Rock Mass Scale Effects on Tool Wear in Hardrock Tunnelling – practically significant and scientifically neglected?

Gebirgsmaßstäbliche Einflussfaktoren auf den Werkzeugverschleiß im Felstunnelbau – baupraktisch relevant und wissenschaftlich vernachlässigt?

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Abstract
The investigation of rock abrasiveness and the assessment of tool wear represent important tasks in the course of any recent tunnel project. This especially applies to mechanized tunneling (TBM, shield, roadheader), where wear plays an important role for the working cycle and consequently for construction time and costs. Starting from a normative "vacuum", increasing knowledge and standardization work has led to an increasing application of laboratory scale tests, such as the CERCHAR method (CAI) or the Rock Abrasiveness Index (RAI). However, it must be taken into account, that larger scale - rock mass - factors, such as discontinuities, rock type distribution and stress conditions do additionally influence tool wear. Indeed, the negative consequences of adverse rock mass conditions may be of a much higher degree, than an increase in intact rock abrasiveness. The proposed paper is intended to give an overview of the current state of knowledge and to resume in practical suggestions for investigation, description and contractual aspects of such effects in rock tunneling.

Zusammenfassung
Die Untersuchung der Abrasivität des anstehenden Gebirges und die Bewertung des zu erwartenden Werkzeugverschleißes stellen heute im Vorfeld jeglicher Tunnelbaumaßnahme wichtige Aufgaben dar. Dies gilt insbesondere für maschinelle Vortriebsverfahren (TBM / SM / TSM), bei denen die Auswirkungen von Verschleiß eine besondere Relevanz für Arbeitszyklus, Bauzeit und -kosten besitzen. Ausgehend von einem normativen „Vakuum“ in diesem Bereich haben mit zunehmendem Erkenntniszuwachs und dem Einsetzen entsprechender Gremienarbeit auf Laboruntersuchungen basierende Kennwerte, wie der CERCHAR-Abrasivitätsindex (CAI) oder der Abrasivitätsindex RAI zunehmenden Eingang in entsprechende Regelwerke gefunden. Dennoch ist festzustellen, dass über den Maßstab des intakten Gesteins hinaus auch größermaßstäbliche Faktoren, wie z.B. Trennflächengefüge, Gebirgsaufbau oder Spannungszustand signifikanten Einfluss auf den Werkzeugverschleiß nehmen. Die Folgen dahingehend widriger Verhältnisse können sogar um ein Vielfaches gravierender sein, als eine Erhöhung der Abrasivität des intakten Gesteins alleine. Der vorgeschlagene Beitrag stellt praxisorientiert den derzeitigen Stand der Erkenntnisse dar und gibt Anregungen für die Erkundung, Bewertung und bauvertragliche Berücksichtigung derartiger Situationen im Felstunnelbau.

1. Tool Wear – Contractual Risk

Disregarding the chosen construction method – either mechanical or conventional tunneling -, the wear of rock excavating tools has always been a highly relevant factor, influencing construction performance and expenses. However, wear phenomena do not only directly affect related wage and material costs for the exchange of worn tools, but are additionally able to affect in many ways the whole working cycle, including standstills and overall machine availability.

For tunnel works, which are based on a construction contract between a client (for instance public authority) and a contractor (usually construction company) it is therefore important to clearly define relevant geological-geotechnical causes for tool wear and to fairly distribute the risks connected with this topic. For instance, tunneling contracts in Germany and Austria usually locate the ground related causes for wear in the risk sphere of the client, while the choice of an appropriate construction method, choice of excavation equipment and associated performance and wear estimates are located within in the risk sphere of the contractor.

Starting from a normative "vacuum" in this field of engineering geology, laboratory procedures, such as the CERCHAR test (see Figure 1.1) or mineralogical and geotechnical indices, such as the Equivalent Quartz Content or the Rock Abrasivity Index (RAI) have in the meanwhile seen an increasing use and are undergoing further standardization. With the introduction of the Supplementary Volume for the national German Standard for Construction Works, VOB, in 2015, the CERCHAR test and the so determined CERCHAR Abrasivity Index, CAI have been referred to as standard method for the assessment of hardrock abrasivity, also in the field of tunneling (DIN 18312 standard).

