PREDICTING TOOL WEAR IN DRILL AND BLAST

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Drill & Blast is a commonly used excavation method for the construction of underground openings (e.g. tunnels, caverns) in hardrock conditions worldwide. Wear of the employed tools may take place during different steps of the working cycle, affecting a wide range of machinery and materials. Although excavators, dump trucks or conveyor belts are also permanently exposed to the excavated rock mass and therefore undergoing geologically influenced wear, the wear of the rock cutting tools (i.e. drilling bits, excavator chisels, picks) is the most expensive wear phenomenon.

Drilling equipment and bit tool wear

Common blasthole diameters range from 38 to 48 mm and are typically drilled by use of hydraulic rotary percussive drilling hammers (impact power of about 15 to 20 kW). In most geological conditions, predominantly button bits are used which consist of a number of cemented carbide buttons inserted and/or solded into holes of a steel body (Figure 1). The properties of the button bit can be adjusted effectively to the local circumstances by variation of the amount of inserted buttons, button composition, button geometry, solding and steel quality or the bit's flushing system.

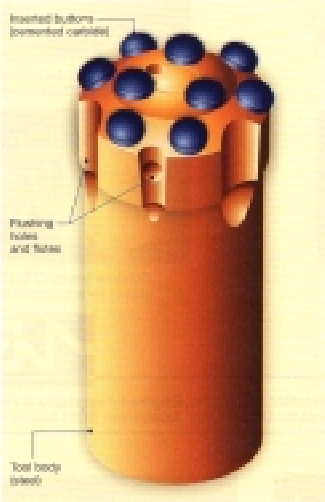

Figure 1. Main characteristics of a button bit.

Tool wear will occur under certain loads and temperatures just as one result of a complex tribological system. The material removal is caused by microscopic and macroscopic processes such as abrasion, adhesion, material fatigue or brittle failure of tool materials. Mode and rate of these processes are controlled by a vast variety of factors coming from the main fields of geology, tools and logistics. Engineering geologists, material scientists, mining and civil engineers have been researching these effects through the last decades at universities, research institutes and machine manufacturers to identify and quantify main influencing factors. Rock properties, joint features, weathering / alteration of rock, water situation, composition of inhomogenous rock masses and underground stress situation have been identified as major geological factors. Tool characteristics, flushing, feed, rotating velocity, temperatures, tool handling and rock supporting methods represent some main factors from the fields of tool and logistics.

CLASSIFICATION OF BIT WEAR

Wear type and the *wear rate* can be used as parameters describing the effect of the wear process. The *wear type* describes the specific form of wear observed on the tool. It can be described qualitatively by use of a wear classification system (Tab. 1). The *wear rate* describes the velocity of material removal from the tool. This term is normally expressed in drilled meters per bit [m/bit], also entitled the "drill bit lifetime". The wear rate is a basic factor for the calculation of tool consumption and wear costs. It can be obtained on site from measurements on single tools or calculations based on stock lists and delivery notes.

Classification of bit wear type

The bit wear type can be used as a "fingerprint" of the wear process. From its classification valuable information can be obtained about the typical processes taking place and geological and machinery causes for the encountered wear forms. A easy-to-use classification system for button bits is given in Table 1. It is evident, that transitions and mixed types between the presented types are possible.

Normal wear (BB-A1) may be observed when tool body and hard metal inserts are more or less evenly undergoing abrasive wear. This wear type is typical for abrasive rocks with high compressive strength, for example quartzite, gneiss, granite or quartzitic sandstones. The evenly wear distribution can be explained by

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the low penetration of the bit in such rock types, so that mainly the hard metal inserts get in contact with the rock and are therefore worn with low wear rates - even by minerals that can be classified as "non abrasive" to cemented carbides.

