Development of High-Hardness-Cast Gears for High-Power Mining Applications

Fabrice Wavelet

Multiple possibilities are available to increase the transmissible power of girth gears. These solutions include: using a larger module, increasing of the gear diameter through the number of teeth, enlarging the face width, and increasing the hardness of the base material.

The first three parameters are mostly limited by cutting machine capability. Module, outside diameter, and face width (for a cast gear) can theoretically be increased to infinity, but not the cutting machine dimensions. There are also practical limits with respect to the installation of very large diameter/large face width gears.

The hardness is the sole parameter that is related to the base material.

Within the past decade, mining industry demand for gear-driven/high-powered grinding mills has pushed the installed power to levels previously thought to be unachievable or impractical. Girth gears are now being used to drive ball and SAG mills having total installed power in excess of 17,000 kW (23,000 hp).

The development of high-hardness materials suitable for these applications has resulted in the design and manufacturing of cast girth gears up to 350 HBW in steel and 340 HBW in ductile iron.

This paper intends to review the related impact in terms of design and manufacturing of such high- hardness gears and present a summary of results from a population of more than 170 gears manufactured from cast materials having hardness in excess of 300 HBW, including almost 20 gears manufactured from cast materials having hardness in excess of 340 HBW, with an approximately equal distribution between cast steel and ductile iron base materials.

Introduction

In the mining industry, users' demand for increased mill power and size has always been present. Continuous developments in the gearing industry have made this possible, to a certain extent: basically, a 36' mill diameter in terms of size and 17 MW in terms of power.

Beyond these values, and sometimes below as shown in Figure 1, is the domain of gearless drives.

This paper intends to review the latest developments made on increasing gear hardness, its impact on gear geometry, and finally the experience with gears above 300 HBW.

Parameters of Influence on Gearing Power

To date, three standards are available to determine transmissible power of a mechanical drive:

- AGMA 2001
- ISO 6336
- AGMA 6014

While the first two can be used on any type and size of gears, AGMA 6014 is the only standard dedicated to open gear applications, such as mills or kilns.

AGMA 6014-B15, the latest version from 2015, introduces two equations that allow the experienced gear engineer to design gear drives.

These equations are made to determine the transmissible power of a gearing based on its resistance to tooth bending and its resistance to surface pitting.

$$P_{atm} = \frac{\pi n_p d}{396{,}000} \frac{F}{K_{Vm} P_d} \frac{J S_{at} Y_N}{K_m K_{Bm}}$$

Equation 1 transmissible power (hp) based on tooth bending resistance (Ref. 3)

$$P_{acm} = \frac{\pi n_p F}{396{,}000} \frac{I}{K_{Vm} K_m} \left(\frac{d S_{ac} Z_N C_H}{C_P} \right)^2$$

Equation 2 transmissible power (hp) based on contact pressure resistance (Ref. 3)

In the above equations, parameters in blue are related to the

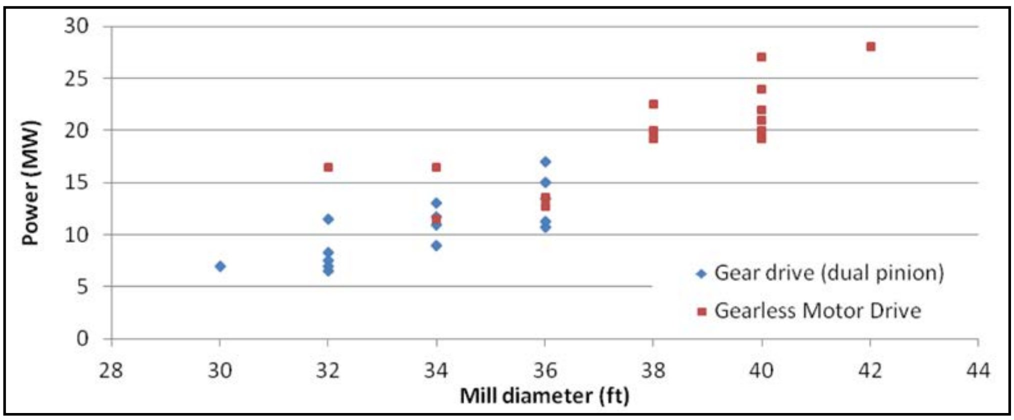

Figure 1 Drive type by mill size and power (Refs. 1–2).

tooth geometry and are notably related to the gear accuracy (i.e., AGMA 2000, withdrawn but still in use, Q10), the module/diametral pitch (i.e. the tooth size), and the gear face width (basically the length of teeth meshing with the pinion).