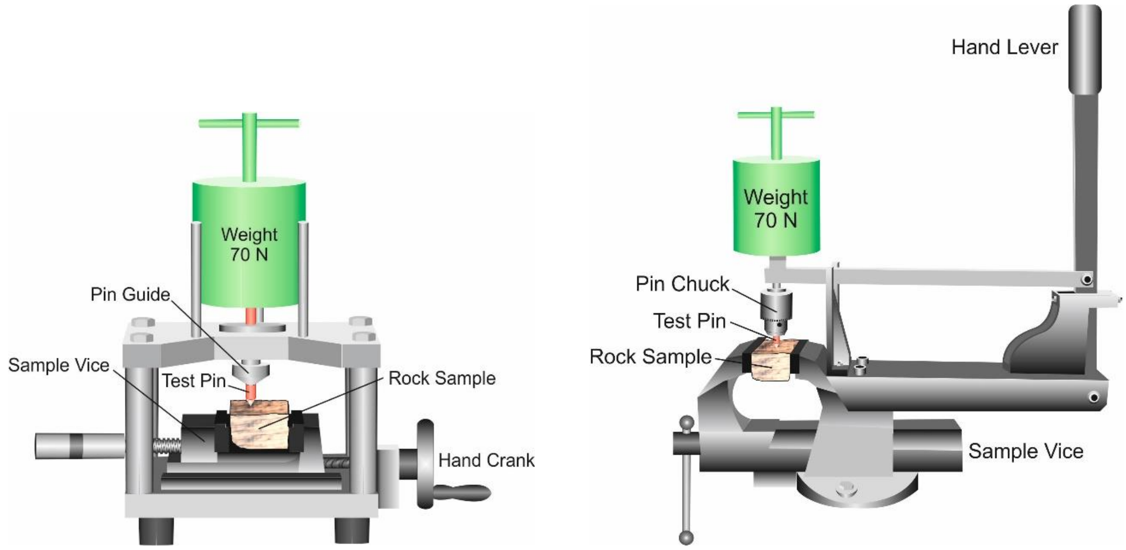

Fig. 1.1: Typical testing layouts for the CERCHAR test.

Although the investigation of rock abrasivity in a laboratory scale is an important and positive step towards an optimized wear prediction and a fair building contract, it has to be concluded, that the final aim cannot be reached by those methods alone, as relevant influencing factors in the rock mass scale must remain neglected.

2. Defining „Tool Wear“ and „Abrasivity“

Based on the now retracted (because not updated) German Standard DIN 50320, the term **"tool wear"** can be defined as progressive loss of material from the surface of a tool, caused by mechanical contact and relative movement between tool and rock mass.

This wear can be caused by various processes which usually do represent interactions between more continuous and abrading modes (→ "abrasive wear") and suddenly occurring events with more or less catastrophic failure of tool parts (→ "tool failure", see Fig. 2.1).

Fig. 2.1: Worn point attack picks of a roadheader, whose replacement was both caused by continuous abrasion, as well as partial failure of tool components (Photo: Plinninger).

However, a definition in the form, that “tool wear” does only include continuous abrasive processes cannot be derived from the relevant standards and literature. On the contrary, the gross wear parameters commonly used in civil engineering and tunneling, such as the "drill bit lifetime" according to German Standard DIN 20301 [drilled meters / bit], the "specific tool wear" [picks / m^3 (solid)] or the "cutter life" [m^3 (solid) / disc] do indeed strongly suggest that an appropriate “tool wear” definition must be able to describe the full life time cycle of a tool between insert of the new tool and replacement of the worn tool - regardless of the type of wear that took place.

While the tool wear has to be seen as one result of the tribological contact between the tool and the rock mass, the term **"abrasivity"** is intended to describe the geogenic causes for tool wear. According to Plinninger (2002) it might be defined as the ability of a rock mass, rock or mineral to cause wear on a rock excavating tool (Fig. 2.2).

