

APPLICATION OF METAL MAGNETIC LINERS IN THE US IRON ORE INDUSTRY

Allan Ellsworth & Shane Hoff, Cleveland Cliffs - Northshore Mining, Silver Bay, MN

Lusheng Zhou & Ming Zhao, China Metallurgical Mining Corp., Beijing, P. R. China

Xinkai Jiang & Richard A. Merwin, Eriez Manufacturing Co., Erie, PA

Abstract

The choice of mill linings in comminution circuits is critical as it affects grinding efficiency, overall cost, and product quality. As a consequence, a variety of liners have been developed over the years in an effort to increase wear resistance, improve grinding efficiency, and reduce energy consumption. One particular type of metal magnetic lining (MML) was developed in China seventeen years ago and has since been installed in over 400 applications throughout the Chinese mining industry. Most recently, one set of magnetic mill liners was brought to the US for installation into a secondary ball mill used for the grinding of iron ore. Protection of the mill is provided through the magnetic attraction and retainment of worn media, ball chips, and other various magnetic particles to the mill wall. This greatly improves the wear resistance and overall life of the liner. The installation and performance data for the magnetic mill liners in a US iron ore concentrator are presented in this paper.

Introduction

Grinding or comminution is a size reduction process and is a key step in liberating the desired mineral from the gangue material so that subsequent processes can successfully concentrate the valuable minerals at acceptable grades. There are many factors affecting the grinding efficiency and overall grinding cost of a mill circuit. Two such factors are the design of the lining profile and the lining material used as these greatly affect the overall grinding cost and mill throughput.

As such, a great deal of attention has been focused on liner design to reduce maintenance cost and increase grinding efficiency. Currently, there are four types of lining for tumbling mills in the marketplace, including:

1. Conventional steel lining,
2. Rubber lining,
3. Steel-cap rubber lining, and
4. Magnetic lining.

Each type of lining fits a different application. The conventional steel lining is commonly used in primary grinding, while the rubber lining is widely accepted as economical in secondary and regrinding applications. One of the latest developments in lining technology, steel-cap rubber lining, utilizes the advantages of both steel and rubber and targets primary grinding applications.

More recently, magnetic mill liners have been used for the protection of grinding mills. One such liner, termed the Orebed Magnetic Liner (manufactured by Trelleborg), was installed in a regrinding pebble mill at the LKAB Kiruna concentrator in Sweden in 1980. A second unit was installed at a sand and iron oxide operation by Trellex in Blue Circle, Westbury. In these examples, the liners were made from permanent ceramic magnets and vulcanized into rubber for the protection of the mill (Anon, 1982). However, the ceramic magnet is embedded in a rubber casing and provides only weak protection for the magnet from charge impact. As a consequence, this type of magnetic lining is limited to applications in which ball size is less than 40-mm (1½-inches), and mill size is less than 3-m (10-ft).

Meanwhile, researchers in China have been investigating the potential for a steel housing for the magnet material (e.g., metal magnetic lining). In 1989, the Anshan Mining Research Institute successfully tested a metal magnetic liner in a regrinding ball mill measuring $\Phi 2.7 \times 3.6$ -m ($\Phi 9.0 \times 12.0$ -ft) (Wang, 2003). Later, in 1992, the JinFa Industrial Trading Cooperation of China developed a metal magnetic liner and installed it in an iron concentrator in northern China. To date, this lining has been operated in this mine for nine years and has shown no visible damage (Zou et al., 2002). Currently, more than four hundred sets of metal magnetic mill linings have been installed within the mineral processing industry in China with the largest ball mill measuring $\Phi 5.5 \times 8.8$ -m ($\Phi 18.0 \times 29.0$ -ft) with a conical media size of $\Phi 35 \times 45 \times \Phi 40$ -mm ($\Phi 1.4 \times 1.7 \times 1.6$ -in rod) (Zhou et al., 2005).

Most recently in July of 2006, a set of metal magnetic lining produced by the JinFa Industrial Trading Co. was installed on a trial basis in a ball mill measuring $\Phi 3.2 \times 5.5$ -m ($\Phi 10.5 \times 18.0$ -ft) at Cleveland Cliff's Northshore Mining

iron ore concentrator in Silver Bay, Minnesota. This paper presents the development of metal magnetic lining and its application at this iron ore concentrator.

Background Information

There are many factors that affect the wear characteristics of a lining. These include, and are not limited to, the liner profile, the liner material of construction, and the ball mill rotational speed. In fact, the selection of the liner profile and material of construction for magnetic mill liners has been a subject of extensive studies.