Parameters in red are a function of the material properties, but all reduced to the hardness.

The least value of these two calculations, themselves divided by a selected service factor, gives the transmissible power of the installation.

In other words, gear power relies on three major parameters for a given transmission error: module/diametral pitch, face width, and hardness.

The Choice of Hardness to Improve Gear Power

Through the past 10 years or so, major developments have been made by manufacturers to improve their manufacturing capacities with the target to increase mechanical drive capacity.

First was to increase the module size: from a common 25.4 module/1" DP (20 years ago), tooth size moved up to modules over 30, and now appears on a regular basis to be over 40. The largest module produced to date is 55 module/0.46" DP.

Consequence of module increase, apart from its important impact on power, is also the increase of outer rim thickness, and consequently the total weight of the gear.

AGMA 6014 recommends a minimum thickness of 4.5× module for the outer rim, not to derate K_{bm} factor in the bending resistance equation. Note that these 4.5× module are calculated based on a standard tooth height of 2.25× module, and 2.25× module below the tooth root to obtain K_{bm} equals unity.

For example, a module 42/0.605" DP, that has been used on nine gears between 2012 and 2016, implies a finished rim thickness of 190 mm, or 210+ mm thick un-machined. Even though this is not a problem for a cast gear, this thickness could be for fabrication. Therefore, larger module also means larger cutting tools, which may lead to use of a different process. The two main processes for tooth cutting are hobbing and single-index cutting. Hobbing tools are much larger than single-index tools at a given module size, implying both a significant difference in terms of cost, and that some machines cannot accept hobs with modules over a certain size.

A move to single-index cutting was needed and required for gears with large modules, i.e., 36 module /0.71" DP and above.

A single-index process is a problem when the tool has to be refurbished during the cut; it may generate high pitch error and/or helix angle errors when the tool is set back into operation.

Developments have been made with tool manufacturers to work with carbide inserts capable of cutting 100% of the teeth to the required quality, with no change in the course of final cut.

Then, the gear pitch accuracy is only a function of machine table rotation accuracy, which can be controlled by dedicated maintenance interventions.

On the other hand, in cast steel gears, a large tooth height (which is about 2.25× module) means deeper cuts into the rim, and this may lead to open micro-shrinkages at the surface (Fig. 2). These indications are well known; they are usually excavated and left as is.

Foundry experience is the key to minimize such indications. Over the past 2 years, 25% of large steel gears (with modules between 33.866 and 42 and hardness at 300+ HBW) have been produced with no indications in the teeth area.

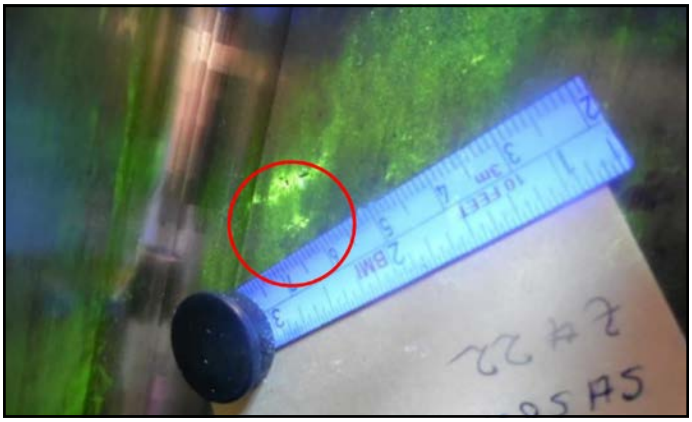

Figure 2 Micro-shrinkage into a cast steel girth gear.

The other 75% have an average 2.9 indications per segment. Modules are between 28 and 42. Considering ductile iron gears, none of the 260 gears produced for the mining industry over the past 12 years have shown this type of indication in the teeth area.

Although quality has improved, cast gears and porosities in the teeth area remain linked in people's minds.

The second parameter manufacturers have worked on is gear size: the more teeth, the larger power, but also larger is the diameter and the mill a gear can be assembled on.

