers is limited due to statically limitations, weather influences and geological conditions, thus underground urbanization becomes more attractive [2]. Although tunneling and mining are pursuing different objectives (tunneling= building of infrastructure; mining= extraction of resources), the used exploration techniques are almost the same. However, for the construction of a tunnel in heavily populated areas like cities, settlements of buildings and an associated damage as a result of a subsidence of the ground has to be avoided. For this purpose, more sensitive and saver techniques have to be used. In this context, tunneling machines, as shown in **Figure 1a** and **1b**, have gained an improved importance within the last decades. Tunneling machines are mobile factories, allowing the mining of rock and soil at the working face, the transport of the minded materials out of the tunnel and the buildup of the tunnel construction by tubbings, mortal and shotcrete at the same time. In the case of the extraction of resources, economic aspects and the accessibility to the deposit (depth) are mainly determining the mining conditions, thus blasting, drilling, rock milling and the use of excavators are commonly used. Beside the cost-intensive underground extraction of hard coal, soft coal is mainly extracted by opencast mining by a large-surface extraction using open cast mine excavators (see **Fig. 1c**), which can operate in a more economical way. This more economic mining process is the main reason for the still pronounced soft coal production in Europe. To ensure competitive lignite exploitation in comparison to low-wage countries, economic mining process as a result of minimized downtimes and increase extraction efficiency has to be ensured. The efficiency of a tunneling and mining process is mainly determined by the geological properties like hardness, bulk density as well as moisture content for example and the associated wear of the used tools [3]. However, strong wear is leading to a blunting of the tools which is counteracting a high extraction rate due to a deteriorated tool

performance [4]. In addition, if the wear limit of the respectively tools is reached, cost-expensive tool changes and repair measures are necessary. Especially in the case of a tunneling process, tool wear is a complex topic. If tunneling occurs by a closed shield technique, tool wear cannot be measured directly, thus there is no time resolved knowledge about the functionality and the remaining tool life. This means that an accurate prediction of the tool life time before a tunneling project must exist with regard to geological reports and experience which were gathered from previous projects. As a result of an insufficient knowledge about the geological conditions, an incorrect planning of tool change intervals may lead to additional maintenance intervals which causing a delay in construction and an increase of the overall project costs. This means that only a comprehensive understanding about the interaction between the tools and the geology allows the right selection of the mining and tunneling conditions (tool, mining method, machine parameters), ensuring an economic operation of a tunneling or mining process. This work focuses on the tribological system of surface mining and tunneling. It is the aim to describe the extraction mechanisms and the occurring interactions between the tool and the respectively ground, from a metallurgical point of view. Therefore, the used tool design and the wear resistant materials will be introduced, briefly.



**Figure 1:** a) Tunneling machine being ceremoniously started b) Tunnel breakthrough c) brown-coal excavator [g]

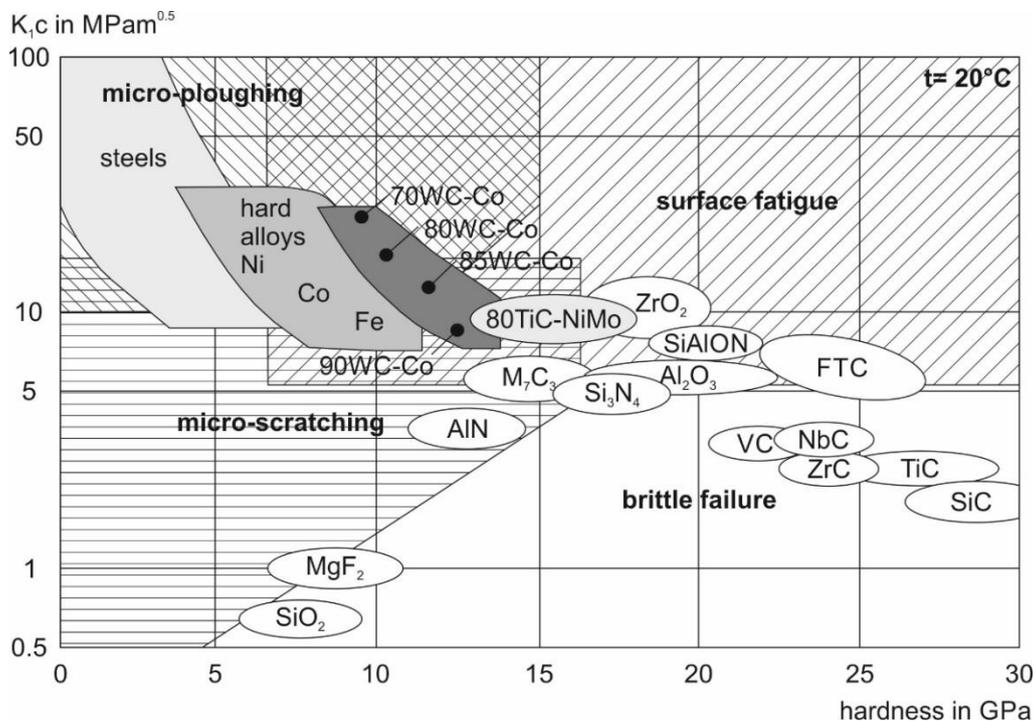
**Materials for Mining and mineral processing:** Soft coal is mainly extracted by open cast mining. Since 1930, wheel loaders are used for this application, allowing an economic mining of up to 240.000 t of coal per day [5, 6]. The coal mining takes place by a bucket-wheel, rotating in front of a cantilever arm, which is penetrating and parallel moved to the material to be mined. Due to the movement, the rotating buckets are collecting the coal and are feeding an adjacent conveyor belt. By a further bench conveyor, the coal or the overburden is transported with regard to the intended purpose to a power plant, a coal storage or to a stacker machine.

During mining, tribo-mechanical interactions between the extracted mineral and the bucket material occur, effecting strong wear by abrasion. Thereby, hard mineral particles (abrasives) are indenting and moved relative to the softer tool surface, effecting material removal, deformation or/and strain hardening. Counteracting these negative interactions, mining tools (teeth and shovel edges) are commonly protected by applying a wear resistant coating on a low alloyed steel substrate. Thereby, the function of the steel substrate can be found in the absorption and transmission of forces to adjacent component parts. In contrast, the deposited wear resistant coating is protecting the steel substrate against external influences. To achieve a high wear resistant and an associated high tool life, deposited materials have to counteract indentation and material removal by the

abrasives as well as catastrophic failure due to a brittle material behavior in the case of an impact load. To fulfill these requirements, wear resistant materials should feature a high hardness and a sufficient toughness, simultaneously. Due to the high hardness of the minerals 550 (apatite) – 1100 (quartz) HV0.05, pure metals do not possess a sufficient protection behavior and will be worn by the abrasives. In the case present, the microstructure of the wear resistant materials have to feature high volume fraction of particles like carbides, borides or nitrides having a higher hardness compared to the abrasives. Conventionally, the requested microstructure can be achieved by hard alloys, highly alloyed in carbon and/or boron, forming carbides, borides and carboborides with the hard phase forming elements like Cr, Ni, Fe, Mo, W, and V for example. For mining applications, Ni- and Fe-base hard alloys are of high importance. Their microstructure consists of a tough metallic matrix and primarily (blocky shape) and eutectically (network like shape) hard phases. In **table 1**, basically hard facing alloying concepts of the three main hard alloying systems for mining applications is tabled.

