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Premature discard of 45 mm ropes operating on a Blair Multi-Rope rock winder

Summary

In September 2005, Driefontein Gold Mine installed four 2500 m long 45 mm diameter CASAR Duroplast ropes on the No. 2 Shaft electrically coupled Blair Multi-Rope (BMR) rock winder, located west of Johannesburg. This was the first time a rope with eight compacted outer strands and a plastic coated steel core was used by the mine for deep vertical shaft mine hoisting.

At the end of May 2006, two of the ropes on one BMR drum had to be discarded due to broken wires in the outer strands at the drum end, detected during routine magnetic testing. These ropes, as a pair, had completed 35,000 cycles (i.e. hoisted 70,000 skips or 604,000 tonnes of rock). The two ropes on the other BMR drum showed no damage at this time. On 20 June 2006 the remaining two ropes were discarded at 38,000 cycles also due to broken wires in the outer strands at the drum end. The average standard rope life previously achieved on the same winder was circa 66,000 cycles.

This paper describes the full operating history of the ropes, the lubrication used and the general maintenance practices. A detailed description of the rope failure mechanisms is given including SEM micrographs. Finally, recommendations are made how this situation can be avoided in the future.

1 Driefontein Gold Mine - No. 2 Shaft BMR rock winder

The rock winder is a BMR installation at Driefontein No. 2 Shaft. The shaft, headgear and the winders were commissioned in 1972 and are responsible for hoisting circa 160,000 tonnes per month of gold-bearing ore which represents 62 % of the Driefontein Gold Mine monthly production. The most important shaft data is shown in Table 1 below. Figure 1 shows the Driefontein No. 2 Shaft concrete headgear and Figure 2 shows views and the layout of the BMR rock winder. The headgear sheaves are manufactured from cast steel and are not fitted with any inserts, Figure 3.

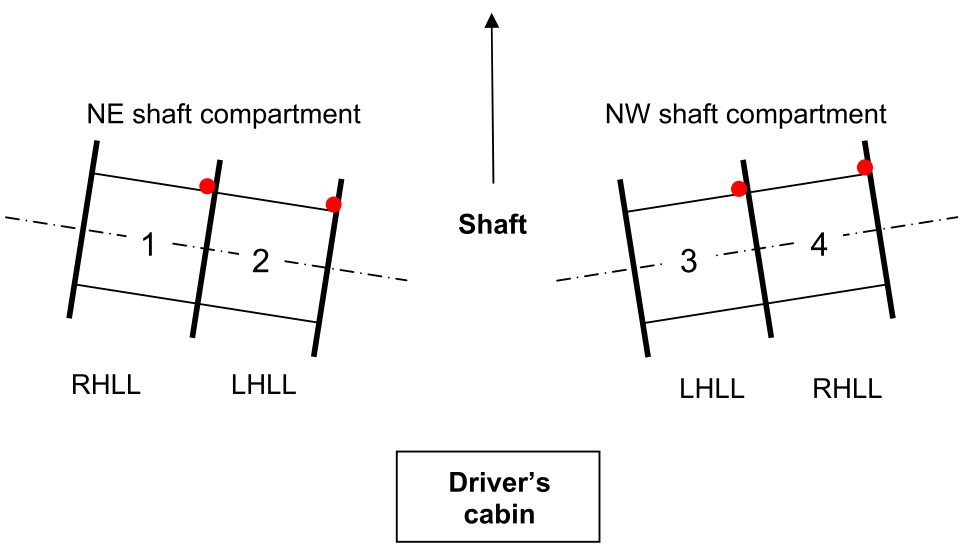
Hoisting depth (m)	2043
Drum diameter (m)	4.27
Sheave diameter (m)	4.27
Skip mass including attachments (kg)	13,022
Payload (kg)	17,250
Hoisting speed (m/s)	18.0
Type of drum coiling	LeBus

Table 1: Driefontein No. 2 Shaft BMR rock winder data.

Figure 1: Driefontein No. 2 Shaft headgear, bottom left four ropes are the BMR rock winder ropes.

Figure 2a: Driefontein No. 2 Shaft BMR rock winder motor. Note that the BMR winder has two separate 8,250 kW electrically coupled drum motors and each drum has two winding ropes.

Figure 2b: Driefontein No. 2 Shaft BMR rock winder drum. Note that the BMR winder has two separate drums and each drum has two ropes. The hawse holes are on the left of each drum compartment as viewed in this image.



NB: both drums are overlay, red dots indicate positions of the hawse holes

Figure 2c: Driefontein No. 2 Shaft BMR rock winder layout. Note that the BMR winder has two separate drums and each drum has two ropes, one RHLL and one LHLL.

Figure 3: BMR rock winder headgear sheaves, note no inserts.

Each of the two winder drums have two ropes. It is therefore necessary to ensure that each rope in a pair carries its equal share of the skip mass and payload. A load compensating sheave is fitted on top of each of the two rock skips that is free to rotate and thereby ensures equal load sharing, Figure 4. This is a typical arrangement for BMR winders in Southern Africa.