As previously said, a 36' SAG mill was the limit a mill can be equipped with a mechanical drive, simply because the largest gear cutting machines were about 14 m/46' in diameter.

Four years ago, a new 16 m/52' gear cutting machine was commissioned in Germany that can allow the manufacturing of gears for mills up to 44' (which does not exist yet) with an AGMA 2000-Q10 quality.

In parallel with developments made on the module and on gear diameter, in order to continue to increase the potential power of gears, work was done on face width.

Building a gear blank with a 1 m face width is not difficult. Cutting such a face width to meet a lead error within AGMA Q10 tolerances, and assuring a good contact through meshing on site, are two challenging objectives with a very large face width.

As for large modules, wide faces can run into a limit as the lead deviation is critical for the power transmission: the larger the tooth, the more difficult the alignment.

In this case as well, single-index cutting seems more practical when talking about face width larger than 600–700 mm. With these new generation tools, profile and lead errors on face width of about 1 m are between 30 and 60 μm, with no undulations. The same dimension cut with a hob can give a lead error closer to the tolerance limit (80–100 μm). Hobbed profile error is about the same as with single-index cutting.

Even though the current limit of the face width is about 1,500 mm, this magnitude will make gear and pinion alignment very demanding, to say the least.

Keeping face width as narrow as possible should be the goal of the gear designer.

With physical limits reached on both the module and the face width, the last parameter manufacturers can act on is the hardness.

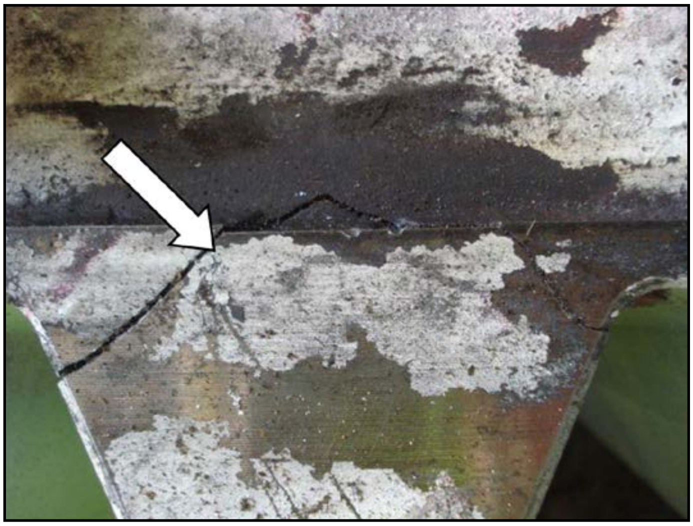

Figure 3 Tooth root crack due to misalignment.

Increasing hardness of the material, and its properties, is very interesting in that it is the only parameter that will reduce gear dimensions, and weight, for the same amount of power.

Less than 10 years ago the maximum designed hardness used was 320 HBW for steel gears and 290 HBW for ductile iron gears. This was simply due to the fact that mills were not needed for more power (based on average module and face width sizes) and also because these hardnesses have been proven over decades of duty.

Today, research makes possible production of cast gears with minimum guaranteed hardness of 350 HBW in steel and 340 HBW in ductile iron.

And tests are currently in process to produce 360 HBW gears — and beyond.

With the current range of possibilities being defined, what are the consequences of a hardness increase on the casting and machining process?

Obviously, reaching a higher range of hardness requires a different chemistry. Table 1 gives different examples for cast steels based on the required hardness.

With such chemical analysis, quench-ability (capacity of the material to maintain the hardness through the section thickness) improves, but the risk of defects increases as well.

To manage this risk, a lot of work and tests have been needed to redefine casting design, whether castings are made of steel or of ductile iron to reduce, if not avoid, internal discontinuities.

This covers, for example:

- ***Risers***: size, location, and the way they cool down was rethought using computerized solidification software to improve their effect on the time of solidification and to move the possible internal indications out of the casting itself, or at least in the non-critical areas (such as the teeth area).
- ***Pouring system***: distribution, position, and size of the ingates were analyzed. Their impact on the flow of liquid metal, as well as the perturbations they are generating, was discussed and led to modifications, i.e. pour at lower pressure, multiple ingates and reduced their sizes or movement of ingate position from the bottom to the side.