**Table 1:** Overview of the essential alloying elements in Fe-, Ni- and Co-based hard alloys [7]

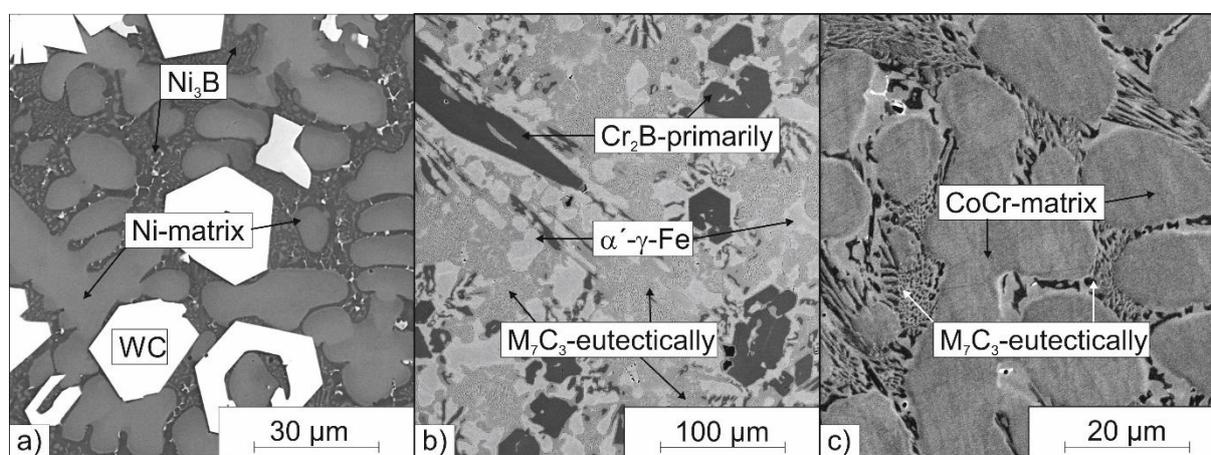
Matrix element	Alloying concept	Metalloid	Hard phase forming element	Type of hard phase
Fe	FeCrC FeCrVC FeCrXC	C, B, N	Cr, Mo, W, Ti, V,	$M_{23}C_6$ , $M_6C$ , $M_7C_3$ , $M_3C$ , $M_2C$ , $MC$ $M_{23}(C,B)_6$ , $M_2B$ , $M_3(C,B)$ , $M_3B_2$
Ni	NiBSi NiCrBSi NiCrBSiX	C, B	Cr, Mo, W	$M_3B$ , $M_2B$ , $MB_2$ , $M_{23}B_6$ , $Ni_3(Al,Ti)$
Co	CoCrC CoCrWC CoCrMoC	C	Cr, W, Mo	$M_7C_3$ , $MC$ , $M_2C$ , $M_6C$ , $M_{23}C_6$ $MB_2$ , $MB$ , $Co_3(W,Mo)$



**Figure 2:** Erosion wear mechanisms of wear resistant materials (toughness  $K_{1c}$ , hardness HV map), with regard to the work of [7-10]

As shown in **table 1**, the metalloids carbon and boron can form different hard phases with hard phase forming elements like Cr, M and V and with the matrix element Ni ( $Ni_3B$ ) and Fe ( $Fe_2B$ ,  $Fe_3C$ ) itself. Thereby, the properties like hardness and fracture toughness of the respectively hard

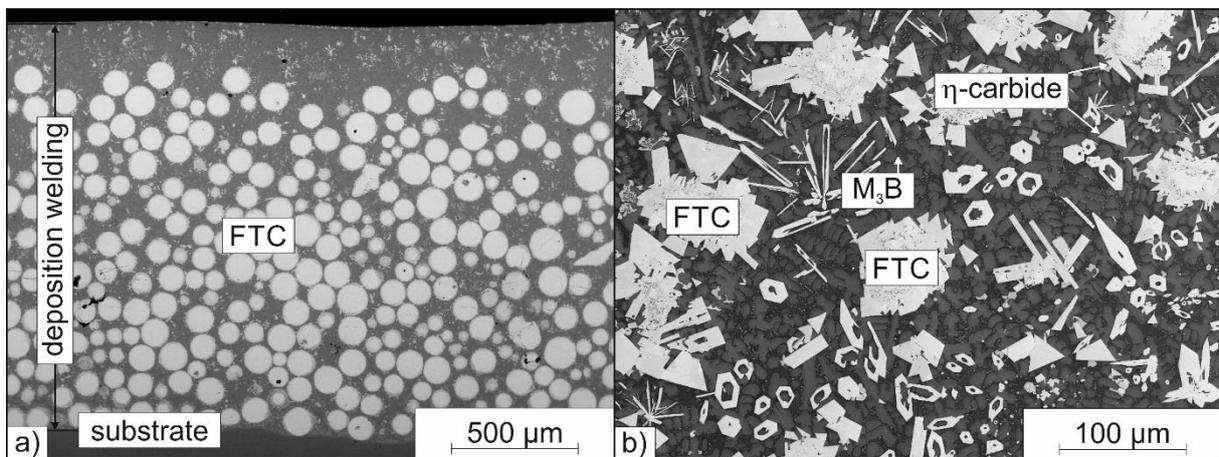
phases depends on the bonding mechanisms which can be more metallic (soft) or strong covalent (hard) (see **figure 2**). In the case of the mainly metallic-covalent bonded hard phases in **table 1**, covalent bonding and the associated hardness increases with a decrease in the ratio of the metal/metalloid-ratio (M/X-ratio), whereby the metal are the refractory elements in the fourth (Ti, Zr, Hf), fifth (N, Nb, Ta) and sixth group (Cr, Mo, W) of the periodic table and the metalloids are carbon, boron and nitrogen. Basically, Cr-rich hard phase of type  $M_7C_3$  and Ni-boride of type  $M_3B$  are of high interest for the here regarded hard alloys, characterizing the basic systems Fe-Cr-C and Ni-B-Si (Si improves weldability). Both hard phases possesses a higher hardness ( $M_7C_3$ ~ 1500 to 2200 Hv0.05,  $Ni_3B$ ~ 1100 to 1400 HV0.05) than the hardest mineral quartz (~1100 HV0.05) and thus effecting a sufficient resistance against abrasion. By changing the hard phase volume fraction (alloying concept, mainly amount of metalloids), the type (alloying concept, changing hard phase forming elements) as well as the morphology (processing route, solidification characteristic) of the hard phases, the respectively hard alloys can be adapted to the present tribological system. In **figure 3**, the microstructure of conventionally used hard alloys for wear protection application is shown in deposition welded condition.



