On the influence of rock mass scale effects on tool wear prediction in hardrock tunnelling

Ralf J. Plinninger[1] and Jan Düllmann[1]

[1]*Dr. Plinninger Geotechnik, Bernried, Germany*

Abstract: The investigation of rock abrasivity and the prediction of anticipated tool wear rates is an important task in the course of any hardrock underground project. This especially applies to any form of mechanized (roadheader, TBM, shield) tunneling method, where the effects of wear play an important role in the assessment of working cycles and the overall machine availability. At present, laboratory investigations and derived abrasivity indices, such as the CERCHAR Abrasiveness Index (CAI) or the Rock Abrasivity Index (RAI) form the baseline for any tool wear assessment. However, it should be kept in mind that such index values are only able to take into account influencing factors in the scale of the intact rock. Larger scale – rock mass – effects, as for instance "mixed face" conditions, unstable rock face conditions, "blockiness" or the primary and secondary stress conditions at the face may play an additionally significant role for the tool wear encountered in-situ. The potential consequences of such adverse effects, causing for instance catastrophic tool failure, have in fact shown to be of a much higher degree than an increase of rock abrasiveness alone.

1 TOOL WEAR – CONTRACTUAL RISK FOR HARDROCK TUNNELLING

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, the choice of excavation equipment and estimated on performance and wear are located within in the risk sphere of the contractor.

Laboratory procedures, such as the CERCHAR test 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 further standardization [5]. These "standard" testing methods actually define the baseline for any wear assessment.

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 DISCUSSION OF TERMS: „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 wear modes (→ "abrasive wear") and suddenly occurring events with more or less (microscopic and macroscopic) catastrophic failure of tool parts (→ "tool failure").

However, a definition in the form, that "tool wear" would 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 [9] it might be defined as the ability of a rock mass (or rock or mineral) to cause wear on a rock excavating tool. However, the abrasivity 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 of the term "abrasivity" (explicitly including rock mass properties) clearly suggest a more 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.

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 [3] and in the meanwhile has also been introduced for conventional excavation. The term is for instance defined in the Austrian Tunnelling Standards ÖNORM B 2203-1 (for conventional tunnelling, [7]) and ÖNORM B 2203-2 (for TBM/Shield Excavation, [8]) 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".

The consequences of such conditions have been presented for a variety of excavation methods, including the application of **roadheaders** (see [10], [11]) as well as for **mechanized tunneling.**

ALBER [1] presents a lucid example for the impact of mixed face conditions on TBM operation. Geologically, the horizontal boundary between a dolomite of approx. 35 MPa intact rock strength and a shale of approx. 13 MPa was encountered. To avoid disk damage and vibrations in this section, the thrust had to be reduced to a level of 0.105 MN/disc, until the different penetrations could be absorbed by the TBM without damage (Figure 1, left diagram). After passing through this zone, the thrust could again be increased to a "normal level" of about 0.145 MN/disc.

Comparable conclusions can also be drawn from the relatively new results published by ENTACHER ET AL. [4] 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. Under 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 [1].

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. As presented in [9], the probability of mixed face conditions will generally increase with an increase in the scale of simultaneous rock excavation.

3.2 Unstable face conditions, “blockiness”

The terms of an "unstable", “collapsing”, "blocky face” or "blockiness" [8] 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. Such rock blocks or plates can reach significant sizes of up to several cubic meters under adverse conditions (see Fig. 1, right image).

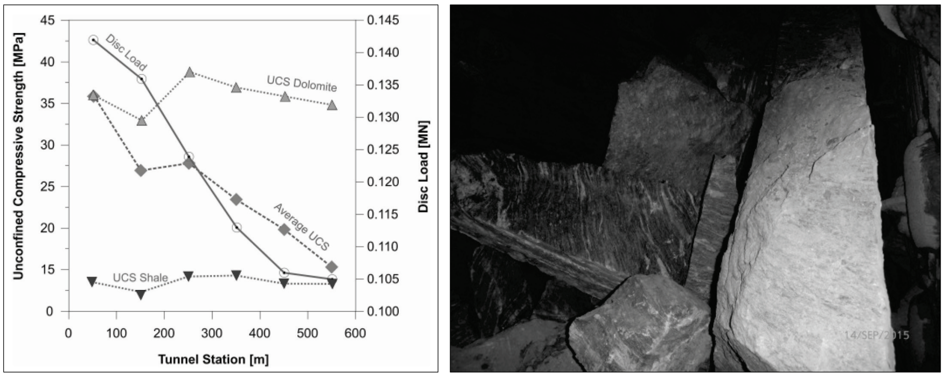


Figure 1: Left diagram showing a schematic plot of rock UCS, mean UCS and thrust evolution for a TBM drivage under „mixed face“ conditions (from: [1], Fig. 4.12, p. 59). Left image showing cubic meter large gneiss blocks in front of a TBM cutterhead. Discs and cutterhead can be seen on the right edge 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 failure 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 have provided clear correlations between blocky conditions at the tunnel face and the increased occurrence of brittle fracture of tools and tool parts (see for instance [13]).

