

Recent cutter technology advances to efficiently bore through extremely challenging conditions in hard rock

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ABSTRACT

For TBMs in hard rock, two of the most important parameters to consider are the cutter performance and the penetration rate. These two considerations are highly dependent on each other, as the cutters are typically the critical components that limit the thrust of the machine—a critical variable that dictates the net penetration rate. In such conditions optimal cutter performance is extremely important, not only to optimize the net penetration rate, but also to minimize the time needed to change cutters and maximize the time available for boring. Over the last five years, massive investments have been made in cutter development to make cutters that can withstand even the most challenging conditions. This paper will present the developments and challenges that have driven the last years' advances in cutter technology, as well as the results of those developments on recent projects.

Extreme conditions for cutters can result in poor advance rates, catastrophic disc cutter failure, or unacceptable wear life of a disc cutter. This includes not only hard rock conditions but also conditions in rock and mixed ground under the water table. Disc cutters are a mature technology, and the options available for making improvements are limited; any realized improvements are likely to be incremental for the progress and cost of any project in extreme conditions.

Extremely hard rock has been considered the limiting factor for hard rock excavation ever since the first successful hard rock TBM was employed in 1952. The challenges from gradually harder rock—and the corresponding need for more thrust to induce kerf cutting—triggered the development from drag bits to disc cutters and then to gradually larger cutters. This steady increase in size ultimately resulted in the introduction of 19-inch cutters at Svartisen Hydro Project in 1988 to bore through extremely hard Norwegian rock. This introduction of 19-inch cutters meant that the bearing capacity overcame the limit of the steel quality. Today, 20-inch disc cutters are the industry standard for hard rock. As the developments above show, the challenges and experiences from sites have historically facilitated cutter development. Nonetheless, over the last five years research and development of a better cutter product has been conducted through several parallel research efforts. These projects included an extensive research program with the University of Trondheim, Norway (NTNU) and a systematic cooperation with long term suppliers to optimize and develop the current alloys and metallurgical processes used in ring steel.

Hard rock under water pressure is another area of development: at New York, USA's Delaware Aqueduct Repair, a Single Shield TBM will bore in rock with water pressures up to 20 bar. The 19-inch diameter disc cutters will utilize pressure compensation that has been tested up to 34 bar to excavate under the high pressures. Both the testing results from the laboratory and the first results from the project will also be presented in the paper.

Key Words: Mechanized Tunnelling, TBM, Cutters, Hard Rock

1. INTRODUCTION

1.1. History

Ever since the first functional TBM was operated at the Oahe Dam Project in South Dakota, US in 1952, cutting tools have been an operational limitation for the TBM operation. The performance of the TBM was improved with the invention of the rolling disc cutter on the Humber River Sewer Tunnel in Canada in 1956, but cutting tools are still a limiting factor for the TBM operation in very hard rock today.

In the early 1980s, 14-inch and 15.5-inch diameter disc cutters were introduced. The 15.5-inch cutter was an improvement over the 14-inch with a larger bearing set and its corresponding increase in thrust capacity. Shortly thereafter the 15.5-inch cutter was expanded to 17 inches by mounting a larger diameter disc on the same bearing set. While the thrust capacity of the cutter hadn't changed, the premise was that the 17-inch disc, with increased sacrificial material, would increase the mean time between cutter changes. This proved to be the case and the 17-inch cutter became the de facto standard even after the 19-inch cutter was developed in the late 1980s for the Svartisen Hydroelectric Project in Norway.

The TBMs employed at Svartisen were the first "high performance" (HP) TBMs. These HP TBMs were designed with both increased thrust and cutterhead power compared with earlier machines. While the 19-inch cutter featured increased thrust capacity, the material of the disc, the chrome/molybdenum/nickel steel historically used, was not up to the task. It was not until the introduction of tool steel, and later modified tool steel, that the benefits of increased thrust capacity were able to be utilized. However, in extremely hard rock the cutter steel is still a limiting factor of operation, hence this continues to be a focus for improvement on cutter ring steel properties.

In later years the 20-inch disc cutter has become the state-of-the-art in very hard rock conditions.

1.2. Theoretical Basis

The experience that Robbins has from site shows that there are clear benefits of going for big cutters with high loads in very hard rock conditions. There are two distinct benefits to be realized by employing larger cutters: higher thrust capacity and longer wear life.

Higher thrust capacity enables efficient boring in harder formations. To efficiently cut rock, the thrust force applied to an individual cutter must overcome the penetration resistance of the rock and initiate chip formation. Once the critical pressure has been achieved, penetration increases rapidly with a relatively small increase in cutter load. The critical pressure increases with rock strength and it is primarily for this reason that larger cutters have been developed to bore in harder rock. This principle is illustrated in figure 1.