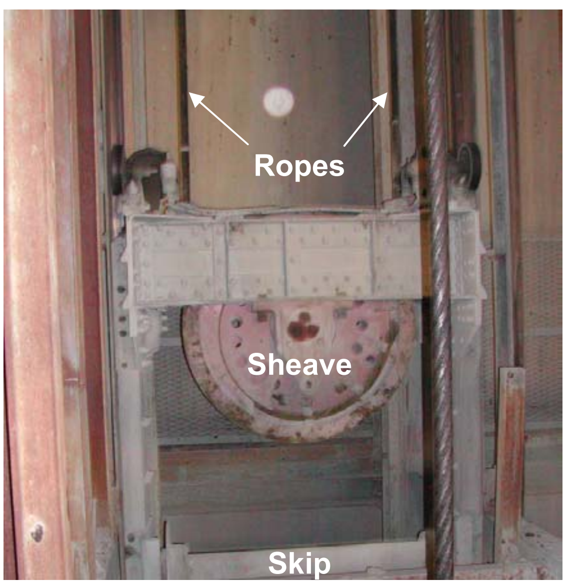


Figure 4: BMR rock winder rope load compensating sheave mounted on top of the skip and removed from skip for routine rope maintenance.

2 Previously used rope design

Until September 2005 the mine used triangular strand winding ropes on their No. 2 Shaft BMR rock winder. These ropes achieved an average lifetime of 13 months or 66,000 cycles, hoisting 2,277,000 tonnes from No. 2 shaft. This average life is based on 23 previous rope sets. The best lifetime achieved by the triangular strand ropes corresponded to 19 months or 94,350 cycles (188,700 skips). The reason for discarding the triangular strand ropes was mainly due to broken outer wires at the drum end of the rope due to damage at the LeBus turn and layer crossovers. Figure 5 shows a typical triangular strand rope cross-section.

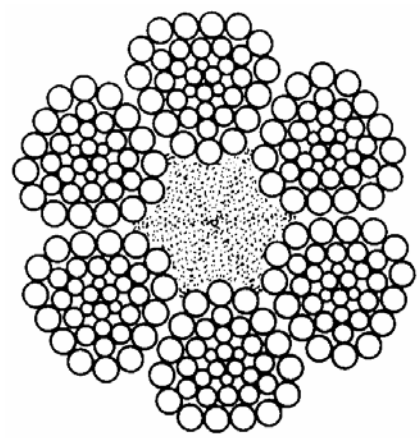


Figure 5: Typical triangular strand rope cross-section, [**1**].

In this paper, a cycle is as per SANS 10294, [**2**], i.e. bank to bank for one conveyance. For a BMR rock winder this means the number of skips hoisted per shaft compartment. For every cycle a BMR rock winder hoists two skips.

3 The new rope design concept

On 25 September 2005 the mine installed four eight-strand winding ropes (Coil numbers EX0501068/01 and /02 and EX0501069/01 and /02). The specification of these ropes as well as the previous triangular ropes are detailed in Table 2 below.

Rope Construction	**Duroplast**	**Triangular Strand**
Nominal rope diameter (mm)	45	45
Rope length installed (m)	4 x 2500	4 x 2360
Rope lay	Right and left hand Lang’s Lay	Right and left hand Lang's Lay
Tensile grade (MPa)	1770	1800
Wire finish	Galvanised	Bright
Rope terminations	Compensating sheave at skip, cow hitch on drum shaft	Compensating sheave at skip, clove hitch on drum shaft
Rope mass (kg/m)	9.08	8.71
Minimum breaking strength (kN)	1588	1489
Rope factor of safety	4.81	4.61
Rope capacity factor	10.69	10.03

Table 2: Duroplast and triangular strand rope specifications for No. 2 Shaft BMR rock winder.

Duroplast ropes are characterized by eight compacted, equal lay outer strands and a fully lubricated independent wire rope core (IWRC). The core is enclosed by a plastic layer which also cushions the outer strands from one another. This plastic layer (shown in red in Figure 6a) between the steel core and the outer strands gives the rope high structural stability, avoids internal rope destruction and protects the core against corrosive environments. The plastic layer seals in the core lubricant for the life of the rope.

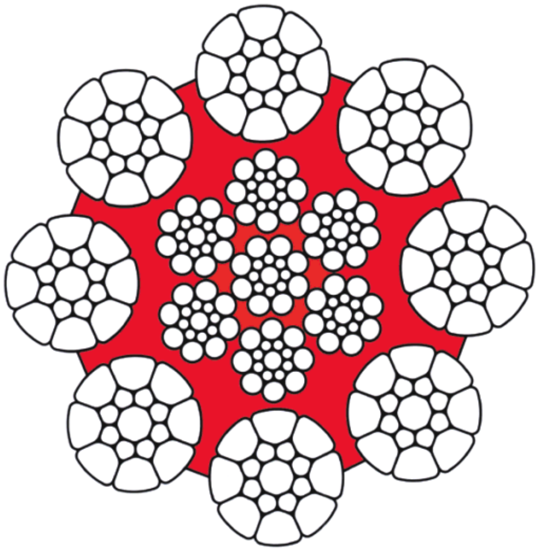


Figure 6a: Duroplast rope cross-section, [**3**].

Figure 6b: 45 mm Duroplast as-installed exterior.

This rope has a high breaking load and good resistance against drum crushing. Ropes like these with a plastic infill have been successfully used in the crane industry for more than 35 years. The first installations of these ropes in mining applications, both in Europe and Australia, date back 17 years.

The eight-strand design provides a round wire rope cross-section. The compacted Lang's lay outer strands provide good abrasion resistance and smooth coiling performance on multilayer drums, Figure 6b. The construction shows lower levels of rotation in service than conventional single layer rope designs.