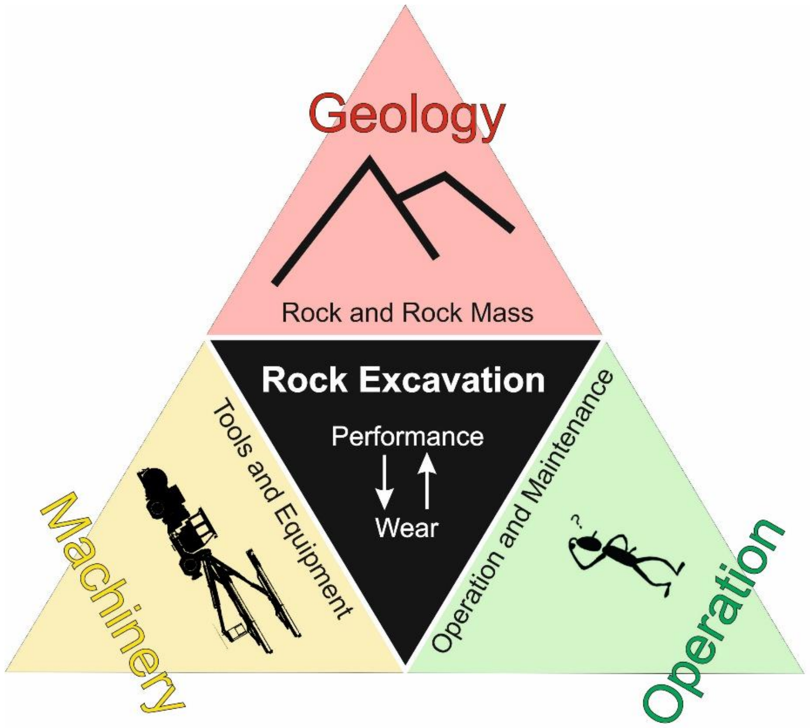

Fig. 2.2: Visualization of the influencing factors in rock excavation (according to: Plinninger, 2002, Fig. 26, p. 30, redrawn).

However, the abrasivity of a rock mass, rock or mineral is by no means an absolute measure, but depending on the specific type and characteristics of the rock tool, as well as the system conditions (pressure, temperature conditions, etc.).

Although the objective and definition of the term “abrasivity” (explicitly including rock mass properties) clearly suggest a holistic meaning of the term, it must be noted that sudden, catastrophic failure of tools and tool components sometimes are excluded in the evaluation or back-analysis of projects. Even if this approach may contribute to the fact that the (so adjusted) wear rates can much better be explained and be predicted by the results of small-scale laboratory experiments, this method on the other hand leads to an obvious underestimation of the economic and scientific importance of catastrophic wear processes, often associated with rock mass scale properties.

The experiences and theories presented in the following Section 3 are intended to show some examples for such effects.

3. Rock Mass Scale Effects on Tool Wear

3.1 Mixed Face“ Conditions

The term „mixed face condition“ is used in the field of TBM tunnelling since the 1980s (see for instance Beckmann & Simons, 1982). While there is no definition available from the applicable German national standards, the term is defined in the Austrian Tunnelling Standards ÖNORM B 2203-1 (conventional tunnelling) and ÖNORM B 2203-2 (TBM/Shield Excavation) as follows:

- for conventional excavation: "conditions with simultaneous appearance of rock types with significantly differing excavatability at one face, requiring excavation with blasting on the one hand and excavation with excavator or roadheader on the other hand side";
- for mechanical (TBM, shield) excavation: „excavation under conditions with simultaneous appearance of coherent layers of rock types with significantly differing excavatability".

Although these definitions leave a considerable space for interpretation especially in the field of mechanized tunnelling, the consequences of such conditions have lucidly been presented for a variety of excavation methods:

For the application of **roadheaders**, effects of typical "mixed-face" conditions have been presented by Plinninger, Thuro & Bruelheide (2001) and Plinninger (2011).

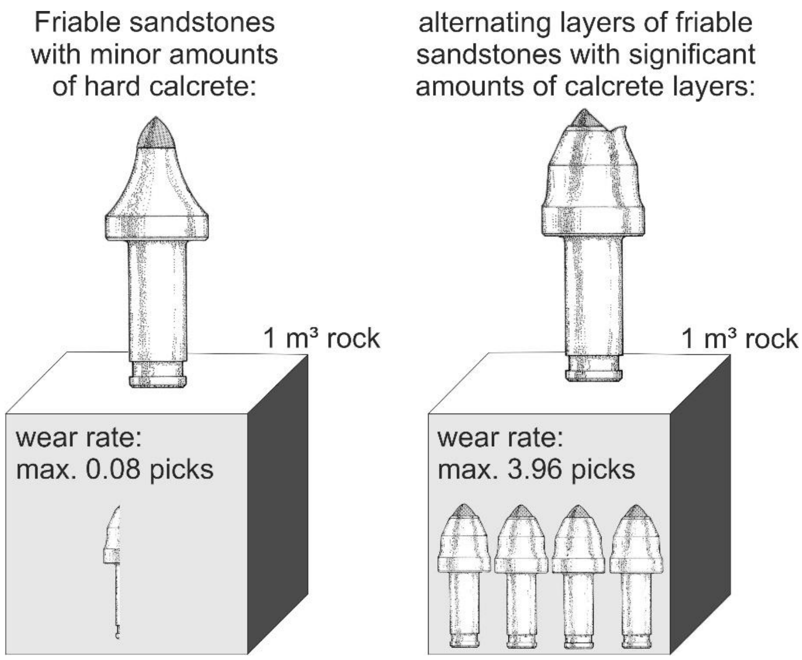

Fig. 3.1: Comparison of tool wear forms and specific pick consumption in homogeneous and “mixed face” conditions during roadheader excavation at Nuremberg Metro (according to: Plinninger, Thuro & Bruelheide, 2001, redrawn).