Table 1: Bit wear type classification

Wear type	Abbr.	Description
New tool	BB-0	**New**, unused button bit.
Abrasive wear	BB-A1	**"Normal" wear:** more or less evenly abrasive wear of tool body and inserts. The tool has been changed in time.
	BB-A2	Predominant abrasive **wear of the tool body.** The buttons may fall out due to missing embedding (->BB-A3).
	BB-A3	**Falling out/breaking out of whole buttons** due to insufficient embedding and binding at the bottom of the buttons.
	BB-A4	**Wear of diameter:** buttons and tool body are predominantly worn down at the sidewall.
	BB-A5	**Continued wear of diameter:** Immense reduction of the bits diameter. Peripheral buttons are broken out.
Wear due to failure of tool materials	BB-F1	**Internal failures of button,** buttons are particularly broken.
	BB-F2	**Total button removal** out of the bits body due to failure of bit-button-connection.
	BB-F3	**Failure of bit shaft**
Thermic wear	BB-T	**Thermic wear types** equal A- and F-types. Specific temper colours may be visible and hint to encountered tool temperatures.
Special types and mixed types	BB-Sp1	**Total wear down.** Bit was changed late. Clear classification of tool wear process mostly impossible.
	BB-Sp2	**Widening of flushing holes,** which may even affect embedding of central buttons and removal of central buttons. Wear type mostly in combination with other types.

Predominant *wear of the tool body* (BB-A2) with possible *breaking out of buttons* (BB-A3) is a typical phenomenon for drilling weak rock types. It can often be observed in poorly cemented or weathered sandstone, sandy marlstone or weathered granite or gneiss. In this rock the bit penetrates deep into the rock mass and produces a lot of debris material, so that both steel body and buttons are more or less evenly exposed to rock and rock debris. Since at the same mineral hardness steel and cemented carbide are undergoing different wear rates, the tool body wears faster than the inserted buttons. Buttons are preparated out of their steel bedding and begin to fall out or are broken out of the bit when embedding is insufficient (BB-A3).

Wear of the diameter (BB-A4, BB-A5) is typical for unstable or highly stressed abrasive rock mass when the drilled hole deformes during drilling. Abrasive rock material is forced to the bit from the walls. First, the peripheral buttons begin to show wear on the outer side (BB-A4), later the tool body itself is affected, the hole diameter of the bit is reduced and peripherical buttons break out (BB-A5).

Macroscopic *failure of buttons* (BB-F1, BB-F2) is mostly independent from the rock's abrasivity and mineral content. It is mostly influenced by the rock´s strength and fabric, properties of the rock mass, machinery, tools and support method. Dynamic impact is the main cause for this material failure. Type BB-F2 (total button removal) can easily be caused by no or bad soldering of the buttons into the steel body. These main factors have been recognised to cause button failure:

- inhomogeneous rock masses with rock of high rock strength in combination with open joints or joints filled with soft rock.
- inhomogeneous rock types with very hard components exceeding diameters of about 2 cm, like conglomerates, fanglomerates or breccias.
- drilling through already installed steel support - like forepoling through lattice arches or anchoring through reinforced shotcrete.

Failure of the bit shaft (BB-F3) is mainly a result of manufacturing problems or bad handling. In these cases, no conclusions may be drawn on geological circumstances.

The occurrence of *thermic wear* (BB-T) of button bits depends on the effectiveness of the flushing system. Under normal circumstances button bits are cooled very effectively by their water flushing system so that tool temperatures normally don't exceed 40°C. If no or insufficient flushing is available thermal wear may occur. Wear types equal those of abrasive wear and wear due to material failures since high tool temperatures only increase those wear mechanisms. When heated above 200°C specific temper colours should show on the steel body and may be used diagnostically to estimate the maximum tool temperature.

The two *special wear types* occur mostly independent from the geological circumstances:

- Total wear down (BB-Sp1) is stated, when the bit is worn down to or below the buttons. In such cases one may not be able to definitely recognise the predominant wear process.
- Widening of flushing holes (BB-Sp2) and flutes is a phenomenon, which in most cases is caused by aggressive flushing fluids or suspended abrasive particles in the flushing. It may even be caused by

cavitation alone which means material loss out of the tool surface due to forming and implosion of microscopic vapour bubbles under high velocities of flow.

Classification of bit wear rate

Table 2 gives a system for the description of the drill bit lifetime for button bits ∅ 43 - 48 mm. These terms have proven to be suited in numerous projects since their introduction by Thuro in 1996.

Table 2. Bit wear rate classification for button bits ∅ 43 - 48 mm (Thuro, 1996).

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Wear rate term	Bit wear rate/ crown life value [m/bit]	Drill bit lifetime term
Very low	>2000	Very high
Low	1500-2000	High
Moderate	1000-1500	Moderate
High	500-1000	Low
Very high	200-500	Very low
Extremely high	<200	Extremely low

PREDICTING BIT WEAR RATES

Testing and prediction methods - an overview

Prediction of tool wear rates can be based on a numerous variety of testing procedures and standards. Procedures cover a wide span of scale, ranging from on-site real-scale drilling test to model tests with simplified tools and furtheron to microscopic and chemical analysis of rocks and minerals. Depending on their scale and parameters they are able to take different factors into account whilst disregarding others. The following chapters present results of case studies, derived from 12 projects in Germany and Austria from 1989 to 2001.