4 New rope discard criteria

Prior to installation of the new ropes, the mine and the rope manufacturer examined SANS 10293 "Code of practice for the condition assessment of steel wire ropes on mine winders", [**4**] and concluded that this standard could be applied to the new ropes. In the case of the 45 mm eight-strand rope the mine could work safely on a maximum of not more than three broken wires in one strand in one lay length as this represents less than 40% of the outer wires in the strand and 2.59 % of the total steel area. This would keep the rope discard state within the bounds of SANS 10293, Section 5.5.1. Outer strand outer wire specifications for the 45 mm eight-strand rope are given in Table 3.

Nominal rope diameter (mm)	45
Total metallic area of rope (mm^2)	1051
Mass of rope (kg/m)	9.08
Diameter of outer wire (mm)	3.40
Area of one outer strand outer wire (mm^2)	9.08
Number of outer wires in each outer strand	8
40% of outer wires in one outer strand (wires)	3.2
One outer strand outer wire as % of total metallic area	0.86
Three outer strand outer wires as % of total metallic area	2.59

Table 3: Discard criteria calculations for the 45 mm Duroplast rope.

At the No. 2 Shaft BMR rock winder, broken wires are detected by traditional magnetic inspections which are conducted by an external independent testing company every month (circa 5,000 cycles). It was generally anticipated that broken wires would eventually form at the drum end of the ropes due to the plastic wear type damage that occurs at the LeBus turn and layer crossovers.

5 Rope maintenance collaboration and practices

The mine and rope manufacturer worked together closely in installing, inspecting and maintaining the eight-strand ropes. The objective of this collaboration was to guide the mine in the use of the new eight-strand rope technology and to maximise rope life and thereby minimise rope cost per 1000 tonnes hoisted by the mine.

Care was taken after installation to double down with full skips to ensure that the load in the dead turns on the drum was at least 50% of the maximum rope operating load. Figure 7 shows the general arrangement for doubling down in the shaft. This is critical to prevent dead turn slackness and associated premature failure of the wires in the dead turns due to secondary bending of the wires caused by the rope layers above. After every backend cut, the ropes were again doubled down with full skips.

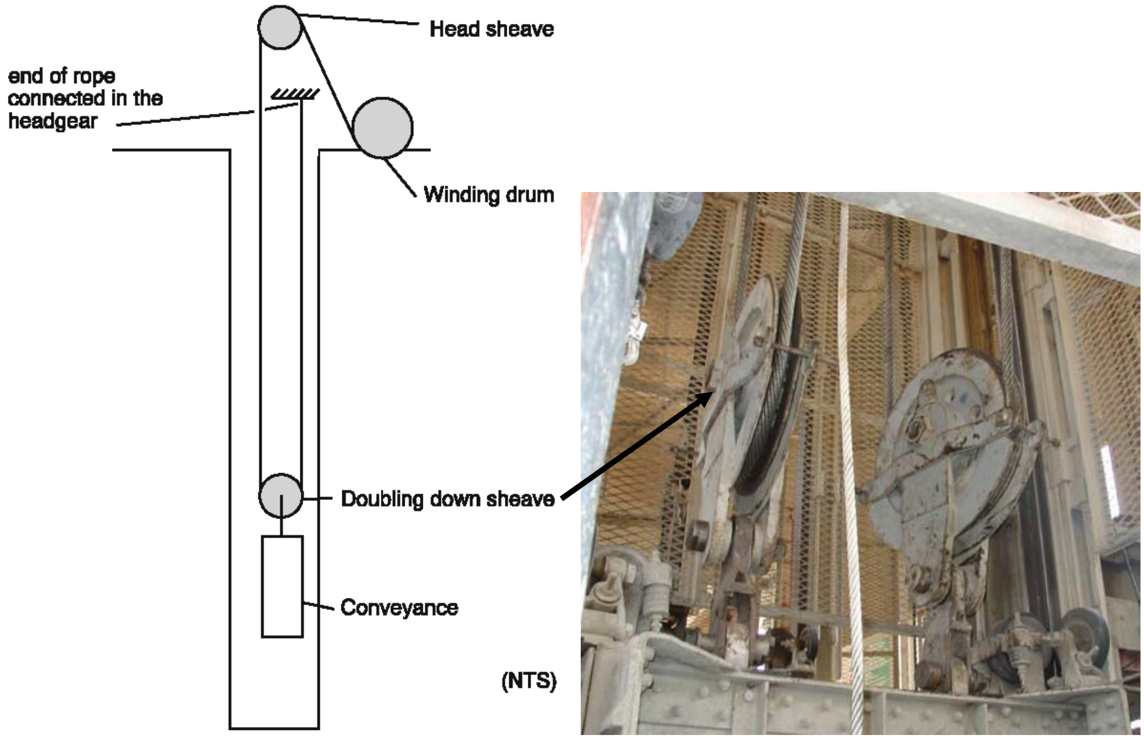


Figure 7: Doubling down arrangement for ensuring proper tension in the dead turns on the drum.

A key difference in the maintenance practices compared to the previous triangular strand ropes was the use of ELASKON Spray Oil 200 applied manually circa every circa 2,500 cycles over the full rope length. In the past, the triangular strand ropes were lubricated manually every two months with FUCHS Noxal No. 8 wire rope dressing.