**Figure 2:** Microstructure of hard alloys: a) NiCrBSi+WC, b) FeCrCB, c) CoCrWC

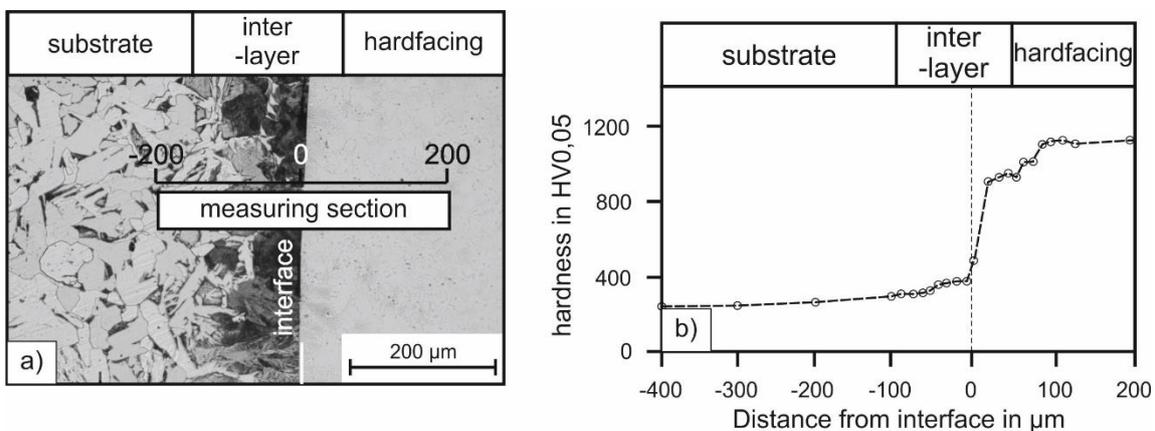
In the case of the presence of coarse abrasives and a high load, small hard phases offer an insufficient protection against abrasion and will be worn out together with the soft metallic matrix. A high wear resistance is only obtainable, if the hard particles are adapted to the acting abrasives with respect to their volume fraction, size and hardness. However, thermodynamic restrictions with regard to the hard phase volume fraction and the solidification path counteracting these demands. In this context, Metal Matrix Composites (MMC), produced by sintering, thermal spraying or deposition welding, should be mentioned as a solution. The microstructure of MMC consists of a metallic matrix with additionally inserted ceramic particles, having a size of several  $\mu\text{m}$  to mm. In **figure 4**, the characteristic microstructure of a Ni-based MMC, processed by build-up welding, is shown. Thereby, coarse carbides (brightly displayed) are distributed homogeneously in the darker displayed Ni-base metal matrix. Typical hard particles are spherical tungsten monocarbides, blocky fused tungsten carbide and Cr-carbide of type  $M_3C_2$ . Selection of hard particle depends on the present tribological system. In the case of sliding wear, tungsten monocarbides or cheaper Cr-rich  $M_3C_2$  carbides are often used due to great costs to property ratio. A special position can be attributed to fused tungsten carbide (FTC). The microstructure of these hard particles consists of a eutectic network of WC and  $W_2C$  needles, possessing advantages if impact load is present. In the case of crack formation, further propagation occurs across the respectively needle interfaces, thus extend the crack length and the associated energy requirements for crack grow. This increased energy requirements results in a higher fracture toughness of about 6 to 7  $\text{MPam}^{0.5}$ , which is extremely high for ceramic bonded materials (see also **figure 2**). Beside the great material properties of tungsten carbides, the availability of raw materials and the metastable material behavior are disadvantages. Metastable behavior of fused tungsten carbide is shown in **Fig 4b**. Thereby, strong reaction of the tungsten carbide with the Ni-base metal matrix is shown, promoting

the formation of more stable but also more brittle  $\eta$ - and  $\kappa$ -carbide-film at the carbide-matrix interface. The formation of this interlayer is promoting a metallurgical embedding of the carbides in to the metal matrix and is soften the abruptly change in properties at the carbide-metal interfaces. Due to the higher M/C-ratio of the  $\eta$ - ( $M_6C=6$ ) and  $\kappa$ -carbides ( $M_{12}C= 12$ ) in contrast to fused tungsten carbides ( $MC/M_2C\sim 1-2$ ) or tungsten monocarbide ( $MC=1$ ), overall volume fraction of the carbides is increased, leading to a strong embrittlement of the MMC. In addition, hardness of the new formed  $\eta$ - and  $\kappa$ -carbides is lower compared to the tungsten carbides. Opportunities to counteract  $\eta$ - and  $\kappa$ -carbides formation can be found in the processing the MMC at lower temperatures to avoid strong diffusion and to use a metal base, having a lower tendency to form these carbides, for examples.



**Figure 4:** Microstructure of Metal Matrix Composites; a) NiCrBSi+30 mass% FTC processed by deposition welding, b) higher magnification of the FTC carbides in Ni-base matrix

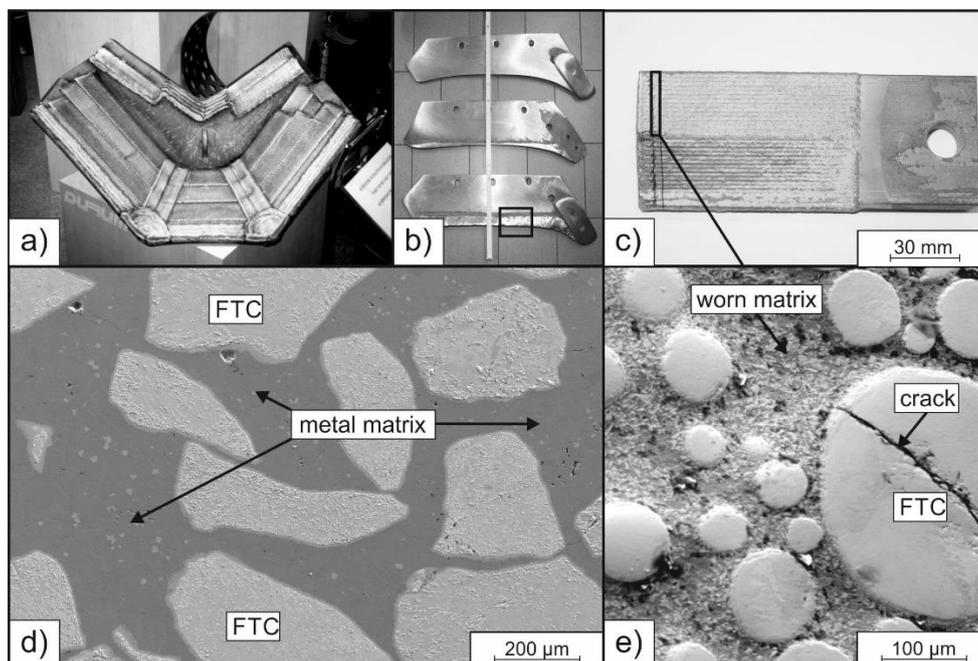
In this context, Ni-base alloys of the systems NiBSi or NiCrBSi should be mentioned, which can be processed at lower temperatures in comparison to Fe-base materials. Due to the lower processing temperatures, less  $\eta$ -carbide formation takes place, thus materials having a high hardness and simultaneously high fracture toughness can be manufactured. Due to this less carbide dissolution, Ni-based MMC are preferably used for mining application, although Fe-base materials are cheaper and featuring the possibility of a martensitic hardening.



**Figure 5:** a) Interface of a hardfacing on a steel substrate; dilution as a result of an energy input during welding, b) hardness track across the substrate-weldment interface

Counteracting the aforementioned disadvantages, some works are dealing with the development of new hard particles [11-12]. In this context, oxide ceramics like alumina, zirconia or covalent bonded

ceramics like SiC, cBN and diamonds are of high interest, which can be attributed to their hardness, fracture toughness or both. On the one hand, oxides possess a worse wettability by liquid melts, thus only mechanical bonding is present. Otherwise, SiC and diamond for example will dissolve strongly in the Fe-base matrix for example, forming more stable phases like Fe-rich silicide and graphite [13]. Metallization of the particles surfaces by thin layer techniques (CVD, PVD) might be a solution and is surely a worthwhile focus of future research. In this context, these layers can promote the embedding of the carbides, while acting as interlayer for oxides or as a barrier coating in for metastable ceramics. As stated above, MMC materials are placed on steel substrate by deposition welding or thermal spraying to protect technical surfaces against abrasion, erosion or corrosion. Typical buildup welding techniques are gas welding, shielded gas welding and plasma powder buildup and laser welding which differ in the type of the heat source (flame, plasma, laser), the respectively filler materials (wire, rod, powder) and the deposition rate (1 to 25 kg) [14]. During build-up welding, heat input leads to a melting of the filler material as well as of the substrate material. As a consequence, the melt pools are blended which is well known as dilution (**Fig. 5a**). The dilution of the substrate material (mostly construction steel) and the highly alloyed hard facing alloy is forming an interlayer. Thereby, the chemical composition of this interlayer can be described as a gradient between the chemical compositions of the mixed materials, thus the change of the materials properties is softened at the interface. On this account, delamination of coating due to thermal stresses, formed at material transition, can be avoided. The change in the materials properties by the gradient transition from the substrate material to the hard facing alloy can be described by hardness profiles across the interfaces. In **Fig. 5b**, hardness profile of a build-up weldment is shown. A hardness profile is characterized by an increase in hardness coming from the substrate material (left side) to the coating (right side). Thereby, rise in hardness can be explained by the heat affected zone, formed in the substrate material, and the dilution effect due to the mixing of the fully melted hard facing alloy and the partially melted substrate material.