In 1975, a magnetically retained lining for rotary grinding mills was first proposed by Andersson (1975). This lining method avoided a bolted mounting arrangement and was easily installed and replaced. Later, Weinert (1982) provided a wide solution for equipment in high-wear applications up to and including ball mills. This solution reduced or eliminated wear by inducing the wear surface with a magnetic attraction force sufficient to hold a significant amount of magnetic or magnetizable particles in place.

The Orebed magnetic lining developed by Trelleborg (Anon, 1982) used embedded magnets to hold the liner in place as well as attract ferromagnetic materials to form a protection layer. To further protect the magnets used in the lining, Miles patented a new design for magnetic lining with steel plates positioned around magnets to protect it from the impact forces induced by the falling steel balls within the mill (Miles 2000).

Anon (1982) also studied the applicability of magnetic mill liners in tumbling mills where the grinding energy is transferred to the ore via the lining. In this type mill, the optimal lining of the mill would consist of a smooth profile, but with sufficient traction to avoid charge slippage (Svensson, 1995). Anon showed that the magnetic liner is designed in such a way that the pattern of adhered ferromagnetic material would provide sufficient charge traction. In fact, the magnetic lining is very efficient in power consumption, media consumption, and mill throughput. It was reported that energy consumption decreased by 11.4% and pebble consumption decreased by more than 30%. Furthermore, after 5000-hours operation, no visible liner wear was detected in these studies.

Rubber lining has replaced steel lining in most regrinding applications and has been found to be longer lasting, easier and faster to install, and transmits lower noise levels. However, an increase in medium consumption has been reported when using rubber liners in lieu of steel liners. Rubber lining is thicker than the steel lining and ultimately reduces the mill capacity (Moller and Brough, 1989).

The early magnetic liner proved to work well in secondary grinding applications. However, the tensile

strength and the tear resistance of rubber are not high enough to resist charge impact on the magnet inside of the magnetic lining. This is due to the characteristics of the rubber that encases the magnet material, as seen in Table 1 (Moller, 1990). The magnets are very brittle. As such, the original type of magnetic lining is only suitable for a limited ball mill geometry and media size. In fact, the ball mill geometry is limited to a media size of less than 38-mm (1½-inches) for a mill diameter smaller than 3.6-m (11.8-ft) diameter. For larger mills, a media size of less than 25-mm (1-inch) is required (Wason, 1999). In addition, the rubber magnetic lining can only be used to line the shell, and not the end caps of the mill.

Table 1. Steel and rubber properties (Moller, 1990)

Properties	Steel	Rubber
Modulus of elasticity, MPa	220000	10
Tensile strength, MPa	400	10-20
Elongation at break, %	20	500
Energy at break, M joule/m ³	50	50
Normal upper temperature limit, °C	400-600	100-150

Metal Magnetic Liners

As a potential improvement, the use of metal encased magnetic lining was extensively studied in China (Zou et al., 2002; Su et al., 2005). The advantage of the metal magnetic liner is that metal magnetic lining combines the best qualities of typical steel and magnetic liners. As shown and compared to rubber in Table 1, the steel metal housing provides the wear resistance and sufficient protection for the magnet material (Zou et al., 2002; Wang, 2003).

Similar to other magnetic linings, the magnets keep the lining in contact with the steel shell and maintain the liner in place. Any magnetic material in the mill charge, either magnetic minerals or ball chips, is attracted to the lining, forming the wear-resistant layer that continually self-generates as more material moves through the mill.

Studies have shown that the mill throughput normally increases with the installation of the metal magnetic lining because of gained working volume. For example, the total thickness of the metal magnetic lining for a Φ5.5×8.8-m (Φ18.0×29.0-ft) ball mill, including the protection layer, is 95-mm (3.75-in), which is less than that of a conventional lining (average 98.25 mm). This results in a larger working volume and therefore a higher throughput (Zhou et al., 2005).

For comparative purposes, a typical application for an older-style magnetic lining is presented alongside a typical application for the metal magnetic liners in Table 2. As seen in this table, the harder casing allows the metal magnetic liners to be employed in applications where larger mills and media are utilized. In this case, the weight of a

ball for a metal magnetic lining mill is 2.4 times that of a ball for a rubber-type magnetic liner.

Table 2. Comparison between rubber magnetic lining and metal magnetic lining installation.