The rigging personnel at the shaft reported that the eight-strand ropes were easier and safer to handle than the triangular strand ropes as they showed very little rotation when being disconnected from the skips and drums during maintenance procedures. The reason for this change in rotation behaviour is a more stable and torsionally stiff construction including its variable lay length design, [**5**]. The plastic layer between the core and the outer strands makes a significant contribution to the rope stability.

The South African mining regulations require that the compensating sheave tangent points at the skips be moved every 3 months (Figure 4). This practice was followed on the No. 2 Shaft BMR winder and the mine had the used tangent point samples tested every time. Two sets of four tangent point tests were done up until the premature discard of the four ropes. These tests showed no significant reductions in breaking strength compared to the new rope tests (average = 99.5% of new rope test values).

6 New rope stretch during skip loading

One specific advantage of changing to the new rope design was significant reductions in rope stretch during loading of the skips. This had the benefit of reduced spillage at the shaft bottom and a more efficient loading process. The observed stretch data for the eight-strand ropes on the No. 2 Shaft BMR rock winder are listed in Table 4.

Rope construction	Duroplast
Rope diameter, d (mm)	45
Tensile grade (MPa)	1770
Rope metallic area (mm^2)	1051
Rope metallic area / d^2	0.519
Number of ropes per skip	2
Rope suspended length (m)	2043
Change in total load, during loading (kN)	169
Rope stretch due to change in load (m)	1.25
Average rope modulus E (GPa)	**131.6**

Table 4: Observed stretch data for the new eight-strand ropes on the No. 2 Shaft BMR rock winder.

7 New rope performance history

The rope manufacturer's service life calculation indicated a significant improvement in expected wire rope fatigue life. Operational improvements in the form of reduced maintenance and easier rope handling were also anticipated.

The mine was offered a rope life guarantee of 165,000 cycles (2.5 times the average TSR life on the winder). During a routine magnetic test of the ropes on 30 May 2006, the damage shown in Figure 8 was found on rope No. 1 (see Figure 2c) and a number of broken wires were found in the same position on rope No. 2. At this stage the winder had completed 35,000 cycles since the ropes were installed end September 2005. The rope manufacturer was present during the magnetic testing and a decision was made to immediately remove ropes 1 and 2 from the winder and replace them with a spare set of triangular strand ropes. Ropes 3 and 4 did not show any damage at that time.

Figure 8: First broken wires found on rope No. 1 on 30 May 2006 on bottom drum layer, 12 turns from drum flange / 1st layer crossover. This damage is in the Section B/B, see Figure 9.

In discussions between the mine and rope manufacturer, it was also agreed that 150 m should be cut off the skip ends of ropes 3 and 4 so that what were dead turns in Section B became live turns (see Figure 9). The objective was to move the acceleration region and increase the lifetime of ropes 3 and 4 assuming that they were suffering from the same damage mechanism as ropes 1 and 2. The cuts on ropes 3 and 4 were made and the next magnetic tests scheduled for 20 June 2006.

At the time of discard of ropes 1 and 2 it was assumed that the reason for the damage shown in Figure 8 related to interaction between the rope and the drum coiling sleeves. Tight drum grooves were found on parts of the drums at the time of rope installation in September 2005.

As the winder is electrically coupled it is feasible to mix rope constructions on the two drums as long as they are changed in pairs. The winder is able to compensate for different rope pair stretch during the wind to ensure that both skips arrive at the loading and tipping positions simultaneously. This is not possible on a conventional mechanically coupled double drum or BMR winder.

On 20 June 2006 ropes 3 and 4 were inspected and a significant number of broken wires were found in the same region as the original wire breaks in ropes 1 and 2. These areas of rope had now been moved into the shaft (as a result of the 150 m front end cuts). The extent of the wire breaks were such that the mine decided to immediately discard ropes 3 and 4. They had completed 38,000 cycles since installation.

8 Reasons for premature discard of the eight-strand ropes

8.1 General distribution and nature of rope damage found

Rope samples including areas with broken wires were sent for examination to both the rope manufacturer and the Council for Scientific and Industrial Research laboratories in Johannesburg. In both cases pieces were cut from Sections A, B, B/B and C as indicated in Figure 9.

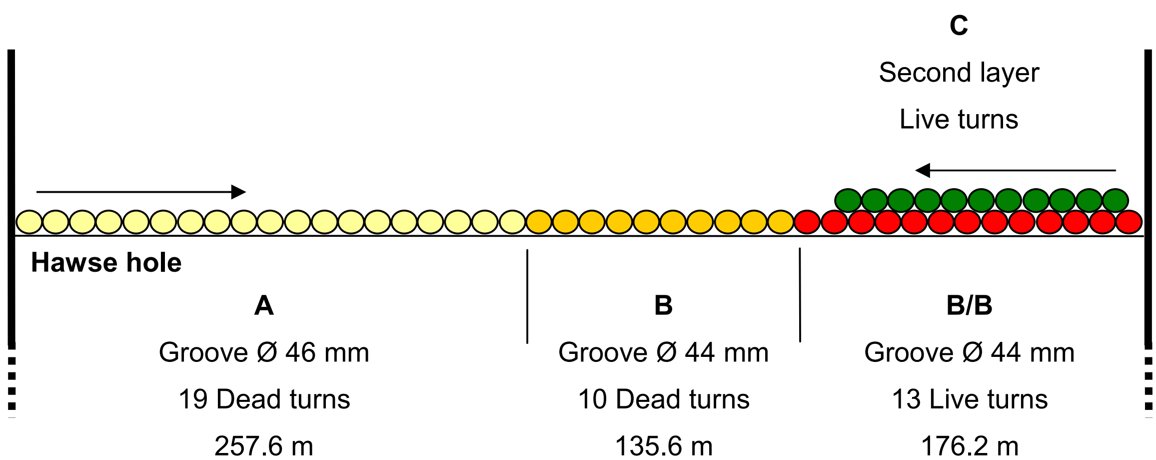


Figure 9: Discarded rope sections relative to drum coiling positions at rope installation, total rope length on drum bottom layer is 569 m, 42 turns.