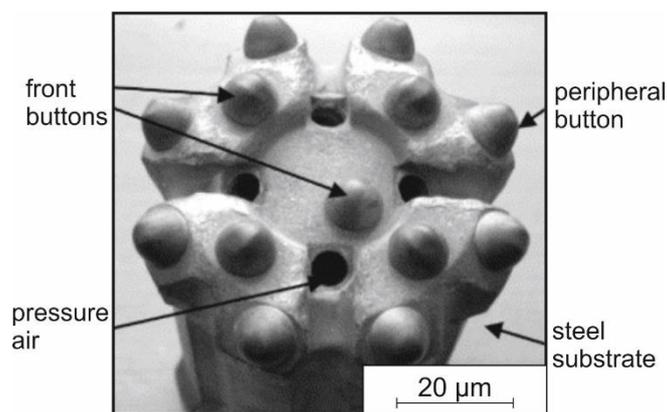


**Figure 6:** Tools for mining and mineral processing locally protected by deposition welding, a) edge of an excavator bucket, protected by a hardfacing, b) cultivator c) mixer blade for minerals, d) microstructure of the a MMC applied on the cultivator (Fig 5b)) by InduClad, e) worn surface of MMC (Fe-base+sFTC) applied on the mixer blade in Fig 5c by laser welding [14, 15]

## Abrasion in Tunneling

The basically selection of a tunneling method has to be determined with regard to geological (building ground and ground properties) as well as technical aspects (transportation and recycling of overburden, tunnel construction). Tunneling can be achieved by drilling and blasting, by tunneling machines and by sawing techniques using cutting blades for example. Subsequently, only drilling and tunneling by using tunneling machines will be described in the following, briefly.

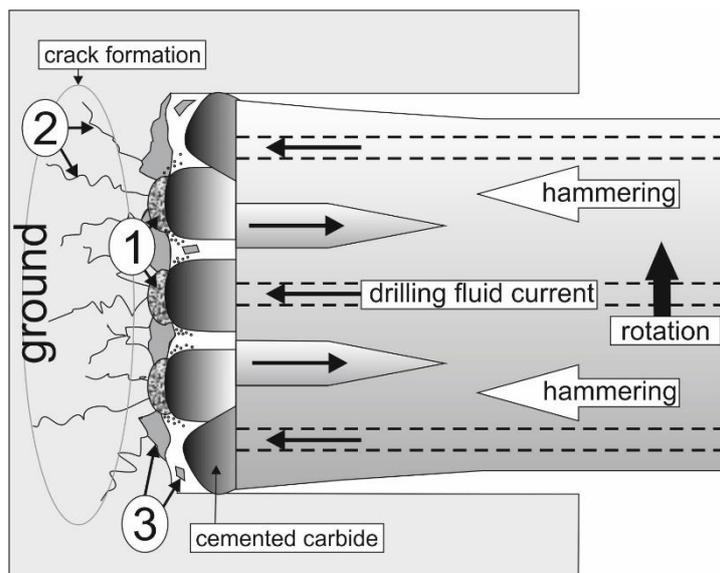
**Drilling:** In the case of drilling, a hydraulic hammer drill is conventionally used. Thereby, a drill bit is placed in the front of a boring bar, which is penetrating the rock with a rotation speed up to 300 rounds/min, a stroke frequency of 40 to 60 hearts and a maximum torque of 500 to 600 Nm. The drill bit consist mainly of a of hot work steel substrate (X38CrMoV5-1, X40CrMoV5-1) which is reinforced by hard metal, cermets or polycrystalline diamond pins (see **Fig. 7**) [16]. Studs made of cemented carbides are typically inserted by brazing or by mechanical clamping if lower loads are present during operation. In addition, channels for flushing purposes are present in the substrate material, supporting material removal. The interaction between the drill bit and the ground during drilling is mapped in **Figure 8**. Thereby, the studs are frequently impacting on the ground which leads to crack formation and crack propagation. After several impacts, a close crack network is formed, promoting fragmentation of the material to be mined. Due to the additional rotating of the driller bit on the working face, the before produced fragments are scratched out and removed sideways by the flush. In the case of a softer and tougher rock the fragmentation is less efficient, thus mineral removal due to the rotating of the hard metal pins is more pronounced.



**Figure 7:** A rock drill bit equipped with 13 CC buttons [17]

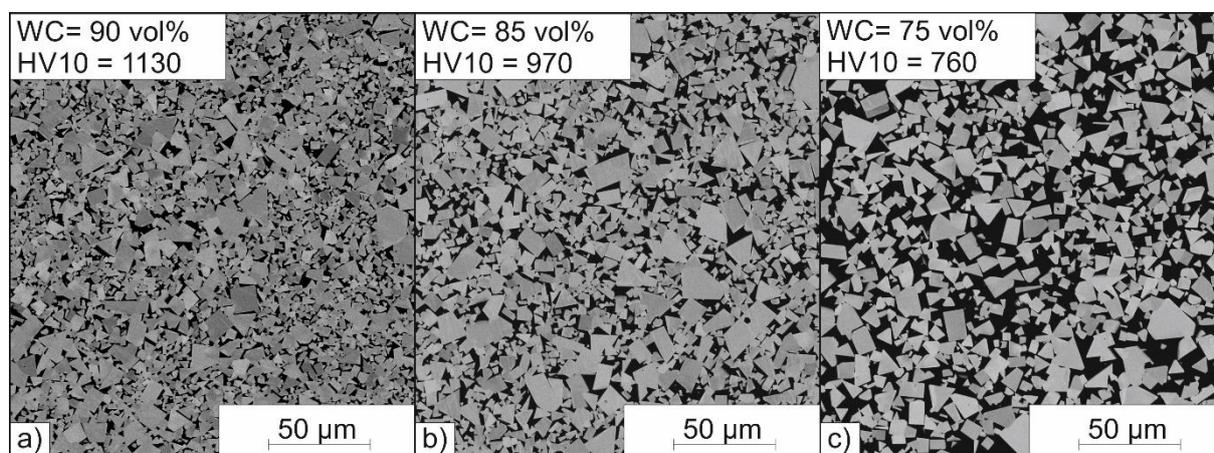
The drilling tool has to be adapted to the geology and the machine parameters with respect to the amount of inserted studs, grade and shape of the used studs (round, sharp) and the geometry of the substrate body (flush pipes, cutting geometry, diameter). Especially, type of cemented carbide is dominating the efficiency of the drilling process. In **Fig. 9**, different microstructures of conventionally used cemented carbide grades for mining applications are depicted. The microstructure consist of blocky tungsten carbide particles (bright displayed) having a size of 2 (fine grain grade) to >6 μm (coarse grain grade) μm, which are embedded into a darker Co-base binder matrix. Thereby, volume fraction of the tungsten carbide is in range of 75 to 90 vol.%. The property of cemented carbide is strongly influenced by the volume fraction of the Co-binder and the size of the tungsten carbide particles. In the case of fine to coarse grain cemented carbide grades, the hardness increase with increase in WC-content and in the direction of smaller WC-particles. At the same time, fracture toughness is decreased in the direction of smaller WC-particles. Especially, high hardness and high temperature stability for turning and drilling of metals is of high interest, thus fine grained and PVD/CVD-coated cemented carbides are commonly used. Counteracting grain growth and oxidation during the operation at elevated temperatures or to improve the chemical resistance, additionally hard particles like Mo<sub>2</sub>C, TiC, TaC, Cr<sub>3</sub>C<sub>2</sub>, NbC and VC are regarded. In addition, novel developments in the field of cemented carbide are dealing with ultrafine grained WC. Contrary to the before mentioned relationship between WC-size and

properties, toughness as well as hardness increases at the same time in the case of ultrafine cemented carbide grades [18, 19].