Investigations during roadheader application for the Nuremberg Metro in alternating layers of friable sandstones and very strong calcrete layers showed a clear relationship between the thickness and frequency of the concretions on the one hand and the wear form / wear rate on the roadheader's point attack picks on the other hand (Figure 3.1).

It should be noted in this context, that referring to the already mentioned Austrian Standard ÖNORM B2203-1, such conditions would have been defined as "mixed face" conditions only if a combined excavation of blasting AND roadheader would have been applied - a circumstance, which also casts doubt on the general applicability of this definition.

In the field of **mechanized tunneling** Alber (1999) describes a situation where a flat lying boundary between a dolomite of approx. 35 MPa intact rock strength and a shale of approx. 13 MPa has been excavated by a TBM. To avoid disk damage and vibrations in this section, the contact pressure had to be reduced to a level of 0.105 MN/disc, until the different penetrations could be absorbed by the TBM without damage (Fig. 3.2). After passing through this zone, the contact pressure again increased to a "normal level" of about 0.145 MN/disc.

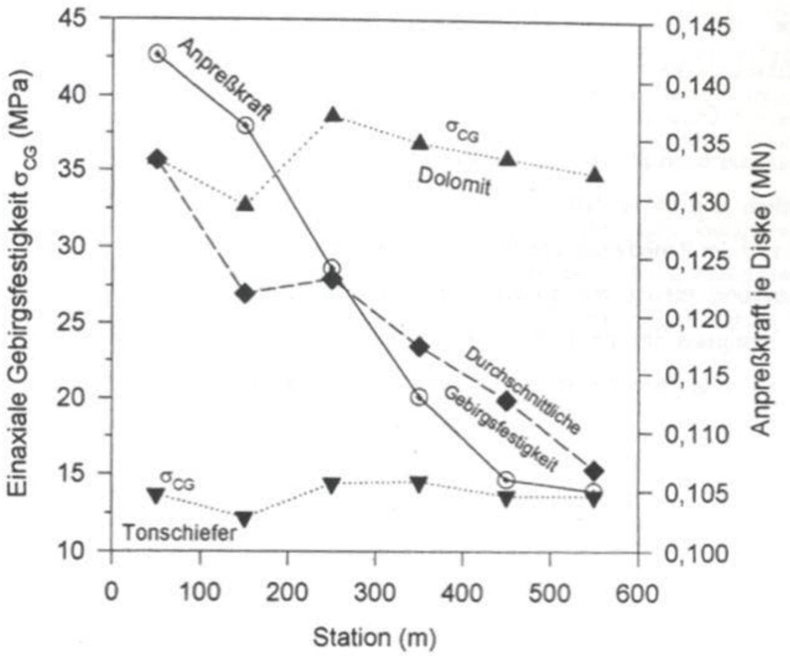

Fig. 3.2: Schematic plot of rock UCS, mean UCS and thrust evolution for a TBM drivage under „mixed face" conditions (from: Alber, 1999, Fig. 4.12, S. 59).

Comparable conclusions can also be drawn from the relatively new results published by Entacher, et al. (2013) from load measurements on TBM disc cutters in crystalline rock with different fracture spacing. In the diagrams presented in this paper, the peak stresses of the discs show significant matches with the boundaries of zones with differing fracture spacing (A / B-boundary lines in Fig. 3.3).

In such heterogeneous ground conditions, the thrust applied on the cutterhead by the TBM cannot be uniformly distributed amongst the discs. The dynamically and unevenly distributed disc loads and associated high peak stresses at single discs are the reasons for disc damages and vibrations as already described by Alber (1999).