The reason for selection of samples from the four sections of rope on each drum compartment was to allow an analysis of the nature of damage in each section and a view of the distribution of damage across the drum compartments. Each drum compartment had 2,500 m of installed rope. It was felt important to consider the way in which broken wires were spaced along the ropes in determining the likely cause of their premature failure.

Figure 10 shows Sections A, B, B/B and C relative to the winder and headgear mounted sheaves. The typical levels of local damage found in the sections are shown in Figures 11, 12 and 13. No broken wires were found in samples cut from Section C and this fact was also confirmed by re-examining the NDT test data from the two discard dates of ropes 1 and 2 and 3 and 4.

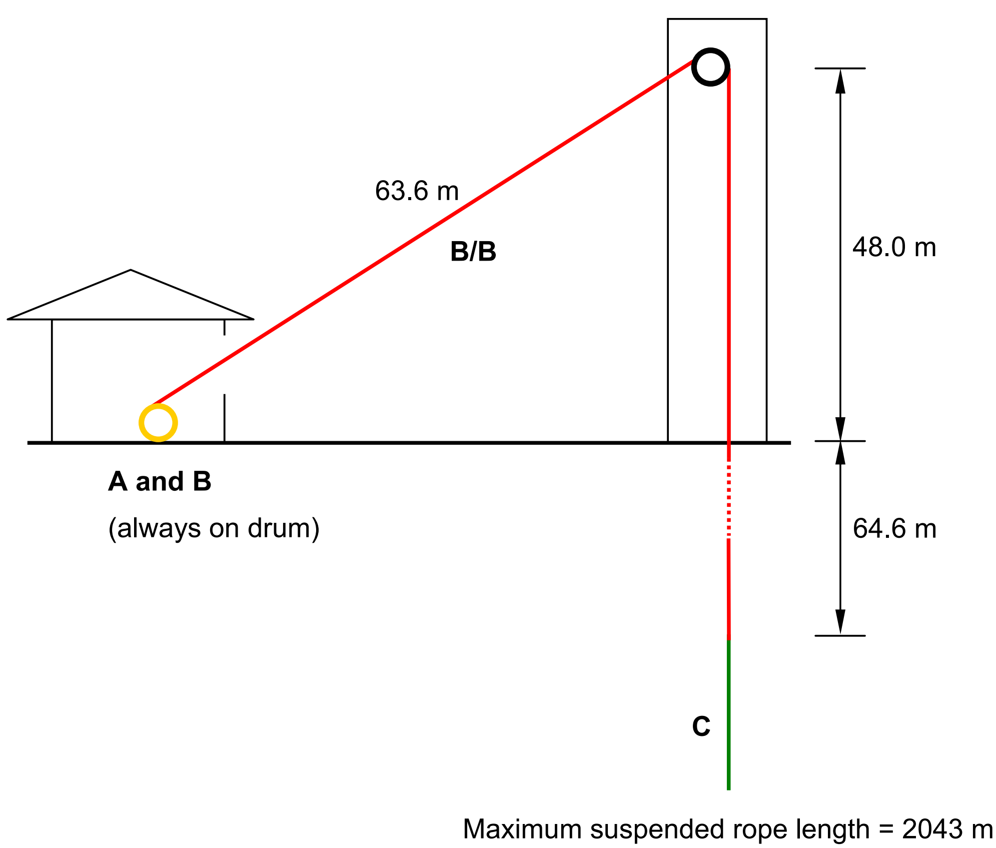


Figure 10: Rope lengths relative to the BMR winder, headgear sheaves and mine shaft.

Figure 11: Typical damage found in Sections A and B, at discard.

Figure 12: Typical damage found in Section B/B, at discard. Note that wire ends have separated.

Figure 13: Typical condition of rope in Section C, at discard.

8.2 Galvanising delta-layer cracking in Sections A, B and B/B

Metallurgical examination of the rope samples showed no deficiency of the steel within the wires themselves in terms of either: composition, microstructure or mechanical properties. The galvanised coating of zinc on the wires, applied for corrosion protection, was considered thicker than what is normal and contained a relatively thick delta-layer, a brittle inter-metallic phase, adjacent to the wire surface. This layer was cracked with the cracking generating numerous stress concentrations which, in turn, could have initiated fatigue in individual wires in Sections A, B and B/B, Figure 14. This phenomenon was considered as a possible cause of failure leading to premature discard of the rope, [**6**].

However, it was also found that all other sections of rope including Section C and stock samples of rope held at the rope factory also had cracked delta-layers. Based on this observation the general assumption was that the whole ropes went into service with such delta-layer cracks yet only in Sections A, B and B/B did the delta-layer cracks correspond to cracking in the steel sections of the wires.