Ball Mill Parameters	Orebed Magnetic Liner for a copper mine	Metal Magnetic Liner for a iron ore in the US
Ball mill size	10.5'x16'	10.5'x18'
Rotation speed, rpm	17.5	18.8
Ball size, inch	1-1/2	2
New feed, TPH	162 Max 103 design	250
Feed -100 Mesh	89% -100 Mesh	80% -30 Mesh
Required product	-325 Mesh	50% -325 Mesh

Mill lining is a major cost in milling operations. These expenses include the capital cost of the lining, the downtime required to replace the liner, and the labor for installation. As a consequence, effort has been expended to improve the life of liners. In fact, there are at least ten wear-resistant alloys developed and used for ball mills. And with steadily increasing installation costs due to increasing labor rates, there is a trend to select the lining which has the best service life, regardless of cost (Malghan, 1982).

The cost of the lining itself is minor compared to the media consumption, downtime, installation costs, and any improved grinding efficiency. Therefore, the overall economics must be considered when a liner is selected. For example, a metal magnetic lining has been installed and operated for ten years in a ball mill measuring $\Phi 3.2 \times 4.5$ -m ($\Phi 10.5 \times 14.7$ -ft). It has been found that the total power draw has been reduced by a total of 7%, the ball consumption has decreased 10%, the mill throughput increased 5.6%, and availability increased 1%. In contrast, the conventional steel lining only lasted one year for this mill, while the metal magnetic liner has been in continuous service for up to a decade. In this case, the purchase price of metal magnetic liners was approximately twice that of the conventional steel linings; however, it was found that the pay-back period was only six months when taking into account the added savings as stated above (Zou, et al., 2002; Zhou et al., 2005).

In addition to the cost savings, the metal magnetic liners also offered other benefits over steel liners including an easier and faster installation, safer method of installation, and maintenance-free operation. As a consequence, the lining costs per ton of ore milled for the metal magnetic liners were greatly reduced compared to the conventional steel lining.

Northshore Mining

The metal magnetic liner consists of powerful permanent ceramic magnets embedded in a heavy-duty

steel housing. The principle of the metal magnetic lining, like the other types of magnetic liners, is to use the ball chips and magnetic minerals present in the slurry to form the protection layer in an effort to reduce downtime and maintenance costs. The metal magnetic liners incorporate all the advantages of other magnetic linings; however, they have a significantly longer service life than the thin rubber-based magnetic linings. These steel housings protect the magnet material and allow the metal magnetic lining to be installed in ball mills up to 5.5-m (18-ft) diameter, while others are severely limited to mill diameter and ball size. These benefits prompted a trial of this technology within a single secondary ball mill at Cleveland Cliff's Northshore Mining operation in Silver Bay, Minnesota.

Installation

Three types of metal magnetic linings, including standard (Type I), combined (Type II), and a heavy-duty version (Type III), have been developed in China to suit different operations. For the Northshore operation, a Type II metal magnetic lining was supplied by Eriez Manufacturing in partnership with the Glenn Corporation. The lining was manufactured by the JinFa Industrial Trading Co., and was installed in July 2006. A typical piece of the metal magnetic lining is about 300 mm long and weighs 17 kg and can be seen in Figure 1. Each piece can be easily moved by hand.



Figure 1. Typical piece of metal magnetic lining.

A complete set of liners was placed in one of twenty-two $\Phi 3.2 \times 5.5$ -m ($\Phi 10.5 \times 18$ -ft) mills used in a secondary grinding capacity and constitutes the first installation of this type liner in a North American plant. Specifically, this iron producer processes taconite ore to extract magnetite. Previously, the ball mill was protected with a steel lining and used 25 to 50-mm (1 to 2 in) balls at a 30% charge

volume. The maximum mill feed rate is 225 tph (250 stph) with 80% of the feed passing 600 microns.

Prior to installation of the metal magnetic mill liners, personnel from Northshore removed the old steel liners. In addition, the existing bolt holes used to secure the steel liners in place were plugged using rubber bungs to stop any leaks, as seen in Figure 2. JinFa supplied an installation team for installation of the magnetic liners. This team, consisting of four technicians, began the installation process at 10:00 am and completed the changeover at 8:00 pm on the same day. The installation was performed without removing the mill charge as seen in Figure 3. All installation work was performed inside the mill.

The total installation time was measured at less than ten hours and no injuries were incurred during the installation process. Please note that this time reflects only the time for the installation of the liners and does not include the time consumed to remove the traditional steel liners. Regardless, the installation time for a traditional metal liner for this ball mill can take up to 36 hours. More importantly, the risk of injuries to personnel was greatly reduced compared to the installation of the conventional steel lining. The completed installation is shown in Figure 4.