On-site and block drilling tests

Real-scale drilling tests, using the original drilling tools and machinery and being performed on representative outcrops or samples of the rock are a reliable testing method to obtain data for tool wear and drilling performance. Depending on the condition and size of the testing area or sample nearly all influencing factors are taken into account. Unfortunately, the procedures are rather expensive with respect to personnel and material costs and therefore carried out most seldomely.

Model tests: Bit Wear Index (BWI) and Cerchar Abrasiveness Index (CAI)

The Bit Wear Index, BWI is - besides the Drilling Rate Index, DRI and Cutter Life Index, CLI - part of a testing procedure used for performance prediction of hardrock excavation methods. The factors developed at the NTNU Trondheim are based on a impact crushing test ("Brittleness test"), a model boring test ("Siever´s Miniature Drill Test") and a model abrasion test ("Abrasion Value"). There are currently no diagrams available to estimate bit lifetime from a given BWI. Bruland (1998) reports that "... the BWI has been found to have some weakness... We are currently working to replace the BWI with VHNR..." (p. 5).

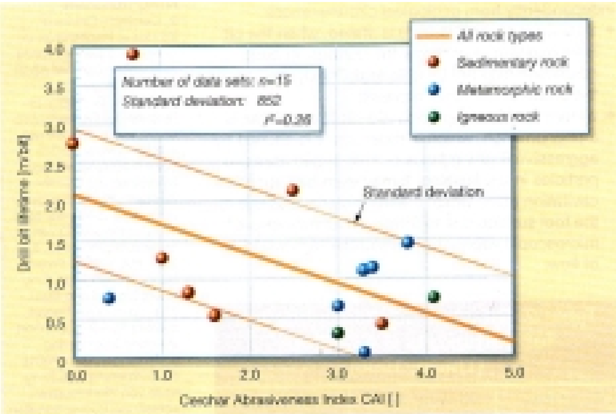

Figure 2. Drill bit lifetime, plotted against CAI.

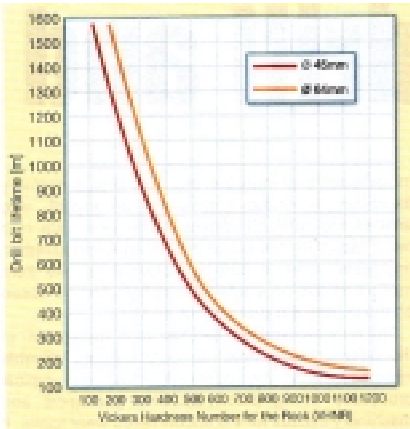

Figure 3. Drill bit lifetime plotted against VHNR (Johannessen et al., 1995)

In western europe the Cerchar scratch test (Cerchar, 1986) is one of most commonly used testing methods when it comes to the laboratory investigation of a rock samples abrasivity. The test is performed on a rock sample of hand specimen size and features a steel needle of defined geometry being scratched over the rock surface under static load. The CAI is then calculated from the diameter of the needle wear flat. The 15 data sets plotted in Figure 2 show only bad correlation between CAI and encountered drill bit lifetimes. Judging from own and Brulands experience one may conclude, that model tests may be used for a quick and cheap estimation of a rock´s abrasivity, but appear to be not suitable for a more precise calculation of drill bit lifetime and drill costs.

Geotechnical wear indices

Geotechnical wear indices are calculated from standard laboratory parameters and so should be available from every standard hardrock investigation program. SiO_2- and Al_2O_3-contents derived from X-Ray Fluorescence Analysis have shown only bad correlation with bit wear rates (Plinninger, 2001). One explanation may be found in the fact, that the . SiO_2- and Al_2O_3 element oxides are only calculated from the analysed Si- and Al- contents of the rock sample so that non-abrasive clay minerals and mica are included as well as quartz and corundum.

AMC, VHNR and EQC are very similar geotechnical parameters using petrographical thin section analysis. They are calculated by multiplying the content of a mineral with a specific hardness value and then adding the values up. The indices vary in the use of different hardness values (Mohs scratch hardness, Vickers indentation hardness or Rosiwal grindig hardness). VHNR and EQC have proven to be suitable for drill lifetime calculation, prediction diagrams are given in Johannessen et al (1995, Figure 3), Thuro (1996) or Plinninger (2001).