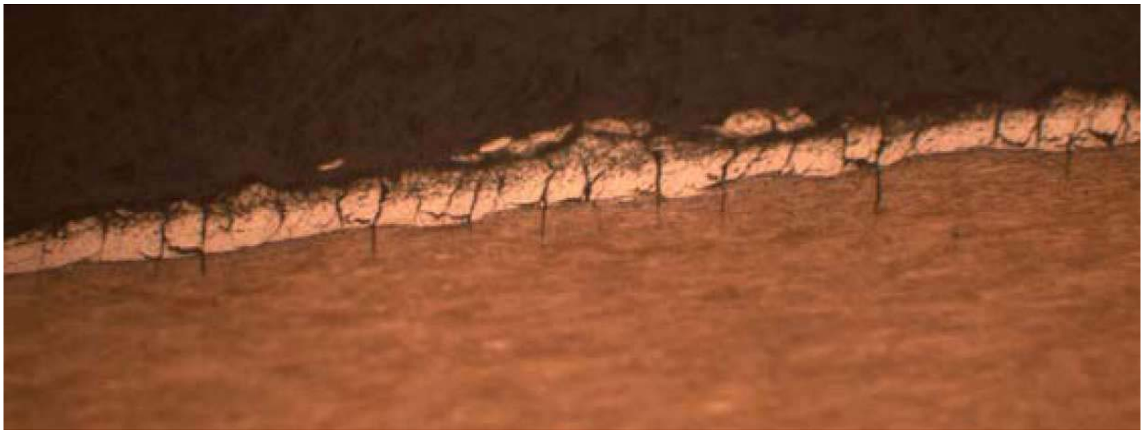


Figure 14: Cracking of galvanised layer in Section B/B, circa 400x magnification, [**6**].

Figures 15 and 16 show typical fracture surfaces of outer and inner wires taken from Section B/B (see also Figures 9 and 12). The general pattern of failure was one of fatigue crack initiation from multiple sites around the wire circumference leading to final fracture in the centre of the wire. This is a typical indication of the rope section having been subjected to high cyclic compressive loads and associated secondary bending of the wires and strands.

Regarding the issue of delta-layer cracking, it was felt that this may have contributed to the degradation of the rope but as it was present throughout the rope lengths it could not have been the primary driver as wire breaks would then have been found in Section C. Section C, especially the first few turns thereof, sees the same tensile loading and bending as the last few turns of Section B/B. It seemed feasible that there must have been some other factor common to Sections A, B and B/B (which were all in direct contact with the drum) that lead to their degradation. The general nature of the damage was consistent across all four ropes.

Figure 15: Typical fracture surface of outer wire from Section B/B, see also Figure 12. Arrows indicate assumed multiple fatigue crack propagation regions towards central region of final failure. Image supplied by Wire Rope Technology Aachen.

Figure 16: Typical fracture surface of inner wire from Section B/B, see also Figure 12. Arrows indicate assumed fatigue crack propagation regions towards central region of final failure. Note also longitudinal cracking possibly from high transverse loading. Image supplied by Wire Rope Technology Aachen.

8.3 Tight drum grooves in Sections B and B/B

An obvious potential driver for the severe damage seen in Section B/B (Figure 12) and to a lesser extent the damage in Section B (Figure 11) is the fact that the drum grooves in those areas were found on all four drum compartments to have a diameter of 44 mm, Figure 17. This anomaly was discovered at the time of installation of the eight-strand ropes in September 2005.

Figure 17: 44 mm drum grooves in Sections B and B/B at installation.

The SANS 10294 code of practice for the performance, operation, testing and maintenance of drum winders relating to rope safety, [**2**], recommends a mean drum sleeve groove diameter for a nominal 45 mm rope of 48.15 mm and a mean pitch of 47.81 mm (compared to an actual pitch of 46 mm). A 44 mm groove would therefore place significant compressive loads on the rope especially if the rope is manufactured with a tolerance on the nominal diameter of +4%, as was the case with the eight-strand ropes. Figure 18 shows imprints of the rope that are assumed to be a consequence of the tight drum grooves in Section B/B. The photograph was taken on the day that ropes 1 and 2 were discarded. The drum grooves in that region were measured again and were still at 44 mm.

Figure 18: Rope imprints on drum grooves in Section B/B after 35,000 cycles.

The 45 mm triangular strand ropes that were used previously on the No. 2 Shaft BMR winder would not have been as susceptible to damage from the 44 mm drum grooves as the 45 mm eight-strand ropes. The reasons for this are that the TSRs show larger reductions in diameter due to tensile loading because of their fibre core and larger reductions in diameter due to unlaying at the drum end once installed. The unlaying at the drum end is driven by a rope torque equalisation process required to compensate for differential loads along the rope length in deeper mine shafts, [**7**]. The 45 mm eight-strand ropes were manufactured with a variable lay length so that the manufactured lay lengths along the ropes would match the values that the ropes would assume in service, [**5**]. This means that there would be (and there was) no reduction in diameter due to lay length changes at the drum end or anywhere else along the installed ropes.

8.4 Dead turn slackness in Sections A and B

The tight drum grooves in Sections B and B/B are a valid explanation for the damage found in those regions. However, for a rope which settled with an operating diameter of circa 45.90 mm (45 mm + 2%) the tight groove issue is not as problematic in Section A where the measured groove diameter was 46 mm across all four drum compartments. In Section A and to a lesser extent in Section B, see Figure 9, it is thought that accumulation of slackness in these dead turns lead to the wire failures shown earlier in Figure 11. The majority of the broken wires were located at the LeBus half turn crossovers where the dead turns would suffer the most if not adequately tensioned.