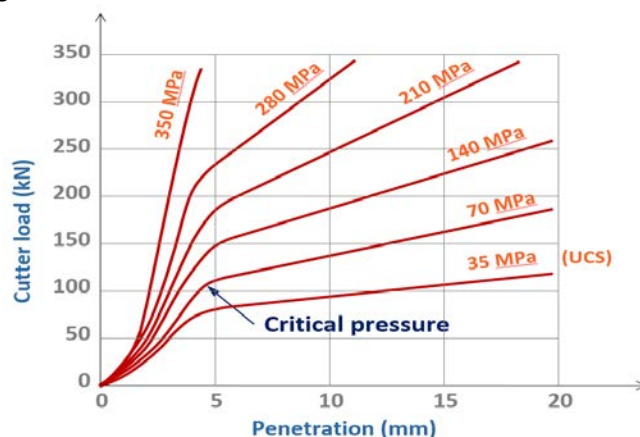


Figure 1. Historical Penetration curves from Robbins.

Longer wear life is the result of an increased volume of sacrificial material in the larger diameter disc ring. The migration from 19 inches to 20 inches on the same bearing core is based on the same principle as the improvement made to the 15.5-inch cutter by installing a larger diameter 17-inch disc back in the 1980s. The relative wear volumes of 17, 19, & 20 inch discs are compared in figure 2.

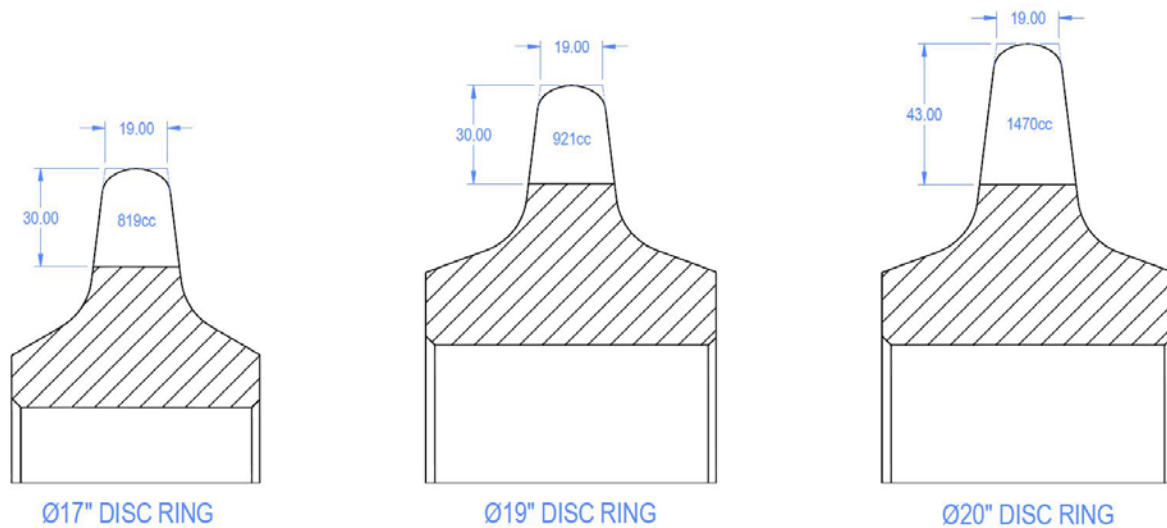


Figure 2. Cross section of cutter rings and calculation of wear volume.

The cross sections of a 17-inch and a 19-inch cutter are effectively identical when considering just the sacrificial portion or “blade” of the disc. In figure 2, 30mm wear has been assumed for the 17 & 19-inch sizes, and the relative wear volumes are given. The 19-inch disc has 12% more wear volume than the 17-inch disc. The 20-inch disc, however, has substantially more wear volume (60%) when compared to the 19-inch ring. The tip of the 20-inch disc has been extended by 13mm on the radius compared to a 19-inch disc while the rest of the disc profile remains unchanged.

The same principle of extended tip discs can be applied to the 17-inch cutter and when geology permits, numerous TBM operators have chosen an 18-inch disc or even a 19-inch disc mounted on a 17-inch bearing core in order to take advantage of the added sacrificial material. This can be an effective solution in pressurized face tunnelling to extend the time between cutterhead interventions.

Another important aspect of the cutters is the tip width of the cutters. A narrower cutter ring tip width will increase the pressure applied under the cutter and make the rock breaking more efficient. However, the thinner tip width also decreases the wear volume of the disc ring and increases the stress in the cutter rings. In very hard rock conditions where the cutters are pushed to their limit, it is common to see some destructive wear such as mushrooming and chipping along the edges of the cutter ring. This is not a significant problem until the destructive wear becomes the dominating wear mechanism for the cutters and/or the cutter wear gets to a detrimental level. Historically the best compromise between the wish to have thinner tip widths and the applied pressure under the cutter has been rings with a tip width of $\frac{3}{4}$ " (19mm). This compromise is dependent on the combination of the steel’s abrasive properties and its capability to handle high stresses or impacts. It is a common practice among cutter manufacturers to either increase the tip width or increase the cutter ring flank angles to increase the contact with the rock and reduce the stresses in the cutter rings by increasing the material that can be worn. This in addition to the abrasive properties of the cutter ring steel makes it apparent that further development in ring steel material is important for improving the performance in very hard rock conditions.

