

# Laboratory Testing of Materials for Tunnel Boring Machine Drag Bits

Dmitri Katushin, Maksim Antonov, Trieu Minh Vu, Der-Liang Yung  
Tallinn University of Technology (Estonia)

dmitri.katusin@ttu.ee, maksim.antonov@ttu.ee, trieu.vu@ttu.ee, derliangyung@gmail.com

**Abstract** — This paper briefly explains the importance and gives the insight on laboratory wear testing of drag bit materials for tunnel boring machines. The analysis of existing wear test methods is given.

## I. INTRODUCTION

Tallinn University of Technology (TUT) participates in the seventh framework programme FP7 New Technologies for Tunnelling and Underground Works (NeTTUN) aiming groundbreaking change in the construction, management and maintenance of tunnels. The building of tunnels is rising due to overpopulation of cities and building of tunnels through the mountains and below the rivers [1]. The main tasks of TUT are development of materials for drag bits with improved wear resistance and estimation of their wear resistance. This paper aims to describe existing laboratory test devices and to analyze their suitability for simulation of conditions experienced by drag bits during tunnel boring.

## II. TUNNEL BORING MACHINE

A tunnel boring machine (TBM) is a machine used to excavate tunnels with a circular cross section through a variety of soil and rock strata. They can bore through anything from hard rock to sand. Cutting tools are fixed at different positions (face, gauge, center, etc) of cutting head (wheel) that is rotated 1 to 10 rpm and advancing approximately 8 cm / min depending on site and stratum. Cutting head may reach up to 16 meters in diameter depending on required size of tunnel. Disk cutters are used for cutting of hard rocks. These disks are press toward the stone with force exceeding rock strength (up to 350 MPa) that leads to the formation of the cracks and rock chips of optimum size. Disk materials were well studied before and their material and design is optimized while the drag bits used for cutting of soft and mixed grounds were researched less. During cutting of soft and mixed grounds drag bits experience varied loading depending on the size of abrasive and number of stones, often are immersed into pressurized slurry, may undergo corrosion etc. That is why drag bits should possess sufficient strength, hardness, fracture toughness and corrosion resistance. TBM itself may costs up to 50 million EUR and one day of immobilization (keeping in standby) may easily reach 100 000 EUR. Due to high shutdown costs and hyperbaric conditions (pressure up to 4.5 bar) in cutting head area it is extremely important to achieve longest possible lifetime of drag bits to reduce the number of shutdowns and human intervention [1, 2, 3].

### A. History

The first successful tunneling shield was developed by Sir Marc Isambard Brunel to excavate the Thames Tunnel in 1825. However, this was only the invention of the shield concept and did not involve the construction of a complete tunnel boring machine, the digging still having to be accomplished by the then standard excavation methods [4].

The first boring machine reported to have been built was Henri-Joseph Maus' Mountain Slicer. Commissioned by the King of Sardinia in 1845 to dig the Fréjus Rail Tunnel between France and Italy through the Alps [4].

### B. Types of Tunnel Boring Machines

- The Single Shield TBM is used for digging tunnels in hard rock formations (fractured rock, soft rock). With this technology, boring and segment fitting are not simultaneous. The cutterhead, equipped with disc cutters which fracture the rock, extends to excavate the tunnel. Then, the erector installs the segment ring to build the tunnel. The excavated material is brought to the surface by conveyors [2].
- The Slurry TBM. In highly unstable terrain, face pressure during tunneling is maintained by counterbalancing the pressure with bentonite slurry, which forms a mud cake at the tunnel face. The front shield of the TBM is filled with excavated material, with the exception of one air-filled part. The pressure within this air bubble is subject to fine control [2].
- The EPB TBM (Earth Pressure Balance Tunnel Boring Machines) permits to excavate tunnels in soft ground conditions (clay, silt, sand...). The front shield of the machine is filled with debris extracted by a screw conveyor. This screw compensates the pressure difference between the bulkhead chamber and the atmospheric pressure. Foam injection renders the material more homogeneous, thus facilitating its excavation [2].
- The Dual-mode TBM is developed to receive two types of removal equipment, each one corresponding to a given type of ground. In this example, the TBM can either operate in open mode as a hard rock shield machine in self-supporting rock or in closed mode as an EPB machine in unstable soil conditions [2].
- The Double Shield TBM allows faster tunnel excavation in hard rock formations as the segments are installed during excavation. The rotating cutter head cuts the rock (front shield advance) and, simultaneously, the telescopic shield advances to lay the tunnel lining [2].