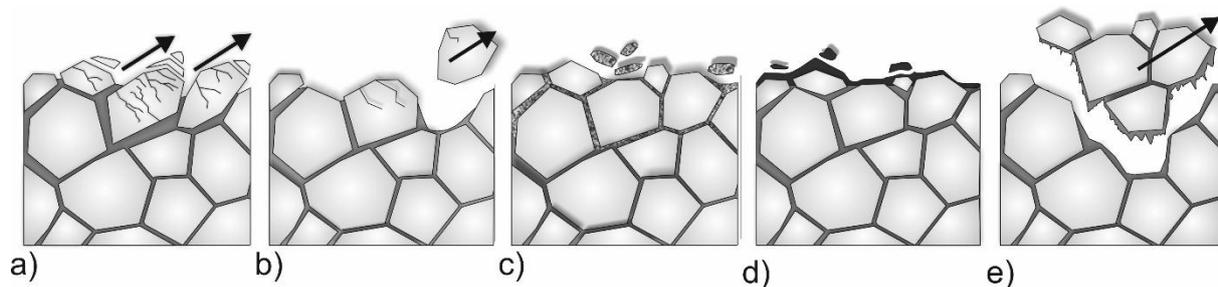
**Figure 8:** Hard rock degradation process by drilling with regard to the work of Thuro [20]

During mining high impact load due to the rapid excavation process, changes in geology and boulders are present. In addition tribo-mechanical load is superposed by thermal fatigue and thermoshock due to high peak-temperatures during impact of about 1000°C, followed by an abrupt cooling. Therefore, cemented carbide for mining applications possesses a coarser WC-grain size and a binder-content of 5 to 30 vol.% compared to that grades used for metal processing, providing a high toughness and a sufficient hardness, simultaneously. For drilling application, cemented carbide grades have a medium to large WC-size (2-5 µm) and a Co-Content of about 5 mass%. Especially, bigger grains are useful for this application because of the better thermal conductivity and a lower thermal expansion in contrast to finer WC-sizes. For tunneling tools, like scraper knives, chisels and reamers as discussed later, cemented carbides which are higher in Co-content of about 10 to 15 mass% are typically used. The properties vary in a hardness range from 500 to 1300 HV0.05 and a range in fracture toughness of 9 to 22 MPa<sup>0.5</sup>, depending on binder content and WC-size (typically 3-10 µm). Compared to cemented carbides for the metals processing, new development of hard metals for mining applications are dealing with an opposed motivation by increasing the WC-grain size and to strengthen the binder matrix by nano-grains for example [21].



**Figure 9:** Microstructure of different grades of cemented carbides used for mining applications; a) hard-grade: medium grain size and high WC-content, b) hard and tough grade: coarse grain size an medium WC-content and c) tough grade: biggest WC-grain size and lowest WC-content

With regard to the work of Betse et al., damage of hard metal during mining operation can be divided into five main mechanisms [17, 22]. 1) During drilling, high impact load can effect crack formation and propagation in WC-grains, leading to a fragmentation of the respectively grains. Thereby, fragments are losing their bonding to the Co-base binder matrix and will be worn out [Fig. 10a]. 2) Beside the material loss due to fragment formation, complete WC-grains can loss their bonding in the binder matrix and will be detached [Fig 10b]. 3) The third mechanism is characterized by an intensively removal by the binder matrix. Thereby, Co-binder matrix is removed by abrasives by scratching mechanisms. However, it is often supposed that the binder is strengthened during the drilling operation, thus the removal of fragments of the binder can be attributed to brittle behavior as described before for the WC-fragmentation mechanism. 4) Combining the before mentioned mechanisms, material removal by the break out of big fragments can occur, as shown in Fig. 10d. 5) At least high temperatures can cause strong oxidation of the WC particles, forming W-rich oxides. If this oxidation process is overlapped by an additional mechanical load, the formed oxide layers can be removed easily due to their brittle behavior, leading to the so called tribochemical wear mechanism. Till now, damage mechanisms were mainly described by a negative change in the material behavior, leading to crack formation and propagation, the formation of oxides and finally to a material removal. However, based on micro scratch experiments using a diamond indenter, we found a more ductile behavior of the investigated hard metal grad (WC-Co5%). As shown in Fig. 11, a plastic to brittle material behavior by scratching could be recognized. Thereby, small scratching loads lead to a more plastic deformation (micro-cutting) of the material, especially of the Co-base matrix. Whereby cracks are formed in the WC grains. If the load is increased, micro scratching and micro ploughing accompanied with a fragmentation of the WC grains is becoming more evident.

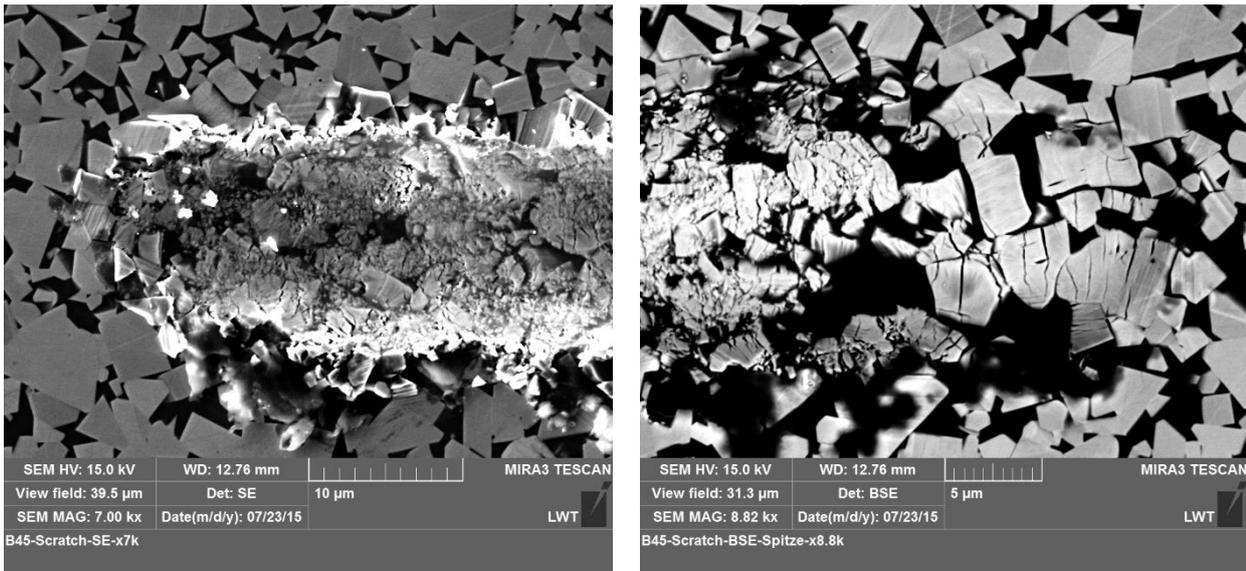


**Figure 10:** Damage mechanisms of cemented carbide during drilling and mining with regard to [17], a) WC-removal by fragmentation, b) outtake of WC-grains, c) removal of the Co-matrix, d) surface oxidation, e) fragmentation of WC-Co-conglomerates

Till now, only the wear of the cemented carbide studs was discussed. However, if drilling occurs in softer rock or soil, steel substrate is worn out by abrasion. The reason for the more pronounced interaction between the abrasives and the steel substrate can be traced back to stronger penetration of the cemented carbide studs into the material to be mined. As a result, abrasives are transported between the respectively hard metal studs and are indenting and scratching the substrate material, promoting wear by erosion. Subsequently, the substrate material is erode continuously by the abrasives and the cemented carbide studs are lose their integration to the substrate material. If the erosion is in an advanced way, there is an insufficient embedding behavior of the cemented carbide studs into the steel substrate, thus a complete ripping out of the studs from the steel substrate can occur. This means a loss in functionality of the tool. For this reason, materials featuring a high resistance against indentation (high hardness) and scratching (sufficient hard phase content) by abrasives should be used.