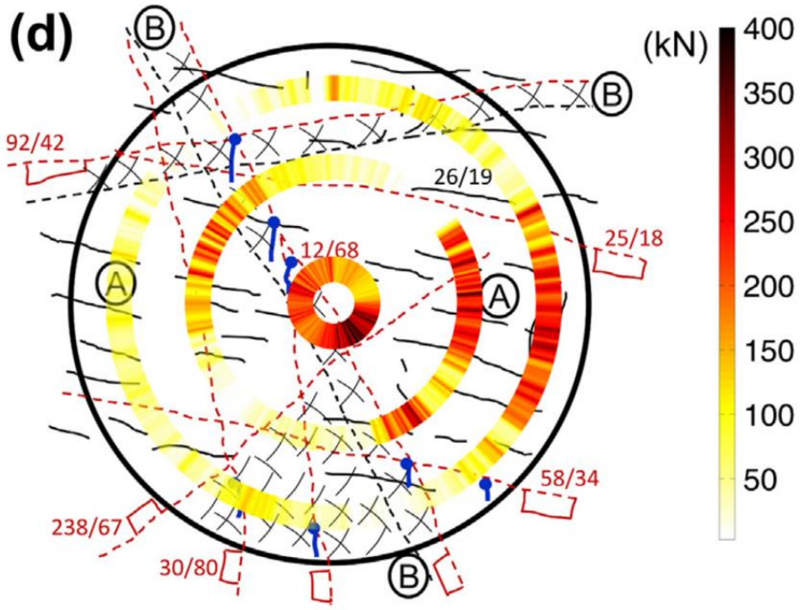

Fig. 3.3: Measured Normal forces FN compared with the corresponding geological mapping (from: Entacher et al, 2013, Fig. 24, S. 495).

A geometric assessment of the "mixed-face" phenomenon shows that the scale of excavation plays an essential role: During blasthole drilling the contact between tool and rock ranges in a scale of some centimeters and thus more on the scale level of intact rock. During roadheader application, but even more for full-face tunnel boring machines, which excavate areas of up to approx. 150 m² in a single turn, the sequence of different rock types and rock layers plays a much more significant role.

According to Plinninger (2002), the percentage of homogeneous rock conditions (no "mixed-face" condition) can be determined by the scale of rock excavation (d) and the layer thickness (m) under the assumption of a rock mass composed of two concordantly alternating rock types as given in the following equation and presented in Fig. 3.4:

$$H = (1 - \frac{d}{t}) \cdot 100$$

with: H *Amount of homogeneous rock conditions [%]*
d *Diameter of rock excavation at a single time [m]*
t *Layer thickness [m]*
Remark: For all cases d ≥ m H = 0 %

Based on these considerations, it is clear that an assessment of "mixed-face conditions" must always be based on the background of the specific excavation method. It is also evident, that for full-face excavation techniques, the subject of inhomogeneous ground conditions and "mixed-face" conditions must have a much greater significance than for example blasthole or exploratory drilling.

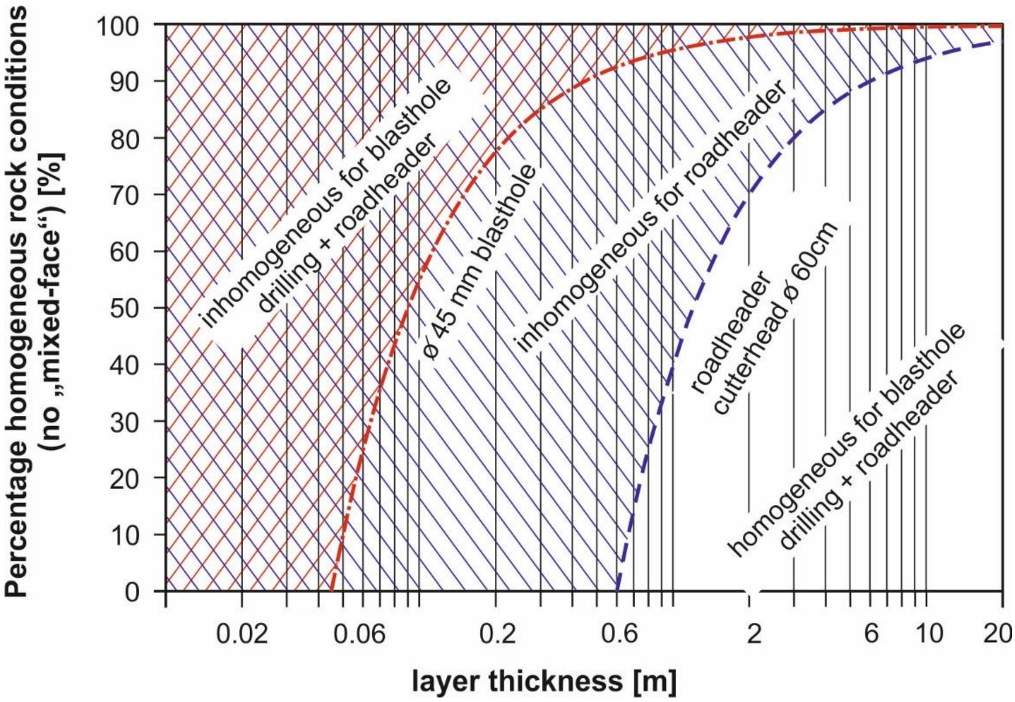

Fig. 3.4: Correlation of the amount of homogeneous / non-mixed-face conditions vs. layer thickness for several rock excavation techniques, including ∅ 45mm blasthole drilling and roadheader application by use of a ∅ 60 cm cutterhead (according to: Plinninger, 2002, Fig. 27, p. 32, redrawn).