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 the issue of stress influences is still discussed controversially and mostly based on model calculations.

In the referring literature (including [12], [2], [5]) 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) on rock excavation and tool wear.

4 TOOL FAILURE AS A RESULT OF ADVERSE ROCK MASS CONDITIONS

4.1 Brittle failure of tungsten carbide 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.

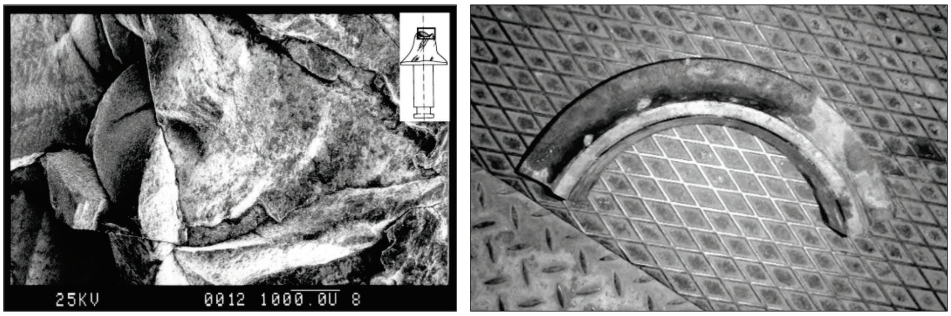


Figure 2: Left image showing shell-shaped brittle fractures in the hard metal insert of a point attack pick, about 16-fold magnification (from: [9], Figure 23, p. 23). Right image showing broken 17“-cutter disc of a hardrock TBM (Photo: Plinninger).

If the tool is subjected to high impact, large parts of the insert can be are broken or the entire insert can be 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 (Fig. 2, right image).

4.2 Brittle failure of steel tools

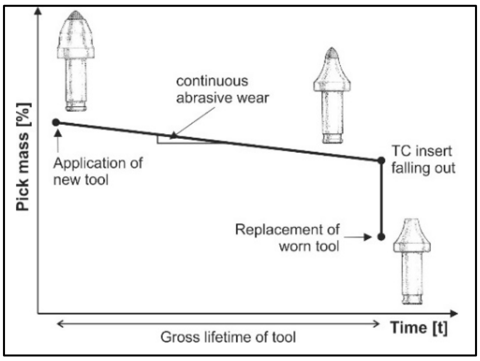
Homogeneous steel tools, as for instance disc cutters or steel bodies of drill bits and point attack picks can also be affected by brittle material failure – although steel is able to perform significantly tougher than hard metals. Such phenomena, for instance fracturing of disc cutters (see Figure 2, right image) have to be rated as one the most expensive problems during operation of a hardrock TBM.

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 discontinuities in 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 Impact of tool failures on wear estimates

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 of Fig. 3.



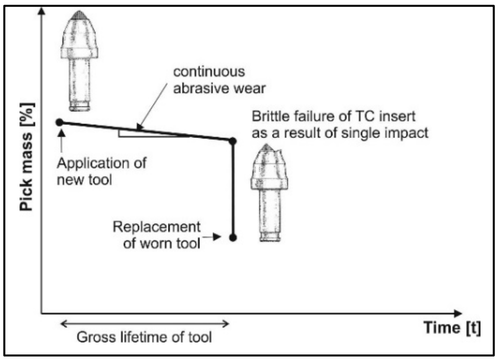


Figure 3: Left diagram showing hypothetical mass loss diagram for a point attack pick that is undergoing continuous abrasive wear („Case A“). Right diagram showing hypothetical mass loss diagram for a point attack pick, that has to be removed after catastrophic failure of the hard metal insert („Case B“).

The left diagram in Fig. 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. In contrast to this, the right diagram depicts a pick, that has to be replaced at any time during operation as a result of catastrophic failure of the hard metal insert.

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 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. 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.

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