### III. DRAG BIT MATERIAL

The part of the drag bit that is subjected to toughest wear conditions is usually made of ceramic-metal (cermet) composite material. Conventionally it is cermet made of tungsten carbide and cobalt (WC-Co). Cobalt content usually ranges from 6 to 15 % by weight. WC grain size is ranging from 2 to 20  $\mu\text{m}$ . Any excess or deficiency of carbon has significant effect on hardness and strength. In general, any alloying impurities like iron chromite, nickel, sodium or sulphur can result in poor combination of hardness and strength. Small additions of titanium carbide (3 – 5% by weight), however, could prevent grain coarsening and increase hardness without affecting the transverse rupture strength. Equally important is the grain size control; hardness and compressive strength increasing with decreasing grain size, whereas the desirable grain size for best rupture strength is from 1  $\mu\text{m}$  to 3  $\mu\text{m}$ . Porosity in the alloys' structure is an unwanted parameter. High porosity gives rise to poor transverse rupture strength but in hard metals, high densities up to 99.5% are achieved and uniformly distributed porosity is usually present, which is not so harmful [5, 6].

Improvement of wear resistance of WC-Co cermets is achievable by combining the coarse and fine carbides in one structure, so that the smaller ones fill the spaces between the larger ones. Double-structuring may help to improve fracture toughness. Development of complex structures with improved wear resistance is possible by additions of different hard phase types ( $\text{Cr}_3\text{C}_2$ , TiC, VC, TaC, NbC, etc.). Resistance to corrosive environments and thermal shocks may be improved by modification of binder phase by Ni, Cr, Re, etc [5, 7].

As far as abrasive wear is concerned polycrystalline diamond compact (PDC) tools are now available with 5-6 times higher hardness than tungsten carbide. However, PDC is more susceptible to brittle failure than cemented tungsten carbide, because its fracture toughness is almost twice lower than that of tungsten carbide with 6% cobalt [5].

### IV. LABORATORY DEVICES FOR DRAG BIT WEAR TESTING WITH FREE ABRASIVE

It is possible to make testing applying fixed (for example against sand paper that is called two-body abrasion) or against free abrasive. When free abrasive is present between two bodies the test is called three-body abrasion.

#### A. Testing in Conditions of Ultra-Low, Low or High Stress Abrasion

Testing in Block-on-Ring configuration may be performed using rubber-coated (according to ASTM G 65 standard) or solid steel ring. During testing using rubber wheel the abrasive is usually not broken and it is called low-stress abrasion. Multi Modular Tribosystem (Fig. 1) allows testing using both wheels while enabling to adjust rigidity and inertia of loading system that is required to make test conditions as close as possible to those experienced in real applications.

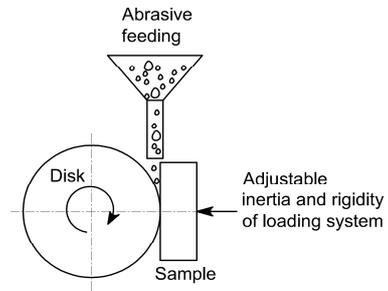


Fig. 1. Multi Modular Tribosystem with adjustable inertia and rigidity of loading system (MMTS) for Block-on-Ring abrasive wear testing (TUT).