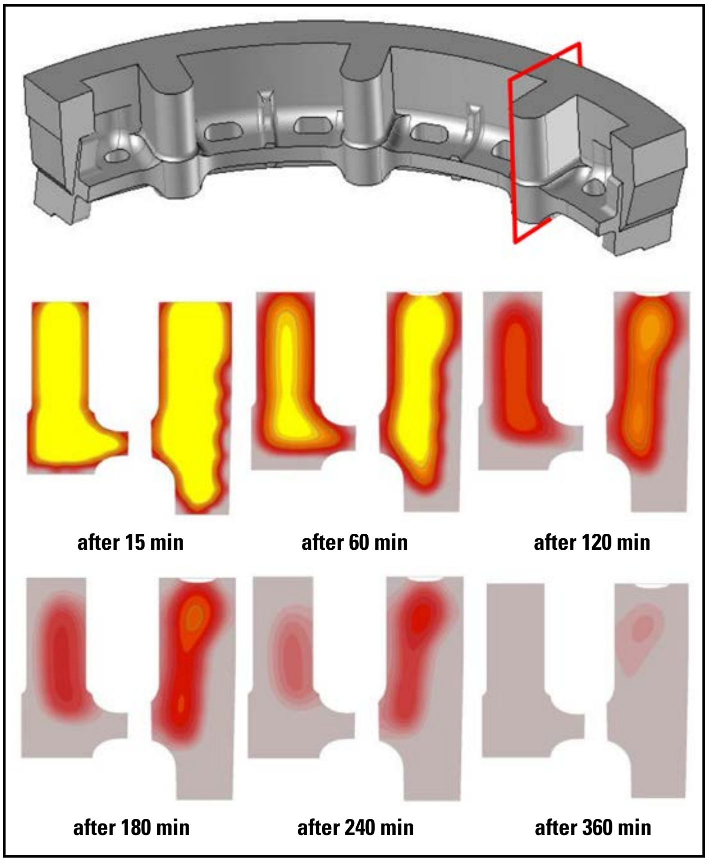

Figure 4 Example of solidification study on a steel gear segment.

Autofeeding slope: in terms of casting thickness, there is always a difference between the bottom of the mold (drag side) and the top of it (riser side). This thickness difference between them is called the auto-feeding slope. Depending on the required quality and the chemistry, this slope can vary from 1° to 5°, and has a significant impact on weight.

Chills: the question of using chills, their number and distribution, was also modified in relation with module size and chemistry. Studies have been conducted in order to determine the correct size, form, and distribution of chills to obtain defect-free teeth.

Improving hardness has also impacted the manufacturing process and has required studies and modifications on the way.

To assure material soundness, some portions of the liquid metal are transferred into an AOD (argon/oxygen/decarburization) converter that allows limited "metal purification." That

Table 1 Examples of required and actual chemistry related to hardness

Material	Hardness	%C	%Si	%Cr	%Ni	%Mo
ASTM A148 Gr 130-115	(300 HBW)	requirements only on sulfur and phosphorus contents				
OF 40131 — A148 Gr 130	≥ 310 HBW	0.43	0.35	1.76	1.72	0.27
EN 10293 - G 35 CrNiMo 6-6	(290 HBW)	0.32–0.38	0.6 max	1.40–1.70	1.40–1.70	0.15–0.35
OF 49131 - G 35 CrNiMo 6-6	≥ 285 HBW	0.39	0.52	1.67	1.54	0.32
G 38 CrNiMo 6-6 *	(320 HBW)	0.34–0.45	0.6 max	1.3 min	1.3 min	0.15 min
OF 76668 — G 38 CrNiMo 6-6	≥ 320 HBW	0.41	0.34	1.74	1.71	0.38
G 40 CrNiMo 7-7 *	(340 HBW)	0.36–0.47	0.6 max	1.5 min	1.5 min	0.15 min
OF 41657 — G 40 CrNiMo 7-7	≥ 340 HBW	0.44	0.36	1.77	1.71	0.45

* Non-standard grades; specifically developed for heavy section and high hardness-cast gears