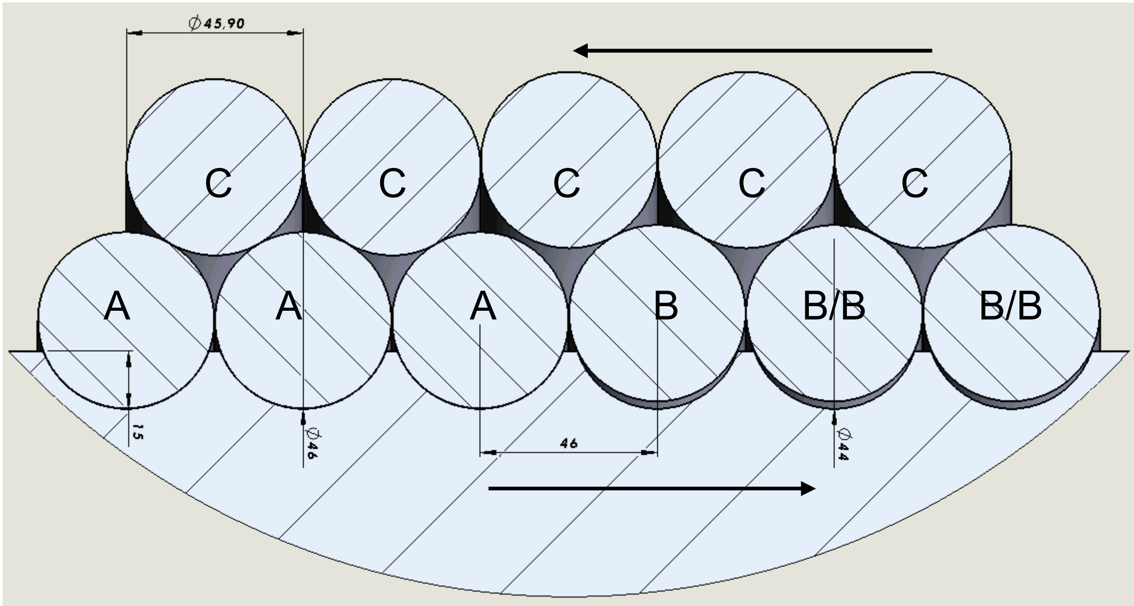


Figure 19: Coiling diameter clearances resulting from undersized grooves on parts of the drums, Sections A and B. The arrows indicate the direction of coiling. Note the coiling clearances in the three 44 mm grooves on the right. Number of turns shown in A, B, B/B and C are for indication of the relative positions only.

It is possible that the tight grooves in the B and B/B areas lead to slackness of rope accumulating in areas A and B. This would explain the rapid deterioration of the ropes in the dead turn regions (A and B). Figure 19 shows the effect that the tight grooves have on the coiling diameter in the 44 mm groove areas. As the upper layers press down on the B/B sections there is a possibility of slackness accumulating which is milked towards B and then A. Even if only a small amount of slackness accumulates every cycle, the sum of this over 1000s of cycles could cause significant problems in both Sections A and B in spite of proper doubling down (Figure 7).

A further illustration of this point is Figure 20 which shows how a rope with an operating diameter of 46 mm would sit initially in the 44 mm drum grooves. The extent of the clearance matches the to-scale drawing in Figure 19. Clearly, as the pressure from the coiling of subsequent layers (up to a total of 4 in the B/B region) increases, the clearance will reduce to zero and cause some slackness in each turn. This slackness in B/B is forced towards B and A by the coiling of C above B/B, see arrows showing the coiling directions in Figures 9 and 19.

There are also ongoing investigations into the possibility that the well documented phenomenon of backslip on drum rock winders, [**8**], could have caused premature development of slackness in Sections B and A in each drum compartment. The eight-strand ropes have a notably higher axial stiffness compared to the triangular strand ropes and possibly lower coefficient of friction with the drum due their smoother outer surface. This could result in a situation where the extent of backslip at the dead turn - live turn boundary, for every cycle, becomes only dependant on the system geometry and payloads when changing from one rope to another. In such a case the axially stiffer rope would suffer a more rapid loss of tension in the dead turns for a given magnitude of slackness introduced per winder cycle.

Figure 20: 46 mm rope groove gauge in 44 mm drum groove, Section B/B, shortly after installation of the eight-strand ropes.

The winder has been in operation for some 35 years. It is believed that the reason circa half of each drum compartment has 44 mm grooves and the rest 46 mm grooves is that the drums were originally manufactured with 46 mm grooves and pitch and that the triangular strand ropes (which settle with a circa 44 mm operating diameter in the live turn region) machined the 46 mm grooves down to 44 mm over the many years of operation.

9 Recommendations for avoiding rope damage in future

Several valuable lessons have been learnt in the process of trying new rope technology on the existing 2043 m BMR rock winder. In this section key recommendations are made for avoiding rope damage and increasing rope operating life in the future.

9.1 Rope diameter selection for existing winders

It is critical that the drum LeBus coiling sleeves are measured accurately before finalising the diameter of rope to be ordered for a winder. Even if the same nominal diameter rope has been used on a winder for many years it is still worth checking that the relationship between the actual drum groove geometry and the intended rope diameter match the recommendations of standards such as SANS 10294, [**2**]. Failure to do this can have a very significant effect on rope life irrespective of the rope construction. Figure 21 shows the typical effect that groove diameter can have on rope life in bending fatigue applications.