2. METALLURGY AND RING SHAPE FOR EXTREMELY HARD AND ABRASIVE ROCK

2.1. Metallurgy

Most disc ring manufacturers produce a ring made from one of the highly-alloyed steels collectively known as “tool steels” and these steels can be either a standard or a modified composition. In addition to specifying the chemistry of the steel, the micro-cleanliness should also be controlled by specification of the production method. The usual production sequence is melting, casting, rolling, forging, rough machining, heat treating, & final machining.

Once the steel melt has been cast and solidified into ingots, it moves to the rolling mill to be reheated and rolled into a much longer rectangular or circular bar with a greatly reduced cross section. Highly alloyed steels are prone to alloy segregation in the cast ingot and the mechanical rolling and reduction of area serves to mitigate such segregation.

The long bars are cut to length and then forged into rings. Of critical importance during the forging process is the temperature drop of the steel. The forging process must be completed quickly enough so that the desired shape is produced while keeping the temperature of the part within the optimal forging range. Internal defects in the ring will result if the temperature is allowed to drop below what is optimal. Robbins prefers the automated closed die forging method although we have successfully used rolled ring forgings in the past. Automation appears to be the key to consistent quality in any forging method.

Machining and heat treatment are the final steps. The steel composition and the forging processes are of course important, but the most important process is the heat treatment of the steel. The heat treatment changes the crystalline structure of the steel and in so doing increases the hardness and strength (positive) but at the same time increases the brittleness (negative). Fracture toughness is sharply reduced in brittle steel. Consequently, a very hard steel may survive in softer geological formations but fail catastrophically in geology that is more challenging. Balancing hardness and fracture toughness can be achieved by both alloy selection and heat treatment processes.

Robbins has recently enhanced the heat treatment process for our standard HD tool steel disc rings to create the XHD disc rings. The enhancements add minimal cost and the result is increased hardness and increased strength but without the normally associated reduction in fracture toughness.

XHD discs produced to a standard cross section have been successfully tested on open-type TBMs operating at the Røssåga project in Norway and the Yin Han Ji Wei project in China. The geology of both projects consisted of granitic rock with strengths ranging from 138MPa up to 300 MPa and quartz content ranging from 43% to 92%.

Preliminary results reported by the contractors indicate that XHD discs exhibit an improvement of more than 20% in cutter life compared to the standard HD discs in the 200 MPa geology where the tests occurred.

2.2. Disc Shape

Robbins has examined the average amount of disc cutter wear and the effect that wear has on penetration rate. Instantaneous penetration is roughly proportional to cutter tip width. New standard discs are 19mm wide at the tip.

However, when they are fully worn they are approximately 30 mm wide at the tip with a given flank angle. This occurs because of the flank angle of the blade portion of the disc. The flanks of the blade portion of the disc are not parallel--instead they form a slight wedge. That wedge angle can deviate between cutter suppliers. An analysis of the wear on each disc at every inspection in 2016 on the Main Beam TBM at Yin Han Ji Wei project in China reveals an average of wear of approximately 19mm. (Figure 3). This equates to an average theoretical tip width of 24mm (Figure 4).

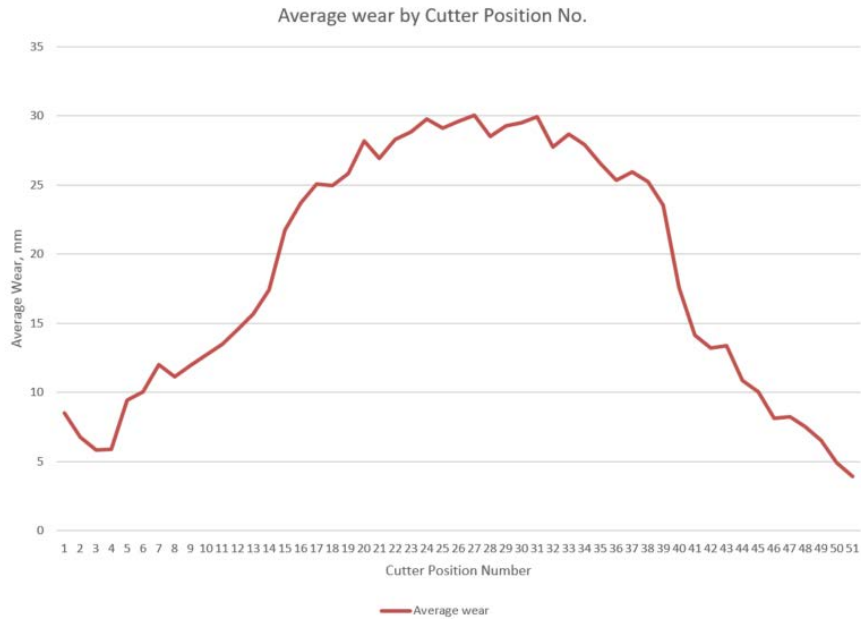


Figure 3 Average wear of positions on the cutterhead at Yin Han Ji Wei.