The Schimatzek wear index was developed in the 1970s in order to estimate roadheader pick consumption in german coal mining operations. Besides the content of abrasive minerals (calculated similar as the EQC) the factor uses the brazilian tensile strength (BTS) and the grain size. Primarily defined for clastic quartz-rich sediments only, Ewendts investigations (1980) lead to a modified Schimatzek wear index, adapted to all kinds of rocks and using the Point-Load-Strength I_{50} instead of the BTS. This modified index has proven to be a more reliable factor for bit lifetime prediction than the EQC. A prediction diagram is available from Plinninger (2001).

The Rock Abrasivity Index and RAI prediction procedure (geotechnical index)

The Rock Abrasivity Index, RAI is a new geotechnical wear index, part of a prediction procedure for drill bit wear rate. This procedure suggests a investigation program taking into account the hole range of scale from rock mass to mineral scale (Table 3). Based on the "mineral scale"- and "rock scale"-investigations, the RAI is calculated for relevant rock types by multipliing the rock´s Unconfined Compressive Strength and Equivalent Quarz content. Rock mass scale informations are then taken into account by use of "positive" and "negative" factors, that can either increase or decrease the drill bit lifetimes derived from the RAI prediction diagram (Figure 4).

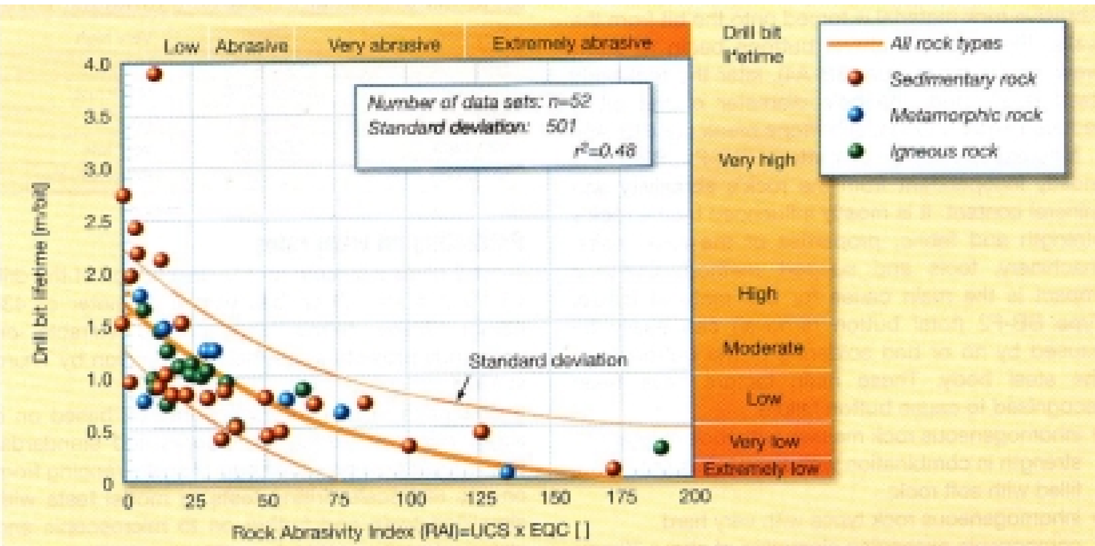

Figure 4. Drill bit lifetime, plotted against RAI

Table 3. Important geological informations about rock mass, rock and minerals for wear prediction.

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1. Rock mass scale (dm-km)
Which areas with homogenous rock composition and identical rock characteristics can be distinguished?
How are these areas located (orientation, thickness, occurance)?
What are discontinuities (joints, faults, bedding planes) like in these areas (number of sets, spacing, roughness, aperture, orientation)?
Are there areas, where the rock characteristics have changed due to weathering or hydrothermal alteration?
What is the water situation like (amount, location and chemical composition of water inflow)?
What is the primary stress field like (orientation and intensity)?
2. Rock scale (cm-dm)
To what amount are identified minerals (see "mineral scale") included
What is the fabric of the rock (grain size & shape, orientation of minerals, degree of density)?
What are the rock's mechanical properties (compressive strength, tensile strength) like?
3. Mineral scale (mm-cm)
What minerals are included in the rock?
In what condition are included minerals (alteration)?

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