3.2 Unstable Face Conditions / „Blockiness“

The terms of an "unstable", “collapsing”, "blocky" face or "blockiness" describe conditions in mechanized tunneling, where the rock mass collapses at the face in front of the cutterhead, forming larger rock bodies besides or instead of the “normal” rock chips that form during cutting (see for instance Austrian Standard ÖNORM B2203-2). Such rock blocks or plates can reach significant sizes of up to several cubic meters (see Fig. 3.5).

Fig. 3.5: Cubic decimetre to cubic meter large gneiss blocks in front of the cutterhead of a hard rock TBM. Discs and cutterhead can be seen on the right edge of the image (Photo: Plinninger).

Depending on the strength and abrasiveness of the blocks, such conditions may present unusual and severe demands for the TBM and its tools. Loose blocks, which are larger than the cutterhead openings have to be crushed between face and cutterhead until they are small enough to pass these openings and be mucked out. As a TBM cutterhead is usually not designed for such "crushing", head structure, front plating and cutters are facing dynamic, locally extremely high impacts and shock loads instead of the more or less continuous rolling movement during regular excavation. Increased failures of tools and tool components (ring fractures, screw breaks, etc.) are frequently observed consequences of such conditions.

The most relevant geological causes for "unstable", "blocky" or "collapsing” face conditions are mechanically effective discontinuities, like joints and bedding planes, which may lead to structural outbreaks under unfavorable orientations. In addition, high rock stress conditions can also lead to rock spalling or rock bursts with often typical, concave or arched profiles at the face and thin, sharp-edged, platy debris.

Although a strictly deterministic assessment of the quantitative impact of such conditions on the lifetime / consumption of disc cutters seems difficult at the present state of knowledge, back-analysis of past projects provide clear correlations between blocky conditions at the tunnel face and the increased occurrence of brittle fracture of tools and tool parts (see for instance Weh, 2007).

3.3 Stress Conditions

The stress conditions in the rock mass at the face have an additional influence on rock excavation and tool wear. Since in situ primary and secondary stress conditions can only be determined with great effort and the impact on the excavation process might only be identified indirectly - by comparison of different conditions - the issue of stress influences is still discussed controversially and mostly based on model calculations as presented in Figure 3.6 (from Alber, 2008).

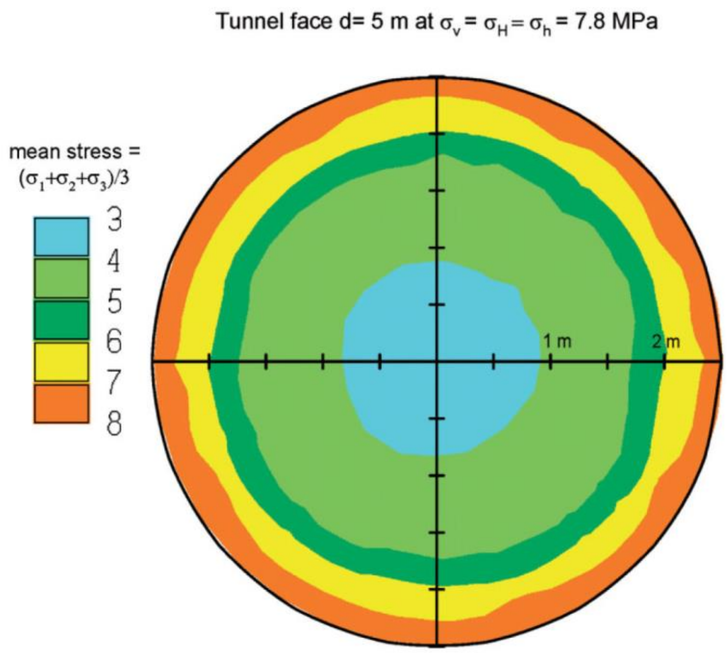

Fig. 3.6: Modelling of stress distribution on a TBM tunnel face (from: Alber, 2008, Fig. 7, p. 35)

In the referring literature (including Rutschmann, 1974, Alber, 2008, Lagger, et al, 2015) considerations have been presented, which postulate that stress conditions, depending on level, orientation and rock mass properties may either have a positive (by forming of new discontinuities), neutral or negative influence (by increasing the resistance against excavation) effects on rock excavation and tool wear.