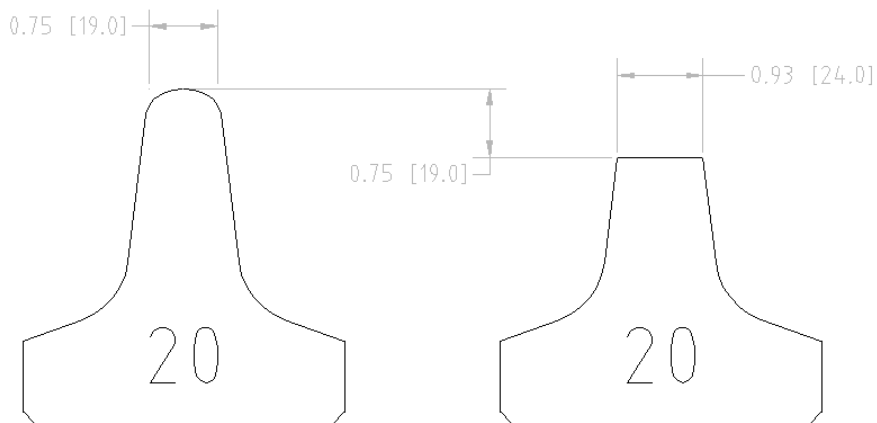


Figure 4 Illustration of tip with different wear values

Average tip width is important because the advance rate of the TBM will be reduced as the tip width of the disc increases. For example, in 190MPa Granitic rock:

- The theoretical advance rate with new 19-mm tip width discs will be 1.36m/hour in massive unjointed rock.
- In the same rock, when the tip width has been increased by wear to 24mm, the theoretical advance rate decreases to 1.06m/hour. This represents a significant decrease in TBM performance.

2.3. Enhanced metallurgy and shape

One proven solution to increase the average penetration rate is to use discs with a narrower tip width. An alternate method would be to reduce the flank angle of the disc blade so that it becomes wider more slowly as it wears, effectively staying “sharp” longer. The risk of using a disc with reduced flank angle is that the mechanical stress within the disc will be increased and such stress could result

in bulk fracturing when the cutters are subjected to shock loading. Clearly, to mitigate the risk, a steel with both increased strength (hardness) and increased fracture toughness would be beneficial.

2.4. Experience from site: The Røssåga project: Testing of XHD Rings

The TBM tunnelling part on the Røssåga HEPP in Norway consisted of 7400m long main headrace tunnels. In addition, it was decided to bore the access tunnel at a decline of 10% and a curve radius of 500m. As well, the project included building a new underground power station and other tunneling works related to the new power station. The tunnel was excavated with a 7.23m MB-TBM equipped with 49 19-inch cutters.

Immediately after the TBM started boring, extremely hard rock with average rock strengths of above 200 MPa and some zones with strengths above 280 MPa were encountered (see Figure 5). In addition, the rock was massive with very limited fracturing, with NTNU fracturing classes below St. I- and highly abrasive with Cutter Life Index (CLI) values ranging from 4,5-11 and averaging just above CLI=5.

The extreme rock properties and the geometry of the initial works signified some of the most challenging boring conditions for any TBM and would put any TBM and cutter to the ultimate test. The extreme conditions caused low cutter life (approximately 100-150m³/cutter), which again affected the production of the project. To improve the situation, the Robbins cutter department got involved and did a detailed analysis of the geology, machine performance, cutter wear and cutter failure mechanisms. Based on the findings of the analysis the cutter department worked together with the steel supplier and heat treatment shop to optimize the cutter ring properties to the geology encountered. The Robbins Company's experience and years of experimenting on steel alloys and heat treatments allowed the cutter department to do qualified considerations and develop some different cutter rings with properties that could enhance the cutter life. After initial trials with several different materials/heat treatments that performed well, one of the versions, XHD, stood out and showed a very promising reduction of the destructive wear of the rings. The XHD cutters utilize the same alloys as the Robbins HD rings, however there are changes in the heat treatment process that improve the properties of the ring in extremely hard rock, as seen on Røssåga.



Figure 5. Extremely massive and non-fractured cutting face. *Photo: Andersson.*

The improvement of the XHD cutter rings is hard to quantify on the project because of gradual introduction of the new cutters and changes in the geology, but it seems likely that the performance in the very hard sections was improved by a minimum of 25%. The benefits of the XHD are also likely to explain the superior cutter life for the remaining of the project, even in the relatively softer ground.