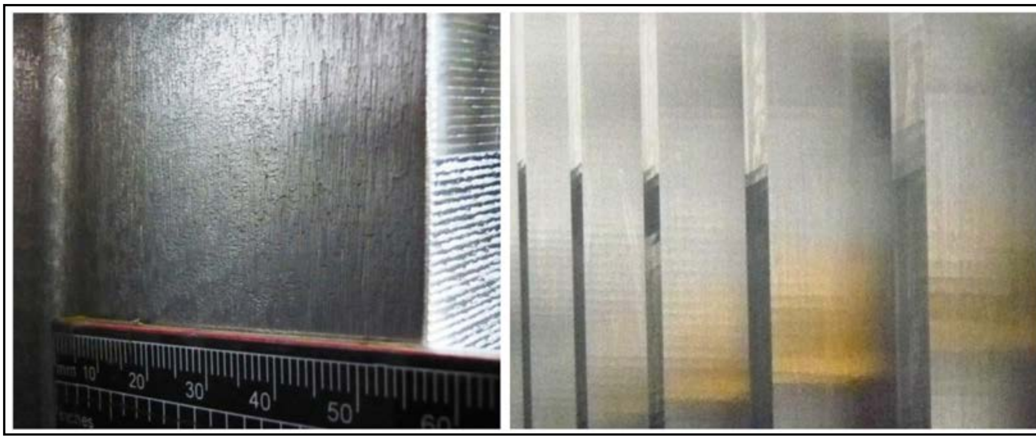

Figure 5 (Left) Surface "scraping" on a tooth flank due to HSS tool wear on a 300 HBW gear: Ra 5 µm; (right) 320 HBW gear cut with carbide tools: Ra 0.6 µm.

type of additional work allows minimizing nitrogen content to less than 20 ppm and improves impact resistance of the final material (even though it is a secondary property for gears in normal conditions of service).

Another side-note for manufacturing relates to upgrading, or process welding, of the blank. Higher hardness in conjunction with larger amounts of alloying elements implies specific welding procedures that requires being qualified and repeatable.

With an equivalent carbon for welding above 1, 320, HBW material is classified as "difficult to weld" by AWS.

Repair conditions will need to be the following:

- Pre-heating will be around 300° C (to pass over martensitic transformation starting point, Ms)
- Temperature during welding will be maximized to 450° C (to avoid embrittlement by chromium carbide precipitation)
- Post-weld heating must be maintained at 300+° C for 2+ hrs to allow diffusion of hydrogen and avoid martensite precipitation, then embrittlement
- Tempering of the integral casting to smooth heat-affected zone and avoid quenching products leading to brittle microstructures

That type of repair does not permit approximations and shall be done in a shop, both to control the heat-related deformations and the results obtained in terms of microstructure.

Another point to consider when manufacturing higher-hardness gears is the machining; the use of high- speed steel (HSS) tools becomes very limited. Most of the tools need to be made of either carbide or ceramic, which have a different behavior in relation to the gear material (in the way they cut, their productivity, and their operational parameters).

Figure 5 shows a recent case of the consequence of HSS tool wear during hob cutting. The surface finish was so rough that this gear needed a recut. Tooth thickness was reduced and finally fell below the required value. Verification of the bending resistance safety factor was needed to make sure this gear still met the requirements of the application.

As a comparison, Figure 5 also shows the results obtained by the use of carbide inserts on the cutting tool.

The conclusion is that, depending on gear size (outside diameter and face width) and hardness level, use of HSS tools above 280 HBW should be questioned.

On the inspection side, developing higher hardness grades makes no difference in terms of inspection techniques; ultrasonic and magnetic particle inspections can be used the same way as on any other material grades, with the same acceptance criteria.

Nevertheless, a study was performed on the impact of increased hardness over the ultrasonic velocity in ductile iron gears.

Ductile iron gears above 300 HBW have been recorded close to, or sometimes below, the standard limit of 5 450 m/s (Fig. 6), with no impact on the quality of graphite nodules.

This reduction in terms of velocity is mainly due to the microstructure, which is related to the hardness level.

The use of high-hardness gears (of or above 300 HBW) in a mill driving system also has some consequences on the pinion.

As per AGMA 6014, hardness difference between pinion and gear has a beneficial impact on gear rating (work hardening effect; C_H factor). For that reason, the gear industry usually considers a minimum difference of 40 HBW points in excess of the gear design hardness for pinion hardness.

Thus, a 300 HBW gear implies use of a pinion at 340 HBW minimum, which can be in the higher range of hardness for a through-hardened forging of this size. In such conditions, gear hardness maximum can be equal to pinion hardness minimum, and this can affect pinion wear and reduce its lifetime.