The lining was inspected after running the mill for one month. No lining was found have fallen off of the mill wall and no individual pieces were found to be damaged. A solid protection layer formed with a wave profile that reflects the layout of the magnet poles (Figure 5).

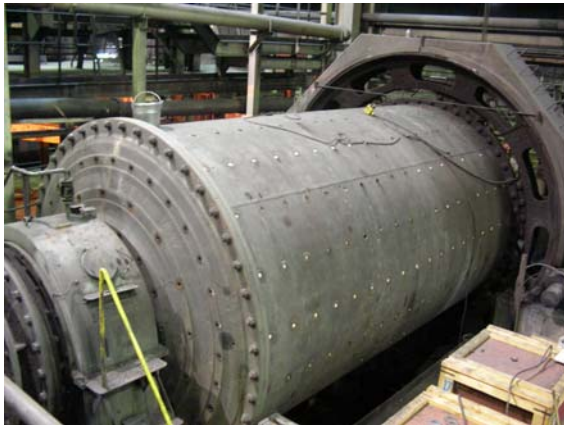


Figure 2. Outer mill surface with plugged bolt holes.

Grinding Efficiency

Material in a grinding mill is subject to three different processes including impact, abrasion, and attrition. Particles are reduced in size as they impact against both each other and grinding media. Although the impact is relatively energy efficient, the impact in the ball mill is insufficient to achieve high grinding efficiency. Through attrition, material is ground by the pressure of the grinding charge and this is typically an energy-efficient process (Svensson, 1995). On

the other hand, abrasion is energy intensive since it breaks down particles by surface wear.



Figure 3. Installation of metal magnetic lining with mill charge in place.

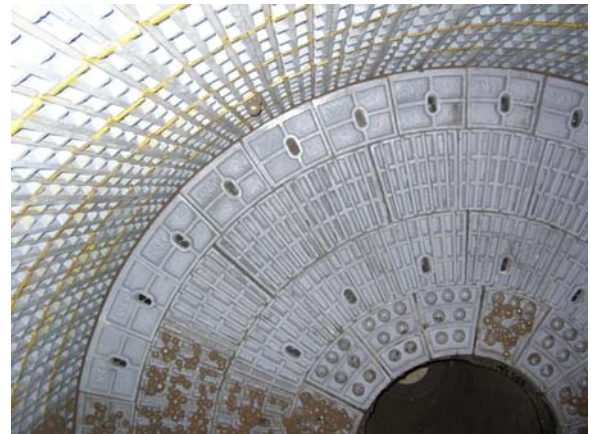


Figure 4. Installed metal magnetic liner on mill wall and mill end caps.



Figure 5. Metal magnetic mill liners with protection layer of ball chips and magnetic minerals (Courtesy of Kevin Berglund).

The grinding efficiency of a ball mill is greatly affected by the profile and material of the liner due to the fact that the driving force of the mill is transmitted via this lining to the charge. At low speed or with smooth linings, the media tends to roll down to the toe of the mill and comminution by abrasion and attrition occurs. This type of grinding is preferred in a regrinding process due to the increased generation of fines while cascading material in the mill at lower mill speeds. Operating at higher speeds leads to grinding through impact and is not preferred.

The wave profile generated by the magnetic force from the metal magnetic liners provides an optimal lining surface which will lift the material and induce an efficient cascade of material (Svensson, 1995). This wave profile can be seen in Figure 5. This profile will remain constant and optimal for the full lifetime of the lining, which can be several years. In contrast, and because conventional metal liners undergo continuous wear, their profiles are continuously changing. In fact, they are often too steep at installation and worn too shallow at the end of their useful life. As such, a lower grinding efficiency is often cited when compared to the metal magnetic mill liners.

In a ball mill lined with metal magnetic liners, the charge is more compact than the conventional liner due to the wave profile of the wear layer formed by the magnetic force. Therefore, attrition becomes the dominant action in the mill. The corrugated grinding surface formed by the magnetic force reduces the abrasive action of the ball mill and, therefore, increases grinding efficiency.

At Northshore, the product from the primary grinding mill is split into two streams with one reporting to the mill lined with the metal magnetic liner system and the other feeding a parallel mill with a conventional steel liner. Two tests have confirmed that the mill lined with metal magnetic lining has an identical product particle size distribution when compared to the mill outfitted with the conventional steel liner. This indicates that there is no reduction in grinding efficiency when using the metal magnetic mill liners. Figure 6 shows the various size distributions after approximately 900 hours of operation, while Figure 7 shows data with up to 1800 hours of operation. For both mills, the various product size distributions are identical.