Based on the rock testing and geological mapping the NTNU-model estimated a net penetration rate on the project of 1,37 m/h and cutter life as low as 88 m³/c on the first 5200m of the project). This illustrates to a certain degree the extremely challenging nature of the rock mass encountered. For the same length of the tunnel the actual net penetration rate was 2.12 m/h and the cutter life was 284 m³/c. When also including the last 2km of the tunnel the net penetration rate increases to 2.22 m/h and the cutter life to 306 m³/c.

The big deviations in the estimated and actual performance are likely to be explained by the test samples not being completely representative of the encountered geology and that the NTNU model might underestimate the performance of modern hard rock TBMs. It is, however, apparent that the TBM and cutters performed better than expected in the geology encountered.

There have also been trials performed of the XHD cutter rings on the Yin Han Ji Wei Project in China, which is operating in granitic rock of about 200 MPa. The results as of late 2017 indicate an improvement in cutter life of 23% compared to a Robbins HD ring in comparable geology and machine operation. Because the standard shape XHD discs tested at Yin Han Ji Wei performed significantly better than the industry standard, the next step will be to produce and test XHD discs with reduced flank angle. The goal is twofold: to increase penetration rate by reducing the average tip width on the cutterhead, and to increase disc ring life with enhanced metallurgy. Initial field test results are very promising but the final results are not yet available.

3. HIGH PRESSURE OPERATION

Another very challenging condition that has become more common over the last few years is cutter performance under high pressures. One example of this is the 6.5m diameter Single Shield TBM equipped with 19-inch pressure compensated disc cutters for the Delaware Aqueduct Repair project in the USA. Cutters capable of withstanding 20 bar are required for this project.

Robbins has developed and patented a pressure compensation system for cutters that differs from previous designs. The design utilizes a pressure-compensating retainer for operations of cutters at elevated pressures. Fourteen pistons are located in the seal retainer portion of the cutter, whereas the customary method is to add one or two pistons to the cutter shaft. The pistons are visible in Figure 6 as the circular pattern outboard of the shaft where the oil filling hose is connected. Pistons located in the retainer have proven to be more clog resistant, especially in soft ground tunnelling, than those located within the cutter shaft. Theoretically, the cutter will withstand any conceivable pressure but because we had not used this cutter in excess of 5 bar, the cutter was tested up to the 36 bar capacity in a water-filled cutter testing pressure vessel. A static test and a rotating test, both under pressure, were undertaken.



Figure 6. Pressure compensating disc cutter.

3.1. Pressurized Static Test

External pressure on the cutter was increased gradually to 5.0bar within the first minute and afterwards the pressure was increased at a rate of 2.0bar/min. The pressure was raised ultimately to 36bar, which is the maximum hydrostatic pump capacity. Figure 7 demonstrates the correlation of pressure inside and outside the cutter within the testing time. Internal cutter pressure was increased to be almost identical to external pressure in the vessel. The difference was found to be in the range of 0.15bar.

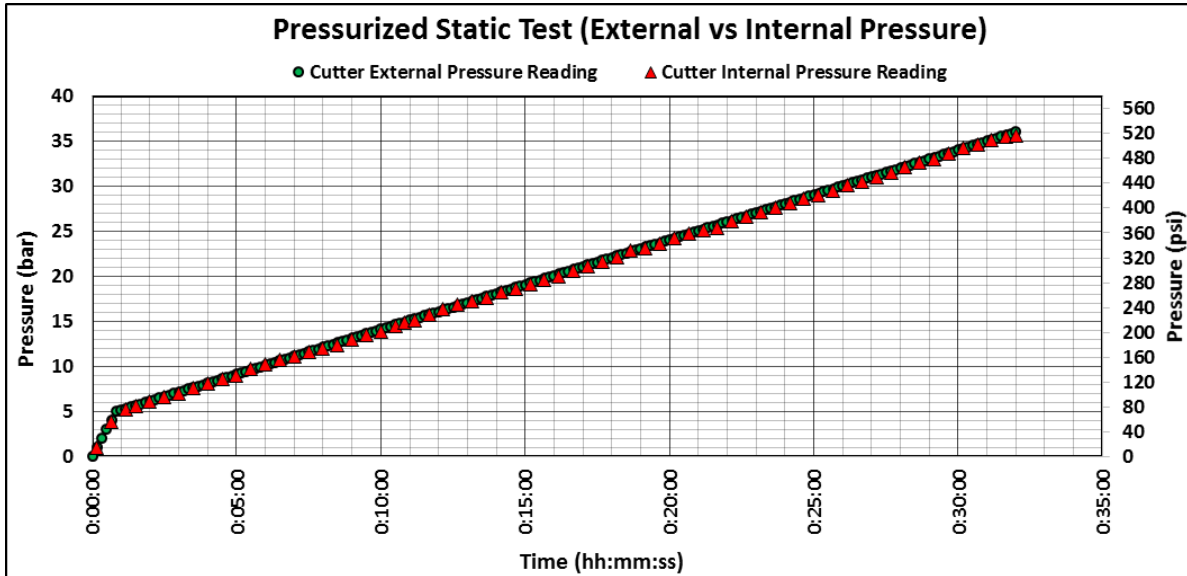


Figure 7. Correlation of pressure with testing time.