**Tunneling machines:** Tunneling machines can be roughly divided into tunnel boring machines (TBM), single/double shield machines (TVM) and combinational shield machines. TBM are commonly used for hard rock where no stabilization of the face is necessary. Thereby, the material to be mined possesses a high strength, thus no risk of falls of rock is present. Enabling tunnel driving, TBM is pressed against the before build tunnel wall by a gripper system and the further

tunnel building can be achieved by tubbings (ring segments made of concrete) placed by an erector in a circular arrangement. At least, the space which is formed between the tubbings and the rock surface is filled by mortar. If some risk due to the falls of rocks may occur during operation, TBM can be also equipped by a shielding system. Tunneling in soft ground and below the groundwater level is a more complex process, because the working face has to be secured against collapsing and the penetration of the tunneling machine by water has to be avoided. For this purpose, shield machines are used which are equipped with a supporting system using compressed air, earth pressure or liquid substances (bentonite). With respect to the ground, different tools are used, which are placed on the shield, as illustrated in **figure 12**. In the following, different tool concepts, the used materials and the wear mechanisms will be described for operating TBM in hard rock and soil.

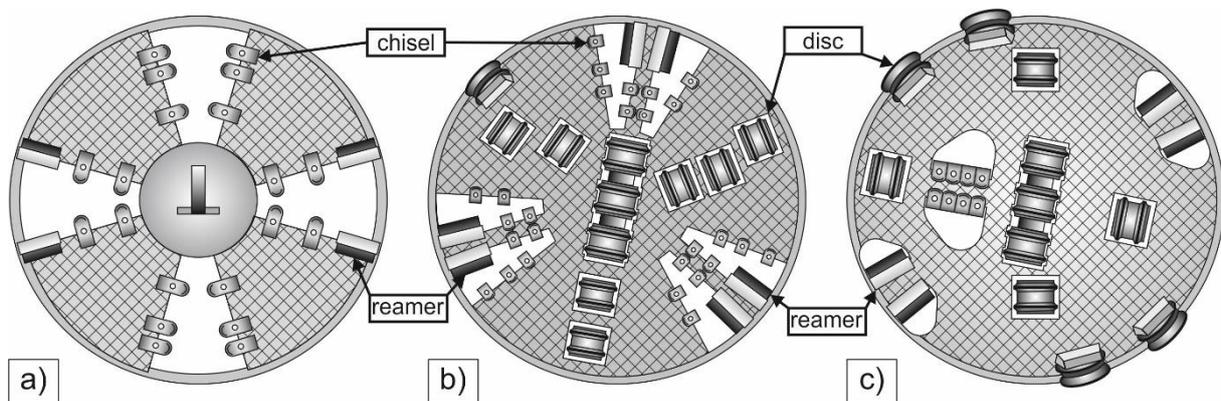


**Figure 11:** Microstructure of a cemented carbide, scratched by a diamond indenter; micro-cutting of the cemented carbide due to the ductile behavior of the Co-base binder matrix; micro-breaking inside of the respectively WC grains

**Tools for hard rock:** Independently of the type of the tunneling machine, similar tools are used with respect to the present geological conditions. Thereby, tunneling tools can be separated into the three basically types of 1) cutting disk, 2) scraper and 3) removers. For hard rock or the penetrating of concrete walls, cutting disks as shown in **Figure 13a** are used. These tools are rotary mounted on the shield at different distances from the center of the cutting wheel. The circumferential layout of the cutting discs has to be attributed to the requirements of minimizing the eccentric forces, the eccentric moments of the cutter head and to reduce the overlapping areas among the cutter discs between two adjacent discs [21]. Due to the high penetration of the machine towards the mineral to be mined, the cutting disks are introducing high hertzian stresses into the ground. Thereby, maximum stresses are formed below the mineral which interacts with the cutting disk. Furthermore, high quasi-hydrostatic stresses are leading to crack formation below and parallel to the rock surface. The following crack propagation occurs between two adjacent cutting disks and finally a chip is extracted due to an elastic spring back of the mineral (see **figure 14**). A detailed analysis of the stress distribution in cutting discs during tunneling can be gathered from the work of Rostami [22].

With regard to the work of Plinninger et al. six different damage mechanisms can be observed during hard rock tunneling by cutting disk, ranging from soft abrasion wear to a brittle fracture and mixed forms of both. From a material technology view on the wear of cutter disks, we distinguish between abrasion, wear due to a brittle material behavior and losses of tools functionality due to strong deformation of the cutter head (blunting of the cutting head). In the case of abrasion, the cutting disk made of martensitic hardenable steel is rotating over the material to be removed.

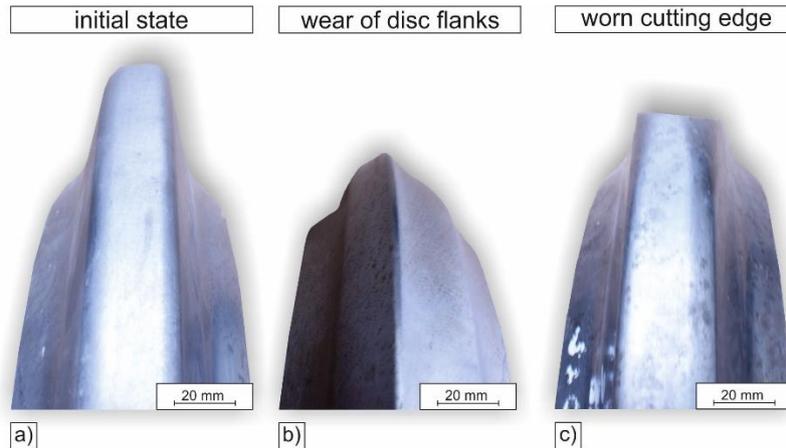
Thereby the abrasives can have a higher hardness than the steel of the cutting disk. In this case, abrasives are indenting into the steel matrix and promote an elastic-plastic deformation of the cutting disk steel, accompanied by strain hardening. In a next step, the abrasives are moved relative to the cutting disk steel surface, leading to abrasion wear by scratching and ploughing. Beside wear of the cutting tip in the case of hard rock, intensify wear at the flanks of the cutting disk may occur if soft rock, soil or clay-quartz like abrasion paste is present. This behavior can be attributed to a stronger penetration of the cutting disk into the softer materials, thus enhanced mineral removal at the flanks of the cutting disks takes place. Counteracting this located wear at the flanks of the cutting discs, CCS-cutter discs (constant cross section) were developed. By these type of cutting discs, the wear at the flanks leads to a self-sharpening effect, thus the cutting behavior is ensured during tunneling. Conventionally, so called V-shaped cutter discs varying in the disc diameter (330 to 508 mm) and disc edge angle are used [24]. Beside abrasion, primary wear of the cutting discs can cause catastrophic failure, if a brittle behavior of the material is present. Generally, this brittle material behavior can be traced back to high impact loads due to a bouncing of the cutting discs on the tunneling face as a result of a change in the geology or due to the presence of big boulders. To achieve a high life time of the tools, a high hardness, toughness and strength must be provided, simultaneously. Due to this account, hot work tool steels like X40CrVMo5-1 (1.2344) and X50CrVMo5-1 (1.2345) are commonly used. Hardness and toughness of both steels can be adjusted by a heat treatment, whereby quenching and tempering temperature has to be chosen with respect to the respectively alloying concept.