4. Tool Failure as a result of Adverse Rock Mass Conditions

Due to the significant technical and economic relevance, it seems necessary from the authors point of view to respond in detail to the phenomenon of failure of tools and tool parts, which is predominantly influenced by the prevailing rock mass conditions. In the following Sections, features and relevance of such wear processes are described for tools with hard metal inserts (Section 4.1) and steel tools (Section 4.2). Section 4.3. gives an insight into the potential impact of tool failure for wear estimates.

4.1 Failure of Hard Metal Inserts

For button drill bits and point attack picks, the hard metal insert(s), usually cemented tungsten carbides, represent the main part of the rock tool. Although these hard metals have a high material hardness and an associated, high resistance capacity against abrasive wear, the material properties on the other hand lead to relatively high brittleness. This results in the effect, that even during more or less continuous abrasion material removal from the tool surface mainly takes place as a result of "microcracking", i.e. microscopic outbreaks from the hard metal surface.

If the tool is subjected to high impact, the danger exists, that large parts of the insert are broken or the entire hard metal pin is ripped out of the steel body by breakage of the bedding. If that happened, the missing hard metal insert is no longer able to effectively protect the tool body from abrasion, which in most cases requires early replacement of the tool. Although brittle fractures of this category per definition are macroscopically visible, the application of scanning electron microscopy gives a further impression on the devastating extent of further damage (Fig. 4.1).

Fig. 4.1: Shell-shaped brittle fractures in the hard metal insert of a point attack pick, about 16-fold magnification. The loss of material (based on the volume of the cemented carbide insert) in this case was about 40% (from: Plinninger, 2002, Figure 23, p. 23).

If the insert is not removed entirely, the differently oriented, typically shell-shaped fractures can also significantly weaken the remaining insert. Since such already prescribed fracture surfaces can easily be activated during subsequent loading, such damage may drastically increase the likelihood of complete wear after only a little period of time.

4.2 Failure of Steel Tools

Homogeneous steel tools, as for instance disc cutters or steel bodies of drill bits and point attack picks can also be affected by brittle material failure - although steel is able to perform significantly tougher than hard metals. Such phenomena, for instance fracturing of disc cutters (see Fig. 4.2) have to be rated as one the most expensive problems during operation of a hardrock TBM.

Fig. 4.2: Broken 17“-cutter disc of a hardrock TBM (Photo: Plinninger).

The occurrence of brittle fractures of any type (hard metal insert or steel parts) is influenced by geological features, mainly the rock´s compressive strength and the discontinuity system at the face, as well as by the layout of tools and machines, as for instance the arrangement, type and quality of the tools, the type of excavation process taking place as well as applied forces.

4.3 Impacts of Tool Failure on Wear Estimation

While the more or less continuous abrasion of rock tools can reasonably well be predicted on the basis of laboratory methods, catastrophic macroscopic tool failures are mainly related to rock mass scale effects as presented earlier in this paper. Such conditions cannot be investigated in the laboratory and therefore cannot be included in such prediction models. If adverse rock mass conditions (including "mixed face", "blockiness", etc.) occur, which are able to cause tool failure, wear estimates based on the assumption of continuous material removal will therefore provide wrong – too optimistic – results, which is explained in the followings diagrams (Figure 4.3 and 4.4).

Figure 4.3 represents the hypothetical decrease of a point attack pick´s mass for a pick which is worn by continuous abrasive wear and is replaced at the end of its (relatively long) service life time because the carbide insert becomes unusable.

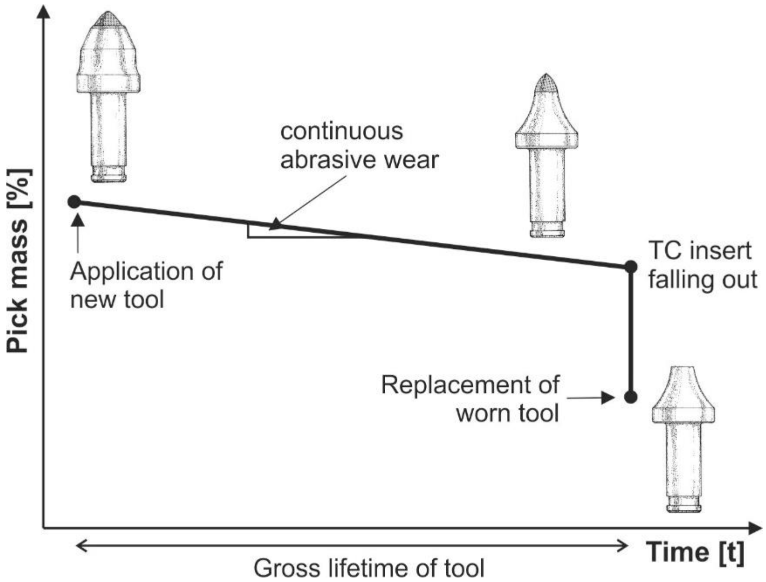

Fig. 4.3: Hypothetical mass loss diagram for a point attack pick that is undergoing continuous abrasive wear („Case A“).