3.2. Pressurized Rotating Test

The cutter was rotated and the speed was gradually raised to the maximum available speed in the motor. The cutter reached 110 rpm (calculated from VFD and observed with non-contact tachometer). The VFD parameters were recorded at each speed ramp-up. At maximum speed, the vessel pressure was increased from zero to 5.0 bar in one minute and the VFD parameters were recorded. Afterwards, the pressure was increased at a rate of 2.0 bar/min up to 20 bar. The cutter rotation continued at 110 rpm and external pressure was kept at 20 bar for 60 minutes. During this period, the VFD parameters and pressure readings were observed continuously and recorded every 5 minutes. After 60 minutes of operation, the pressure was increased again at a rate of 2.0 bar/min. The pressure was raised gradually until it reached the maximum pump capacity of 36bar.

The results showed that at maximum cutter speed, 110 rpm, the operation of the cutter was not affected and the cutter driving torque did not change even though the pressure reached the pump's maximum capacity of 36 bar. The cutter's pressure compensation mechanism balanced the external and internal pressure. The cutter was tested continuously for one hour at 110 rpm and 20 bar. The oil was drained and inspected after the test and no evidence of water ingress was observed.

The pressure compensated cutters for Delaware Aqueduct Repair project are expected to start operation in late December 2017 and the initial results will be presented at the conference.

4. CUTTER MONITORING SYSTEM

Robbins has developed and utilized a cutter monitoring system on several hard rock projects over the last decade and has, over the last year, developed a new generation of the system, known as SmartCutter. In hard rock tunnelling, continuous information from the cutterhead is essential. The ultimate goals of cutter instrumentation are to monitor real-time individual cutter operation, acquire

more realistic cutterhead thrust force values, and gain a better knowledge of the geology in front of the cutterhead. Analysis of this information can provide in-depth knowledge of machine excavation. Information about cutter operation has direct and indirect advantages: It helps better predict and monitor cutter usage rates, and it can reduce the cost of unplanned cutter or ring replacement, which can result in a better planning of inventory, manpower, and cutter rebuild requirements. Another merit of cutter instrumentation is to maintain assembly health by monitoring individual cutter operation. An instrumentation system can notify an operator of uneven or harsh ring wear and makes it possible to prevent unnecessary seal or bearing changes. Additionally, it can prevent cutterhead damage caused by a late cutter change.

The results from the recent projects are very promising and provide very accurate and valuable data as given. The latest generation of the system is currently being installed on all cutter positions on the Delaware Aqueduct Repair project.

4.1. Experience from site: Cutter disc monitoring on the AMR Double Shield Hard Rock TBM

The AMR machine is a Double Shield TBM operating in India with a cutterhead diameter of 10.0 meters and a total of 69 cutter positions. During a trial of the new generation of cutter monitoring sensors throughout July, August, and September 2016 several cutter positions were monitored during operation. The location of these cutters changed from the gage area to the face area as the cutters were moved inward to positions where the allowable cutter wear is greater.

Figure 8 shows the AMR SmartCutter system diagram. Each instrumentation box was installed on the wedge bolt of the cutter housing. Two gateways were installed on the structure of the machine conveyor. Two gateways ensured the communication link was maintained at all times. In the event of a loss of communication the operator was alerted on the monitor with a red alarm. The instrumentation battery capacity was increased beyond the normal cutter wear life, meaning that instrumentation could operate throughout one or more cutter changes. Additionally, the battery capacity and status was continuously reported and displayed on each instrument at the operator screen.

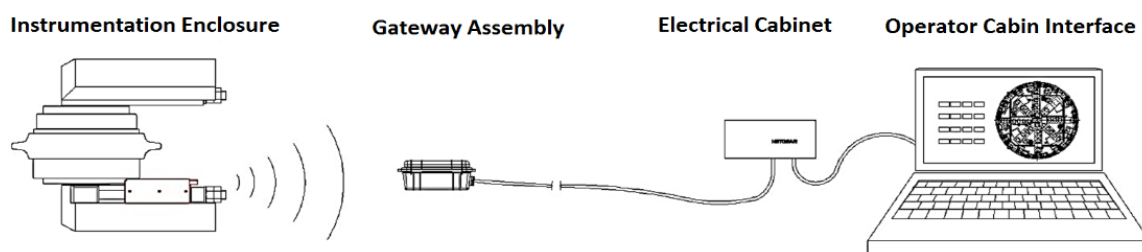


Figure 8. System diagram.