**Fig. 12:** Different types of tunneling machines; front view of the shield. Shield configuration is adapted to the machined ground; a) standard configuration, b) configuration for soil ground, c) configuration for hard rock.

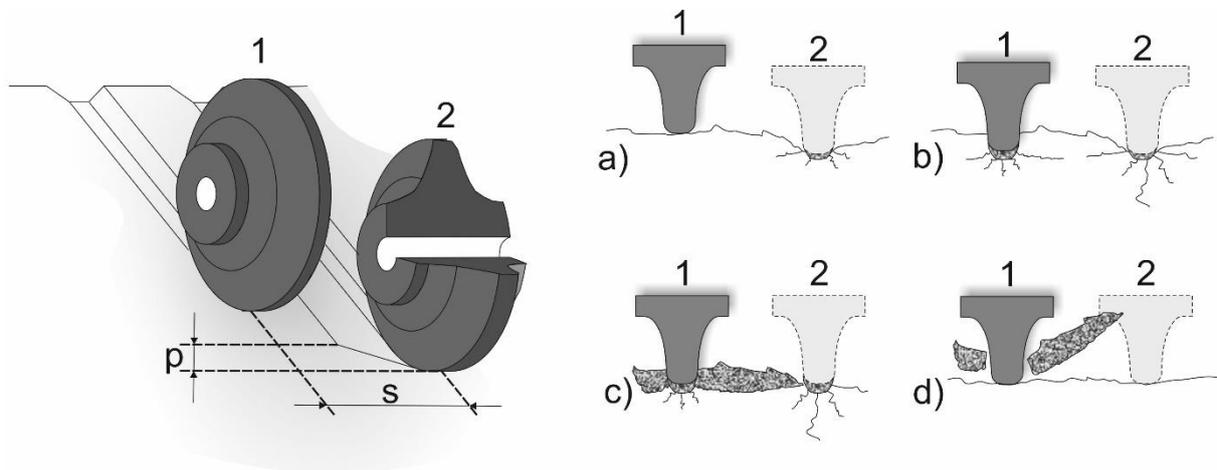
Steel X40CrMoV5-1 possesses high hardness directly after quenching, as a result of a full martensitic microstructure. A further tempering in a range of 100 to 200°C is accompanied with a decrease in hardness and an increase in toughness. However, strong decrease in toughness is present, if the steels are tempered at temperatures of about 300 and 500°C. On the one hand it is proposed that this embrittlement effect at 300°C can be traced back to the formation of cementite (blue brittleness). On the other hand, embrittlement at tempering temperatures of about 500°C (temper embrittlement) may occur due to the segregation of the element phosphor, antimony, tin and arsenic at grain boundaries, thus promoting a brittle intergranular crack propagation [25]. In this context, tempering temperature has to be chosen with respect to these regions where blue brittleness or tempering embrittlement can be avoided. However, hardness increases at a tempering temperature of about 450°C and drops down again exceeding a hardness maximum of about 55 HRC for the steel X40CrMoV5-1 at a temperature of 530°C. This increase in hardness can be traced back to carbide formation, leading to a microstructure consisting of an annealed martensite metal matrix with finely distributed secondary carbides. Based the aforementioned relationships, highest hardness (strength) and a simultaneously high material toughness can be achieved by quenching and tempering at a temperatures of 500 to 550°C. It should be mentioned here that the heat treatment of steels is more complicated than represented here. Thereby,

secondary hardness peak and regions of embrittlement are strongly influenced by the alloying concept and the quenching temperature, for example. For further details on the heat treatment of steels see [25].



**Figure 13:** Tunneling tools used for the excavation of hard rock, a) new disc, b) constant worn disc, c) unilateral wear due to secondary wear (clamping of the bearing)

With regard to the work of Frenzel et al. wear of the cutting discs can be divided into primary and secondary wear. Thereby, primary wear is characterized by a direct influence of the counter body (rock, boulders, soil) to the cutting discs itself. In contrast, secondary wear means that wear takes place on other parts of the discs. Often, the bearing of the cutting discs is blocked by rotation due to damaged bearings or muck adhesion [26]. In this case, cutting discs are clamped mechanically in the bearing which is associated with a unilateral wear. By the conditioning of the muck with foams water for example, secondary wear can be reduced, efficiently. Beside the bearings, secondary wear can as well takes place at the housing of the cutting discs if an insufficient wear protection is given. In this case, seal retainers, hubs and wedges are subjected to an intensified secondary wear.

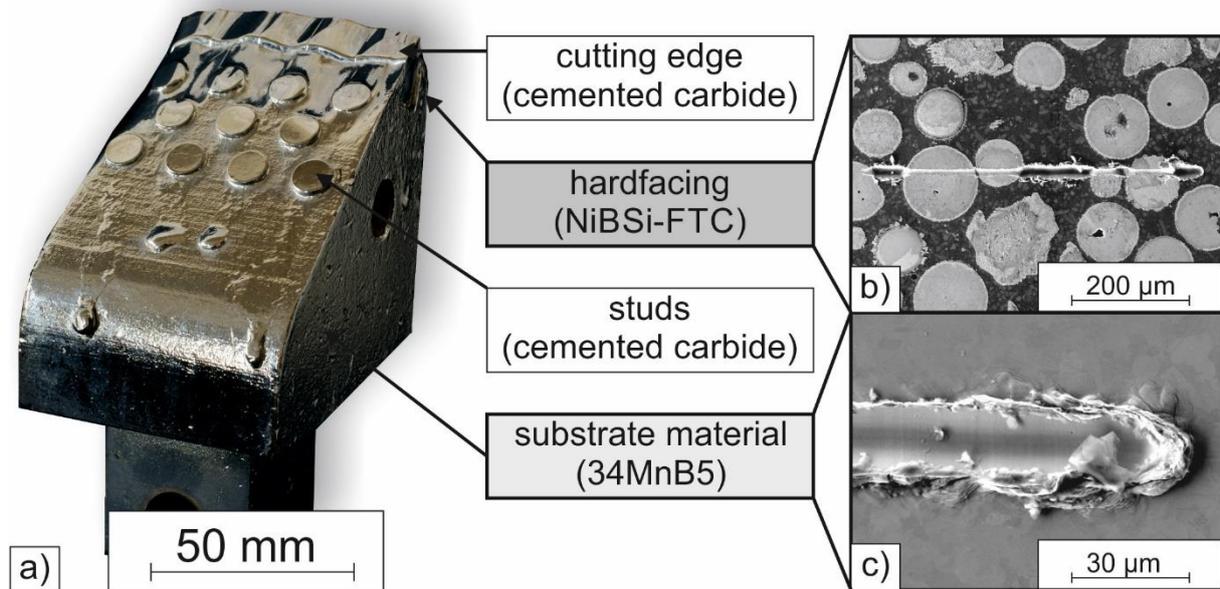


**Figure 14:** Scheme of the hard rock degradation process by using discs by with regard to the work of Thuro [20]

**Tools for soil:** Tunneling in soil is more complicated than tunneling in hard rock. This statement can be attributed to the complex tribological interaction between the ground and the tools. Therefore, the tools have to be chosen with regard to the ground. The standard tool configuration is shown in **Fig. 12a** and **12b**. Thereby, the tunneling shield is equipped with cutting discs, chisels and reamers.