Abrasive is supplied between disk and sample. It is usually dry abrasive but spraying of liquid onto abrasive after nozzle is possible. Sample may be heated or cooled to provide constant temperature from 10 to 450  $^{\circ}\text{C}$ . If testing with slurry is required then it is possible to make tests similar to ASTM G 105 or B 611 standards (Fig. 2). Usually abrasive of size smaller than 1 mm are used. These are one sample tests.

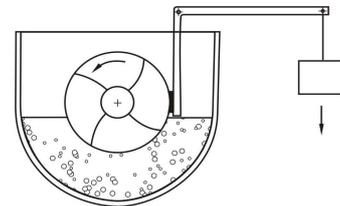


Fig. 2. Device for abrasive wear testing with slurry (TUT).

Ultra-low stress abrasion used for evaluation of the wear properties of oxide scales at elevated temperatures is given in Fig. 3. The load is generated only due to immersion into the abrasive. Up to 36 samples may be treated simultaneously in two abrasives.

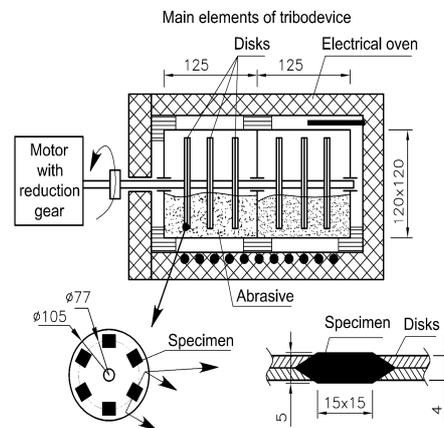


Fig. 3. Device for ultra-low stress abrasion-oxidation testing at elevated temperatures (TUT).

#### B. Testing in Conditions of Impact by Abrasive of Different Size

In dry erosion test the specimen is attacked by the jet of particles that is accelerated by means of centrifugal forces during the rotation of the rotor (Fig. 4). It is possible to vary the impact angle ( $10^{\circ}$ - $90^{\circ}$ ), impact speed (0-80 m/s) and temperature (20-650 $^{\circ}\text{C}$  in elevated erosion test device). Up to 20 samples are tested simultaneously. Similar principle is used in centrifugal type slurry erosion tester (Fig. 5) that allows to attack samples by the jet of slurry that is the mixture of abrasive and liquid. The slurry may not be changed during

test. Both methods do not allow using abrasive larger than 1mm. Up to 30 samples may be treated simultaneously.

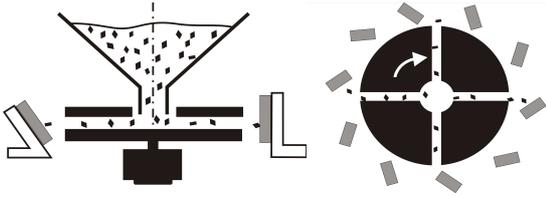


Fig. 4. Dry abrasive erosion test device CAK (TUT).

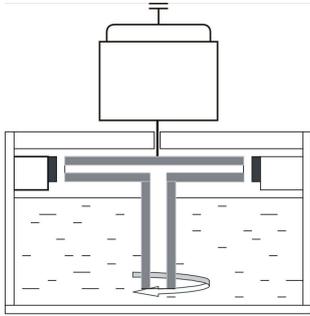


Fig. 5. Centrifugal type slurry erosion tester (TUT).

Larger stones (up to 25 and up to 10 mm in impeller-type and in disintegrator devices accordingly) may be used applying impeller [8] or in disintegrator type impact test devices. Disintegrator allows speeds up to 200 m/s while in impeller-type device it is below 10 m/s. Edges are not protected in impeller-type device that intensify the edge effect (edges are usually worn first and the wear rate depends on radius of the edge).