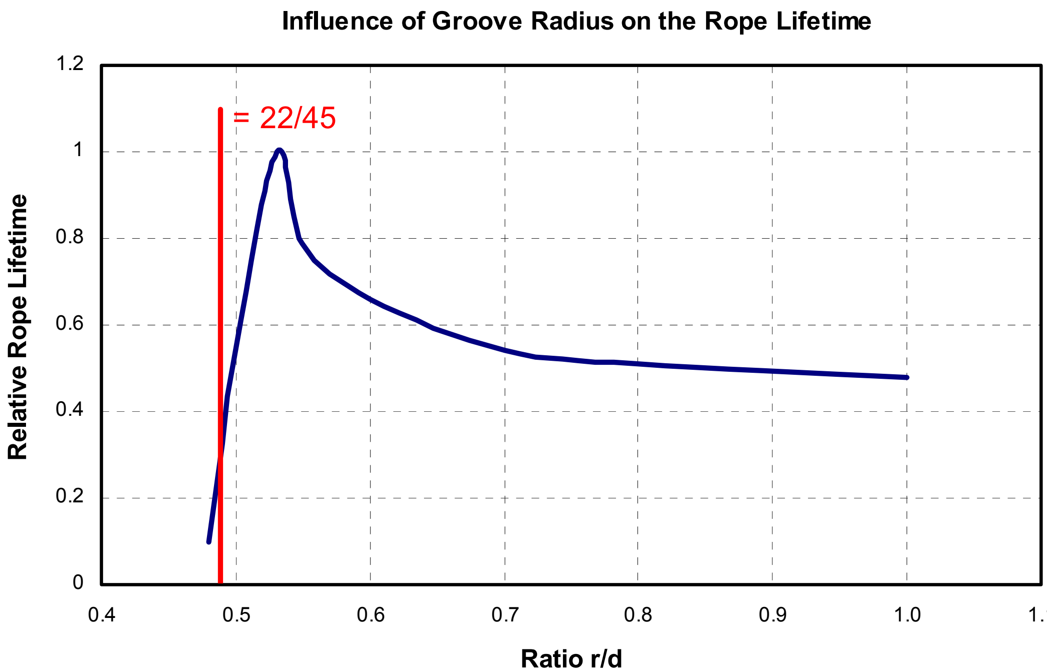


Figure 21: Rope life on sheaves for a varying relationship between rope diameter and sheave groove radius. For tight sheaves (i.e. a r/d ratio below 0.53) the rope life drops off dramatically. The vertical line represents a 45 mm nominal diameter rope in a 44 mm groove. Rope life expectation under this condition is circa 30% of the life in a standard sized groove.

It should also be noted that in deep shafts, different rope constructions will show varying degrees of diameter reduction along the rope length. A 45 mm variable lay length eight-strand rope with a steel core will have a much smaller change in diameter than an standard constant lay length fibre cored triangular strand rope. This means for example that grooves which may be perfect for the TSR could cause serious problems for the eight-strand rope as was the case on the No. 2 Shaft BMR rock winder.

Rope sheaves should also be cut to the correct SANS 10294 tolerance or similar rope equipment standard before new ropes are installed on a winder.

9.2 Monitoring of slackness in dead turns

Rope manufacturers and mine winder operators should routinely monitor the development of slackness in the dead turns on drum winders. This is particularly important when using high stiffness ropes like the eight-strand with IWRC construction discussed in this paper. Slackness in the dead turns can be detected either by pinging the dead turns with a hammer and or by painting a line across the dead turns after doubling down. There will be a clear difference in the pinging sound between tight dead turns and slack ones. Additionally, if a horizontal line has been painted across tight dead turns, any movement of the dead turns would become apparent by a change in position of the line. Regular doubling down with full skips is a very effective way of maintaining proper dead turn tension.

9.3 LeBus groove rope damage

The bolts holding the coiling sleeves to the drums and the general condition of LeBus profile should be checked. Any sharp edges between the grooves should be cleaned off. Before new ropes are installed it is recommended to clean, inspect and lubricate the drum sleeves with an appropriate wire rope lubricant, especially in the live turn region. Risers and wedges must be very carefully inspected to ensure no sharp edges or cracks.

10 Conclusions

This paper has highlighted the operational experiences with four, 45 mm diameter, 2500 m long eight-strand ropes with plastic coated IWRCs operating on a BMR rock winder in South Africa hoisting from a 2043 m depth. The ropes were discarded prematurely at 35,000 and 38,000 cycles. It is assumed that the primary cause of the rapid deterioration was tight drum grooves on all four drum compartments (44 mm and 46 mm rather than a recommended value of 48.15 mm). The tight grooves were only discovered at the time of installation of the ropes and could not be changed.

In the future it is strongly recommended that drum groove geometries are measured before finalising new rope diameters on existing winders. Rope sheaves should also be cut to the correct tolerance before new ropes are installed on a winder. The dead turns on the No. 2 Shaft BMR drums also showed premature wire breaks that are attributed to accumulation of slackness.

It is very likely that the remaining circa 4 x 1900 m of discarded rope that was not damaged on the drum will be reinspected and then reused on another rock winder as all investigations to date, including the discard date NDT tests, have shown that these rope lengths are still in good working order.

The mine and rope manufacturer are considering installing four 42 mm eight-strand ropes on the same winder once the damage mechanism investigations, particularly for the dead turns, have been completed.

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