Selection of carburized and

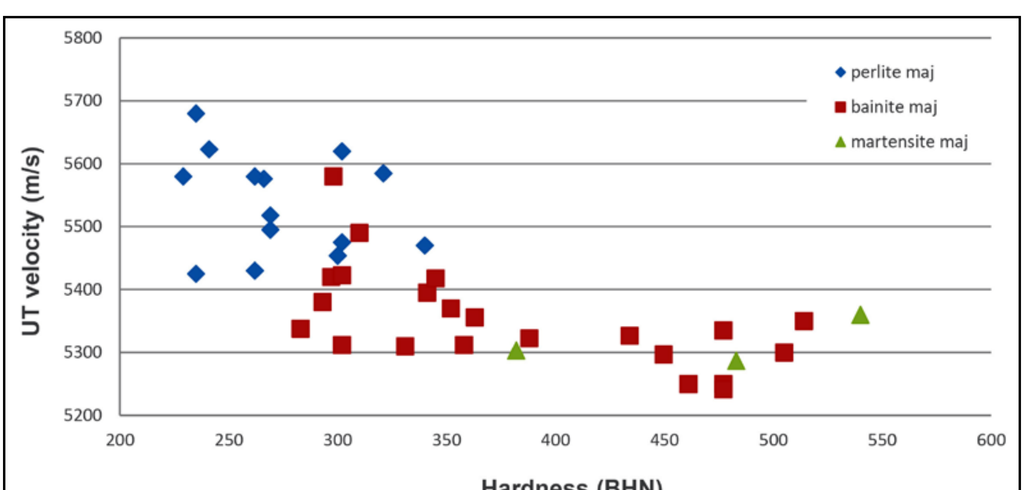

Figure 6 UT velocity vs. hardness (and microstructure) on ductile iron gears.

ground pinions with high-hardness gears is then recommended to improve both power rating and service life.

Gear Design Examples Based on Hardness Variations

The goal in this section is to study the impact that hardness variation can have on the gear design. For that purpose two ball mills have been considered; ball mills are the most-solicited machinery in a grinding circuit because its relatively small diameter causes more stress on the teeth.

- The first example considers an 18' ball mill driven by a 3,500 kW motor, single pinion drive. This type of mill is an average size, both in terms of dimensions and in terms of power.
- The second example is a hypothetical 26' ball mill driven by two pinions for a total power of 20 MW. This type of mill does not exist; the largest and most powerful ball mill to date is a 26' ball mill, dual drive, 17.5 MW.

Results are summarized in Tables 2 and 3 (with complete data in annex).

For a common size ball mill, Table 2 shows an interesting reduction on face width, whether the gear is made of steel or of ductile iron.

Consequently, weight is reduced, as is the final price. Moreover, alignment between gear and pinion with a reduced face width will be easier on site and more consistent across mill rotation.

Table 3 shows a different situation. While the reduction on the face width with a 20 HBW increase is small, it becomes significant with the combination of hardness and module increases.

Nevertheless, cost remains about the same, but the narrower face width allows easier alignment on site.

One can also note that, even though this 26' ball mill is purely a study, gear parameters used to reach a transmissible power of 20 MW have already been used and manufactured before:

- Module 45 is in the high range of module cut to date, but already few gears are in service with such a large value.
- A 900+ mm face width has been cut on many gears in service, obtaining successful alignment and contact.
- 340 HBW is also a value seen on a regular basis on gears in service for a significant time to date (Fig. 7), with good reliability.

Gears Above 300 HBW in Service

Figure 7 shows the number of gears manufactured for the mining industry by the company over the past 12 years.

The demand for gears beyond 300 HBW increases with time, whether they are made of steel or of ductile iron.

In terms of hardness, 2007 shows the first ever gear at 340 HBW. Then, a period of 5 years has been taken to validate such hardness. After 2012, 340 HBW became standard.

A new milestone will be reached this year (2016), with a minimum required hardness of 345 HBW for a steel gear.