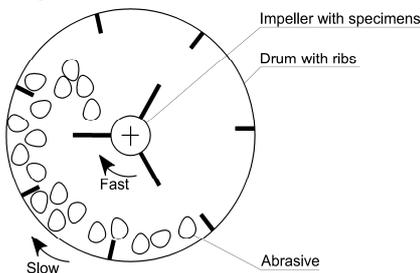


Fig. 6. Impeller-in-drum impact-abrasive wear tester [8].

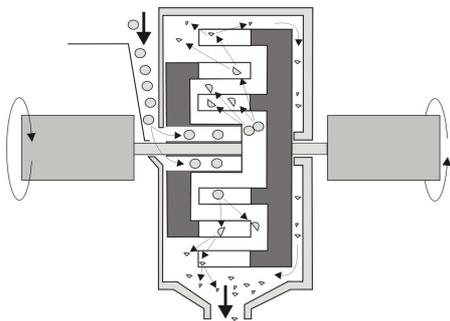


Fig. 7. Disintegrator type impact wear tester (TUT).

### C. Testing in Combined Conditions of Impact and Abrasion

In [9] it is proposed to use abrasive of mixed size to add impact conditions (Fig. 8). The test is similar to Block-on-Ring abrasive wear testing while it has speed limitation. An advantage is that the sample is tested with fresh abrasive however abrasive removal by vacuum cleaner may result in high wear rate of removal system.

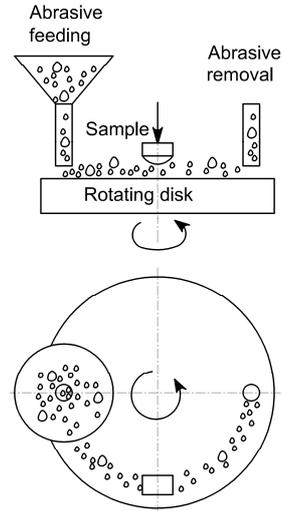


Fig. 8. NTNU device for dry abrasion testing with abrasive of mixed sizes [9].

In [10] and [11] the sample is moved up and down to generate impact. During high temperature cyclic impact abrasion test the plunger impacts the specimen and then slide providing high stress abrasion. The volume removed from zones of impact and abrasion are measured and wear rates in these both conditions could be estimated.

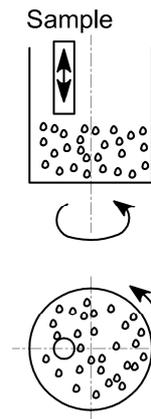


Fig. 9. Three-body pin-on-disk device [10].

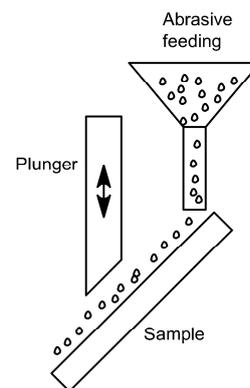


Fig. 10. High temperature cyclic impact abrasion [11].

The soil abrasion testing system proposed in [12] is the only system allowing to make tests under different pressure (0-10 bar). The samples are rotated inside the slurry. The torque required to provide rotation is measured. The edges of

samples are protected to avoid edge effect. It is not possible to change abrasive during test.

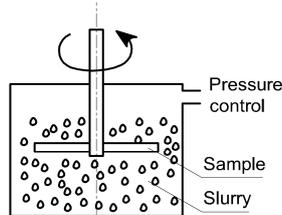


Fig. 11. Pennstate soil abrasion testing device [12].

#### D. Comparison of Tribodevices.

In order to evaluate the suitability of devices for estimation of the wear resistance of tunnel boring machine drag bits they are compared in Table 1.