The magnetic sensor inside the instrument enclosure senses the time of each cutter revolution in milliseconds and reports the cutter speed. Knowing the disc cutter radius, the cutter's distance from the cutterhead center line, and also the cutterhead speed one can derive the cutter speed. Now using the same correlation and knowing the cutter radius and speed, its wear can be calculated. Defining a reasonable sampling and radio data transfer rate is critical to generating meaningful data. At the same time, a detailed data filtering algorithm is required for representative and accurate wear calculation.

Figure 9 shows eight minutes of unfiltered data for a single cutter. From this figure one can determine that the highest speed that has the majority of the data represents the normal speed in which the cutter is rolling without interruption. If there are any hiccups where less than true rolling occurs, a reduction in speed is to be expected. The cutter wear is calculated from known factors and is plotted

on the red line. The cutter velocity perfectly correlates with the changes in cutterhead speed at every step between 9:59 to 10:01 as expected.

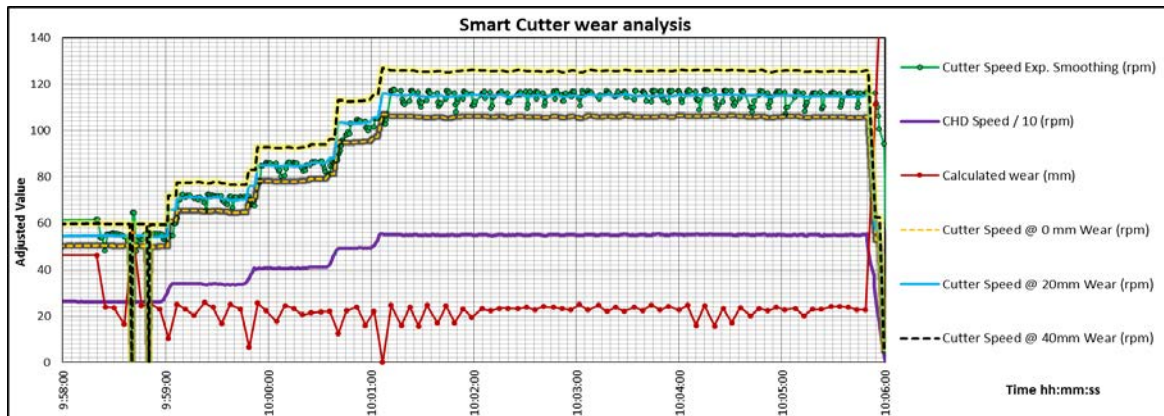


Figure 9. Eight minutes of unfiltered SmartCutter data from AMR (micro analysis).

Figures 10A-B below show the wear results of five SmartCutters after filtering. The cutter relocation is also displayed on these plots. This macro analysis shows a very close correlation of SmartCutter average wear values and the actual field measurements on the cutters, especially within the bold increases in wear. Operators can set certain wear limits for each cutter in the program alert setting. In many cases alerts can prevent unexpected cutter ring wear-related issues from causing further damage to bearings and hubs.