In terms of service, of the over 130 gears produced to date with a hardness equal or above 300 HBW, only three have encountered failures:

- ***Tooth breakage***: a steel gear had a tooth break at the tooth root in service. The origin of the failure was an alignment problem, reducing contact to 30% over the face width. The power was then transmitted through a limited surface of the tooth, inducing a crack at the root. The damaged gear segment was replaced, and the gear was integrally re-cut and is back in operation with no more problems known to date.
- ***Pitting***: another steel gear encountered severe pitting on 100% of its teeth (cavities up to 2–3 mm deep). This was related to a lubrication problem. The gear was recut and stored as a spare.
- ***Outer rim through-crack***: a ductile iron gear developed a

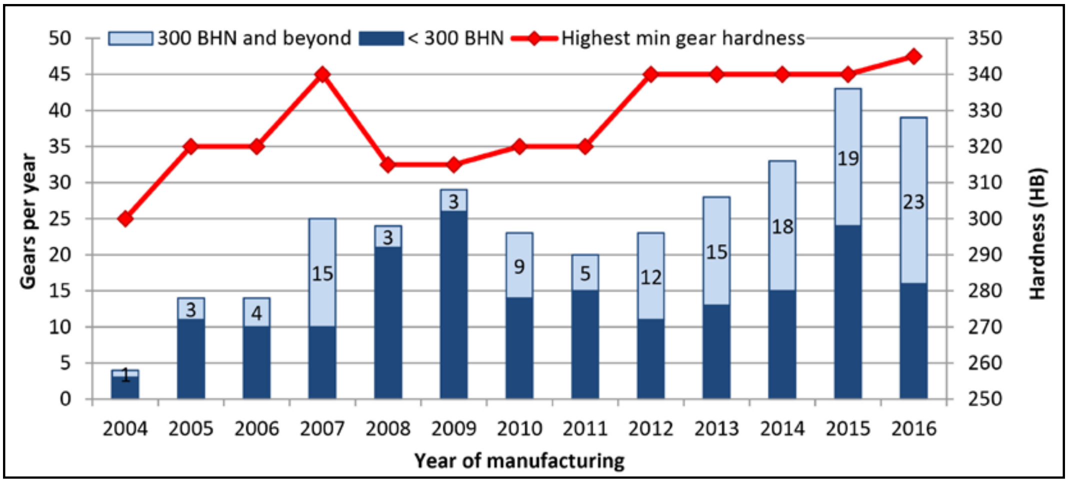

Figure 7 Gears below and beyond 300 HBW and highest minimum gear hardness, per year.

Table 2 Design variations for an 18' ball mill of 1×3 500 kW (single drive)

Design	« standard » 290 HBW, in steel	with 340 HBWHBW, in steel and a reduced face width	with 340 HBW, in ductile iron and a reduced face width
Module	25.4	25.4	25.4
Hardness	290 HBW	340 HBW	340 HBW
Face width	**750 mm**	**620 mm**	**710 mm**
Outside diameter	8011.6 mm	8036.1 mm	8018.1 mm
Transmissible power	3545 kW	3524 kW	3539 kW
Limiting factor	Bending	Bending	Bending
Weight	33 tons	29.2 tons	28.9 tons
Price index	100	92	84

Table 3 Design variations for a 26' ball mill of 2×10 000 kW (dual drive)

Desi gn	« standard » 320 HBW, in steel	with 340 HBW, in steel and a reduced face width	with 340 HBW, in steel with reduced face width and increased module
Module	42	42	45
Hardness	320 HBW	340 HBW	340 HBW
Face width	**1150 mm**	**1070 mm**	**990 mm**
Outside diameter	11058.6 mm	11071.7 mm	11167.2 mm
Transmissible power	10012 kW	10017 kW	10100 kW
Limiting factor	Bending	Bending	Bending
Weight	97.6 tons	92.5 tons	93 tons
Price index	100	98	91

crack through the entire thickness of the outer rim and over one-half of the face width. This was originated by a localized welding on the gear post-manufacture, to secure the mud-guard, close to a threaded hole. The gear was replaced.