Excavation in soft ground is commonly performed by the use of chisels and reamers. These tools consist of a steel substrate which possesses a cutting edge made of cemented carbide. During

processing, this cutting edge is penetrated into the soil and cause a material removal at the working face by scratching mechanisms. During excavation, the removed ground passes across the tool surface, leading to material removal of the tool by abrasion. Therefore, surfaces of the chisel is protected against abrasion by studs made of cemented carbides and a hardfacing next to the cutting edge. The protection mechanism of the cutting edge and the studs made of cemented carbide can be described with the help of **Fig. 15**. The cutting edge shows a wavelike material removal which can be explained by the staggered arrangement of the respectively chisels on the tunneling shield. With regard to our work, material removal of the cutting edge has to be discussed on the mechanisms micro-scratching and micro-braking of the cemented carbide, as discussed before (see **figure 11**). Thereby, nanoscratch experiments show a plastic (binder matrix) to brittle (tungsten carbides) material behavior. In the case of low loads, micro-scratching and micro-ploughing could be observed. If the load was increased, micro-braking of the respectively tungsten carbide particles becomes more evident. But we believe that micro-braking represent the dominating wear mechanism in the case of tunneling tools. Thereby, cracks are formed in the cemented carbide as a result of the dynamic interaction between the tool and the ground. During the further tunneling process, cracks are propagating in the cemented carbide, forming a crack network and thus leading to a brittle material removal. Thereby, growth rate of the cracks is influenced by the load (circumferential speed of the tools, penetration rate, etc.) and the geology (density of soil, water content, particle size distribution, etc.).

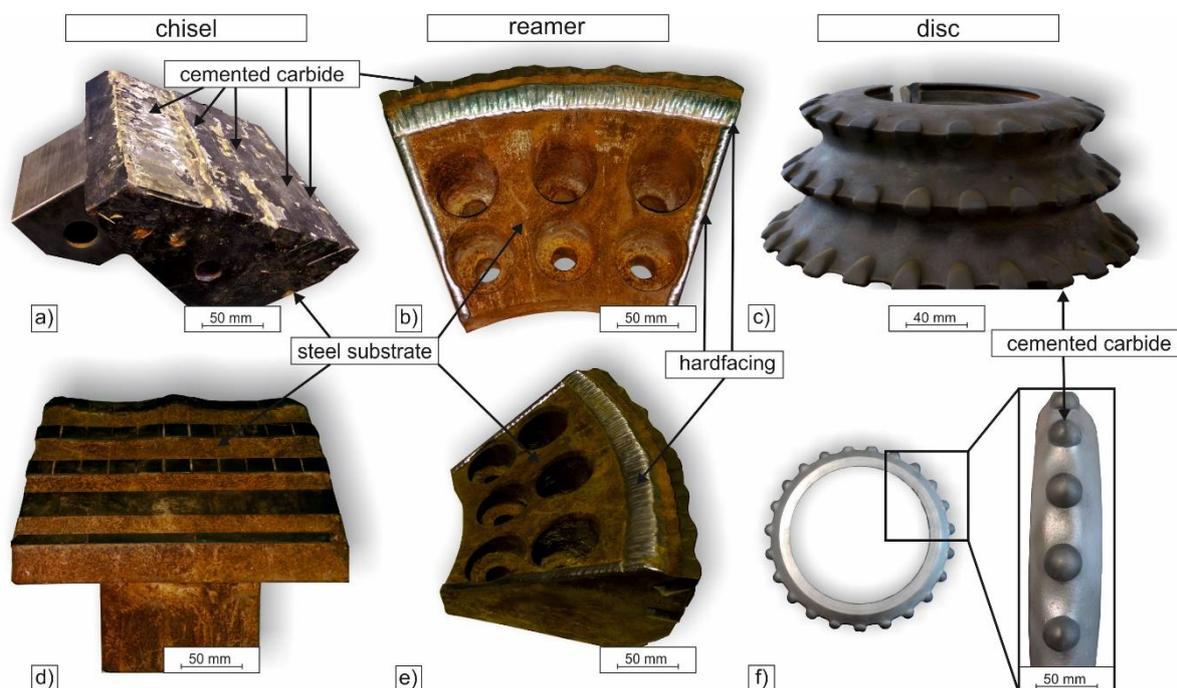


**Figure 15:** Build-up of a chisel which is locally protected against abrasion by studs and a cutting edge made of cemented carbide and a hardfacing; Interaction of the respectively materials against scratching are shown for the hardfacing in **figure 15b**, for the substrate material in **figure 15c** and for the cemented carbide in **figure 11**.

In addition, strong wear of the substrate material can be observed directly behind the cutting edge. Thereby, material removal is pronounced sidewise of the studs, indicating a washing out of the substrate material by abrasion. In the further course of the substrate removal by wear, studs and the cutting edge are exposed, which might result into a break out of the cemented carbide components due to a loss of embedding. After a removal of the cemented carbide, strong wear of the substrate material will take place, leading to total failure of the tool within a very short time. Due to the fact that the tunnel shield can rotate clockwise as well as counter clockwise, tools have to be protected against wear from both sides. Commonly, MMC-hardfacings (NiBSi/NiCrBSi-FTC) are applied on the substrate material by build-up welding techniques (see **figure 15**). The microstructure and the wear mechanisms of these hardfacings were explained before, wherefore at

this point a repeated description shouldn't take place. However, scratch across an MMC (NiBSi-FTC) hardfacing is shown in **figure 15b**. Thereby, scratch width was decreased strongly if the indenter was coming from the metal matrix and strikes on a carbide.

In addition, failure of the chisels or reamers can also occur due to a strong plastic deformation of the respectively tools. These strong plastic deformations are the result of high impact load, which might occur if big boulders, metallic parts like T-beams or retaining walls are present. These massive structures in the ground cannot be crushed and therefore removed by the cutting tools. As a consequence, the tools are hitting periodically on the aforementioned structures which are remaining in front of the tunneling shield. To avoid undesirable interactions between the chisels and the reamers with boulders or retaining walls, tunneling shields are as well equipped with cutting discs. It is the tasks of the cutting discs to crush the boulders and therefore to counteract a damaging of the chisels and reamers by the boulders due to an impact load. In **figure 16**, different tools which are used for tunneling in soil (chisels, reamers, discs) and hard rock (discs, reamers) are displayed in new and worn condition.



**Figure 16:** TVM-tools; a) chisel (initial state), b) worn reamer, placed on the exterior sections of a tunneling shield, c) cutting disc with cemented carbide studs, d) worn chisel, e) worn reamer, worn discs with cemented carbide studs

**Conclusion and outlook of current research:** In this paper the tribological systems of surface mining and tunneling processes were discussed with regard to the commonly used tool concepts, the different materials and the acting wear mechanisms. Thereby, hardfacing alloys, cemented carbides and metal matrix composites were introduced in this context. Based on the microstructural scale, the interaction between the tool microstructure and the present geology and the resulting wear mechanism was introduced, briefly.

Commonly, tools for mining and tunneling applications are made of a weldable construction steel substrate which is locally protected against abrasion by hardfacings or inserted cemented carbide studs or cutting plates. In both cases, high amount of the critical element tungsten is required for the materials production. Counteracting a further shortage of suitable wear resistant materials, new materials as a substitution candidate have to be found. In this context, hard particles for the production of MMC materials and hard particles for the production of new cemented carbides or cermet are required.

The inaccessibility of the tunneling tools counteracts a mapping of the wear condition during operation. On this account, the remaining service life cannot be determined. As a result, maintenance times for a tool change are designed in such a way that a complete breakdown of the tunneling tools will not take place. If the geology is changed unpredictable, wear limit can be achieved earlier or later. In both cases, an efficient use of the tool is not reached. Therefore, high technological as well as scientific interests exist to evaluate the tool life based on a realistic wear prediction before a tunneling project. Nowadays, wear prediction of the tunneling tools base on experiences gathered from previous tunneling projects or were evaluated in laboratory scale by determining the abrasivity of the present ground. However, all laboratory tests (LCPC, Cerchar) do not map the real tribological system and the existing experiences are just giving a rough idea about the wear behavior. Summing up, to counteract the aforementioned disadvantages, new realistic wear test and data logging systems which allow evaluating the remaining service life have to be developed.

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