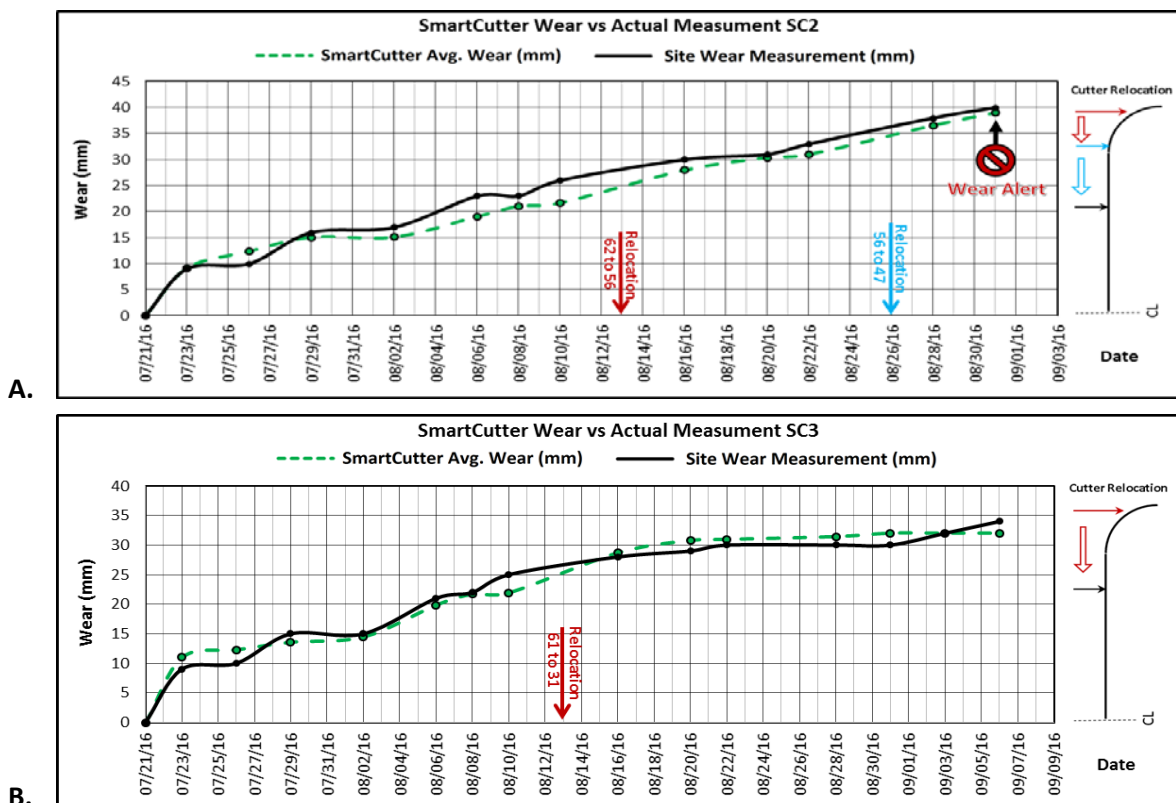


Figure 8. SmartCutter wear reading in comparison to job site measurements for SC2 to SC3.

5. NEW CUTTER DESIGNS UNDER DEVELOPMENT

5.1. Clamp Disc Cutter

The below cutter assembly, figure 11, differs from a conventional cutter in two fundamental ways. First, the disc is mechanically clamped to the hub versus being shrink-fitted to the hub with a weld-on retention ring. Secondly, the disc is much lighter (narrower) than a traditional disc.

This design enables the rapid change of the disc during maintenance. The disc weight is less than 50% of the weight of a traditional disc of the same outside diameter.

A greater proportion of the total disc material is the sacrificial wear material. Because of this, more expensive disc materials become practical. More of the cutter can be used before it needs to be changed, making for a cost-effective way of excavating long-distance tunnels or tunnels where high wear is anticipated.

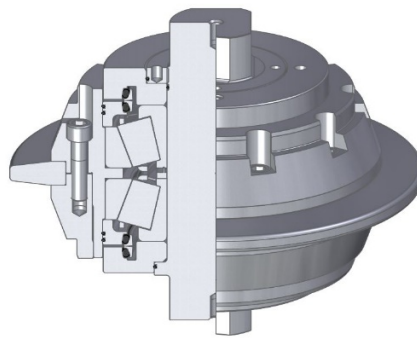


Figure 9. Principal drawing of clamp disc cutter.

The 17-inch version of this new design has been undergoing testing with promising results. The 20-inch version will be tested in early 2018.

5.2. Traction Control Disc Cutters

This special disc shown in figure 12 has been designed for use when mixed ground conditions or soft ground conditions can be expected in hard rock. When a TBM encounter soft soils with standard hard rock discs installed, there is a probability that the friction between the disc and the soil will be insufficient to make the cutter rotate. When the cutter fails to rotate it will eventually wear flat on one side. This can occur quickly if the ground is somewhat abrasive.

The Traction Control cutter design combines a standard disc profile for hard rock with protrusions on the flank of the disc that are similar to a “mill tooth” layout, giving the ability to penetrate the soil and force the cutter to rotate.



Figure 10. Picture of Traction Control disc ring.

6. CONCLUSION

The recent technological developments detailed in this paper offer good opportunities to optimize cutter life and TBM performance on projects in hard rock conditions. To be used successfully requires a careful analysis of the conditions and whether these developments are optimal, but in projects with particularly challenging ground they can make all the difference.

Contractors should carefully consider whether the use of larger discs will provide an economic benefit. The choice of 20-inch cutters over 19-inch cutters coupled with a well-developed cutterhead management program can provide longer time between cutter changes and longer overall life between rebuilds.

Contractors will also benefit from carefully considering the technology applied by each manufacturer to their disc cutters. Any competent manufacturer can make a disc cutter but the proof of the quality of the disc will not be apparent until the steel meets the rock. Nearly all disc cutter manufacturers now offer a tool steel disc ring and most have similar composition. It is, however, less the composition of the disc ring than it is the subsequent processing that makes the difference in performance. Less expensive disc cutters will not be economical in hard rock when considering the total cost over the duration of a project and this becomes more and more significant as the rock becomes ever more challenging.

A well-thought-out cutter strategy along with the latest in high cutter qualities and tool steels developed to optimize cutter life can have a huge impact, not only on cutter cost but also on TBM performance and the overall schedule for the project.

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