Conclusion

- The demand for more and more powerful mechanical drives grows every year. The main reasons, as seen from end users, are that they want to increase their output and productivity while working with a reliable system that is proven and that they can fix and maintain themselves.
- With limits reached on module and face width, increasing hardness above a standard level of 300 HBW became a target for many manufacturers.
- Pros and cons make the hardness choice arguable: it reduces global weight, allows narrower face width, and actual hardness is always higher than designed hardness, giving a "resistance" bonus, and it is an economical benefit most of the time. In the meantime, a high-hardness gear requires attention and cautions in terms of manufacture, as during the welding process for example, but this relies on the supplier, not the customer.
- The difficulty of increasing hardness to reach higher power is not solely a question of the minimum that can be reached (300, 320, 340 HBW) but more a combination of high magnitude with heavy section gears (150+ mm finish machined).
- The past 12 years have seen the development of high hardness gears, and it has proven to be a correct option, if not the right choice.
- Based on the number of gears made by the company above 300 HBW in service, compared with the number of failures encountered by this type of gear (knowing they are independent from the material), makes the hardness a reliable choice.
- Of course, proper lubrication, alignment, and survey of such a gear must be done as for any other gear in order to maintain its operation-ability through its lifetime.

References

1. Tozlu, F., M. Pasquier, F. Wavelet, F. Lessard and B. Mc Naughton. "QdX4 – a Mechanical Drivetrain Solution for High-Powered Grinding Mills," *SAG Conference* 2015, Paper 42.
2. Tozlu, F. and M. Fresko. "Auto-Genous and Semi-Auto-Genous Mills — 2015 Update," *SAG Conference* 2015, Poster P12.
3. AGMA, 2015. "Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment,"
4. ANSI/AGMA 6014-B15.
5. Uherek, F. "How to Spec a Mill Gear," AGMA Fall Technical Meeting 2013, Ref. 13FTM21.
6. Pasquier, M. and F. Wavelet. "Ductile Iron for Open Gearing — a Current Perspective," AGMA Fall Technical Meeting 2013, Ref. 13FTM23.
7. Ferry Capitain, 2011–2012. "Manufacturing Data Books," 41570 and 41602, Russian Copper."
8. Ferry Capitain, 2011–2012. "Manufacturing Data Books," 41657 and 416658, Constantia."

Fabrice Wavelet has been with Ferry Capitain (Groupe CIF, France) for the past 20 years. He first served as quality manager and for the last 12 years has been a project manager specializing in mining products. This work deals with all technical issues on the metallurgic side as well as on the mechanical side of the manufacturing of large and high-accuracy components for the mining industry. In 2010 he joined the AGMA Mill Gearing Committee and participated in the latest revision of the 6014 standard, which is dedicated to open gearing. Aside from these activities, Wavelet has also written technical papers — notably for AGMA — covering the manufacturing and inspection of large cast components for the heavy machinery industry.

For Related Articles Search

cast gears

at www.geartechnology.com

Annex: Characteristics Used for the Gear Design of Two Different Mill Examples

Ball Mill 18' **1×3500 kW**

Type	Ball Mill 18'
Mill rotation speed	13.9 rpm*
Inside diameter	5700 mm
Design standard	AG MA 6014-B15
Bending strength safety factor	Ksf = 2.5
Pitting resistance safety factor	Csf = 1.75
Lifetime	219 000 hrs
Mating pinion	Ix pinion Z23 CH&G 56 HRc

Material	Cast steel	Cast steel	Ductile Iron
power (kW)	3545	3524	3539
hardness (HBW)	290	340	340
module	25.4	25.4	25.4
face width	750	620	710
pressure angle	25	25	25
helix angle	6.4	7.8	6.8
gear teeth number	312	312	312
outside diameter	8011.6	8036.1	8018.1
limiting parameter	bending	bending	bending

Ball Mill 26' **2×10000 kW**

Type	Ball Mill 26'
Mill rotation speed	11.55 rpm*
Inside diameter	8300 mm
Design standard	AG MA 6014-B15
Bending strength safety factor	Ksf = 2.5
Pitting resistance safety factor	Csf = 1.75
Lifetime	219 000 hrs
Mating pinions	2× pinions Z21 CH&G 56 HRc

Material	Cast steel	Cast steel	Cast steel**
power (kW)	10012	10017	10100
hardness (HBW)	320	340	340
module	42	42	45
face width	1150	1070	990
pressure angle	25	25	25
helix angle	6.9	7.4	8.6
gear teeth number	260	260	244
outside diameter	11058.6	11071.7	11167.2
limiting parameter	bending	bending	bending

*** Based on 75% of the critical speed, and with critical speed (CS):** $CS = \frac{43.305}{\text{inner diameter (m)}}$ **(Ref. 4).**

**** With a pinion tooth number reduced to 19 to maintain pinion speed to 140–150 rpm.**