In contrast to this, Figure 4.4 depicts a pick, that has to be replaced at any time during operation as a result of catastrophic failure of the hard metal insert.

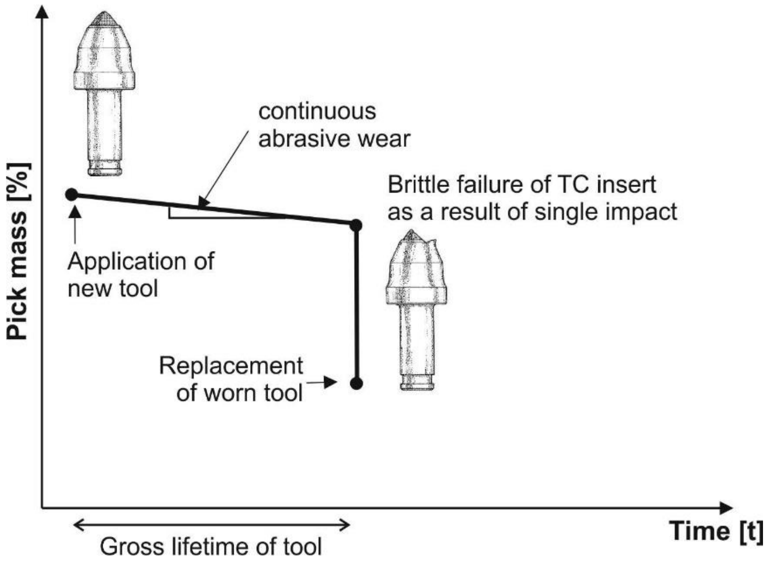

Fig. 4.4: Hypothetical mass loss diagram for a point attack pick, that has to be removed after catastrophic failure of the hard metal insert („Case B“).

In both cases, the same wear rates are determined, if only abrasive wear is considered. Although these rates might deterministically be derived from rock scale laboratory investigations, such as the CERCHAR test, such properties are of no use for an appropriate assessment of tool lifetime in “Case B". In case of tool failure it appears essential for the assessment of the actual tool wear rate, to add a probabilistic assessment of the likelihood and frequency of impacts / loads which might cause brittle material failure and cause an immediate replacement of the tool.

5. Conclusions and Suggestions

From the presented experiences and theories, the following conclusions may be drawn:

1. The term "abrasivity" should in a holistic way describe the potential of a rock mass to cause any form of tool wear to a rock tool. To restrict the term solely on the ability of intact rock to cause more or less steady, continuous abrasion, underestimates the task of the geologists and geotechnical engineer to determine and to describe all relevant ground parameters required for an appropriate wear assessment.
2. Tool removal as a result of catastrophic failure of tool parts (inserts, shank, etc.) is nevertheless still "tool wear", although it might be useful to separately describe and classify such phenomena and to separate them from abrasive wear phenomena during back-analysis.
3. Beyond the scale of intact rock, wear-relevant rock mass conditions, such as "mixed-face" conditions, "blockiness" or unusual stress conditions can have a significant effect on rock excavation and the wear of rock tools.
4. The occurrence of such adverse ground conditions has in principle to be located within the risk sphere of the client / owner.
5. To ensure a fair risk distribution and to allow a bidder / contractor to compensate for such effects, information on type, probability and frequency of such adverse rock mass conditions should be included in the Geotechnical Reports and specific positions should be implemented in the referring Bill of Quantities.

A view over the borders of Germany shows that some of the mentioned phenomena are already incorporated into the standards of other countries. For instance, the Austrian tunneling contract standard ÖNORM B2003-2 defines rock mass sclae factors like "mixed-face conditions" or "blockiness" as "difficulties" which either cause higher costs or reduce the performance of excavation. Consequently, the regulations of the ÖNORM B2003-2 do demand estimates on distribution, bandwidth and local association for such difficulties in the tender documents - a noble aim, which even in Austria is still not common status.

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