Table 1. Comparison of laboratory tribodevice' suitability for simulation of drag bit wear conditions

Device vs test conditions	Impact	High stress	Fresh abrasive	Wetting of abrasive	Pressurized chamber	Controllable rigidity and inertia	Available in TUT
MMTS for Block-on-Ring abrasive wear testing (Fig. 1)	-	+	+	+	-	+	+
Slurry abrasive wear testing (Fig. 2)	-	+	-	+	-	-	+
Ultra-low load abrasion-oxidation (Fig. 3)	-	-	-	-	-	-	+
Dry erosion (Fig. 4)	+	-	+	-	-	-	+
Slurry erosion (Fig. 5)	-	-	-	+	-	-	+
Impeller-in-drum (Fig. 6)	+	+	-	-	-	-	-
Disintegrator (Fig. 7)	+	+	+	+	-	-	+
NTNU (Fig. 8)	+	+	+	-	-	-	-
Three-body pin-on-disk device (Fig. 9)	+	+	-	+	-	-	-
High temperature cyclic impact abrasion (Fig. 10)	+	+	+	-	-	-	-
Pennstate soil abrasion testing device (Fig. 11)	-	+	-	+	+	-	-

## V. CONCLUSIONS

It is rather impossible for single laboratory tribodevice to replicate all conditions characteristic for wear of drag bits of real tunnel boring machine. It is usually recommended to study separate wear processes since it allows better control over the process. By providing the MMTS with smart loading, abrasive feeding and sample rotation systems it is possible to simulate real conditions as close as possible.

## ACKNOWLEDGMENT

The authors would like to thank "New Technologies for Tunnelling and Underground Works" project (NeTTUN; FP7 NMP.2011.4.0-2; Grant agreement 280712) financed by European Commission, Doctoral Studies and Internationalisation Programme "DoRa", Estonian Ministry of Education and Research (Project SF0140113Bs08) and European Social Fund (Project "Doctoral School of Energy and Geotechnology II) for financial support of this study.

## REFERENCES

- [1] Gernot Beer. „Technology innovation in underground construction”, Ed. CRC Press, 2009.
- [2] "Underground work" – information from NFM-Technologies web-page, <http://www.nfm-technologies.com/-Underground-work-.html>, accessed on-line, 20.11.2012.
- [3] M. Spencer, A. Stofa, E. Bentz, S. Cross, C. Blueckert, J. Forder, W. London, H. Wannick, B. Guggisberg R. Gallagher. „Tunnel Boring Machines." IMIA Working Group Paper WGP 60 (09).
- [4] Bagust, Harold (2006). „The greater genius? a biography of Marc Isambard Brunel." Ian Allan Publishing. p. 65.
- [5] S. T. A. Gillani, N. Butt. „Excavation Technology for Hard Rock - Problems and Prospects." Pak. J. Engg. & Appl. Sci. Vol. 4, Jan 2009 p. 24-33.
- [6] „Cemented Carbide, Sandvik new developments and applications." Available online
- [7] K.Brookes. „Looking again at large grains in hardmetal tools. Metal Powder Report." Elsevier. 2006.
- [8] R.D. Wilson, J.A. Hawk. „Impeller wear impact-abrasive wear test." Wear 225–229 1999 1248–1257.
- [9] B. Nilsen, F.Dahl, J.Holzhauser, P.Raleigh (2007). „New Test Methodology for Estimating the Abrasiveness of Soils for TBM Tunneling. Proceedings of Rapid Excavation and Tunneling Conference", Society for Mining, Metallurgy, and Exploration Inc., 2007, p.104-116
- [10] J. Tervaa, T. Teeri, V. Kuokkala, P. Siitonen, J. Liimatainen, „Abrasive wear of steel against gravel with different rock–steel combinations, Wear", 267 (2009) 1821–1831
- [11] A. Zikin, M.Antonov, I.Hussainova, L.Katona, A.Gavrilovic´ „High temperature wear of cermet particle reinforced NiCrBSi hardfacings." <http://dx.doi.org/10.1016/j.triboint.2012.08.013>
- [12] J. Rostami, E. A. Gharabagh, A. M. Palomino, M. Mosleh (2011) „Development of Soil Abrasively Testing for Soft Ground Tunneling using Shield Machines. Tunnelling and Underground Space Technology," 2012 p. 246-256