To further investigate the effect of utilizing the metal magnetic liners, the mill outfit with the new liners was run at 95% of the power draw as the mill operating in parallel with the conventional steel liners. It can be seen in Figure 8 that the product particle size distribution did not change after the power draw to the mill was reduced. This fact supports the observations seen in Chinese applications where power consumption was dropped by an average of 7%, resulting in immediate cost savings. This preliminary result may be an indication of potential power savings for Northshore and will be further investigated over a longer period of time.

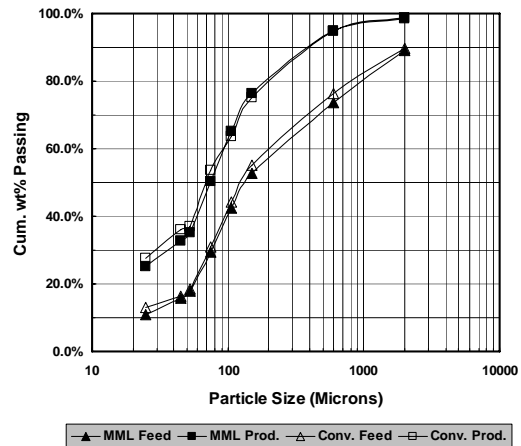


Figure 6. Side-by-side comparison for product size distributions for operation up to 900 hours after start-up.

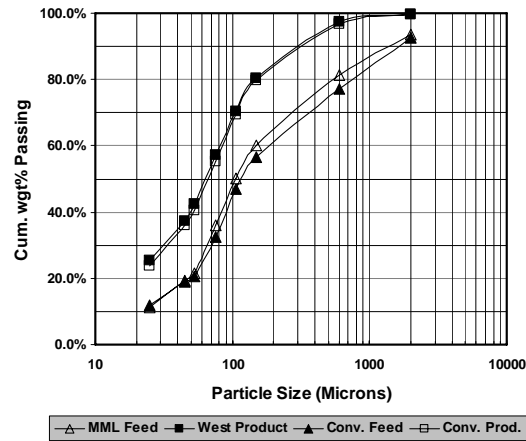


Figure 7. Side-by-side comparison for product size distributions for operation up to 1800 hours after start-up.

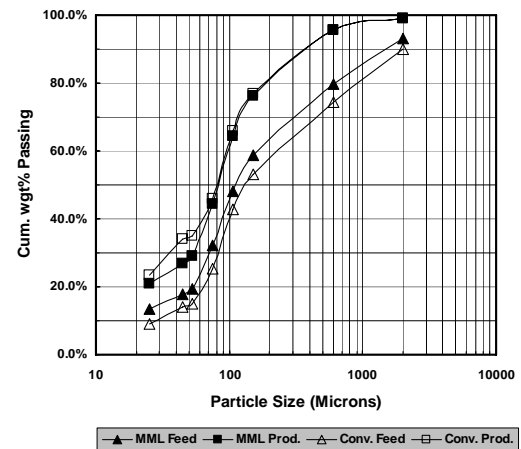


Figure 8. Side-by-side comparison for product size distributions for operation up to 2200 hours with MML mill operating at 95% power draw.

Summary

Several conclusions can be drawn from this work and from the installation of the metal magnetic mill liners at Cleveland Cliff's Northshore operation. These include:

1. The metal magnetic mill liner (MML) system uses steel to house the magnetic element and offers better protection than liners that use rubber as housing material. Furthermore, metal magnetic liners can be applied in a wider variety of grinding applications, especially those that exhibit severe grinding forces.
2. Preliminary side-by-side results from the Northshore installation indicate that, while operating at the same feed rate, the product particle size distribution did not change after the installation of a metal magnetic liner, which was installed to replace a conventional steel liner.
3. The product particle size distribution at Northshore was not altered after reducing the mill power draw by 5%. This indicates that the metal magnetic lining may offer an efficient means to reduce the power consumption and increase profitability. More tests are to be completed to confirm this finding.
4. The installation of metal magnetic liners is easier and safer than conventional steel liners. In fact, the metal magnetic liner weight is approximately 17 kg, while a conventional steel liner weighs approximately 454 kg.
5. The installation of a metal magnetic liner is faster to install than a conventional steel liner. Four workers completed the installation process in only 10 hours.
6. The metal magnetic mill liners self-adhere to the mill wall and there is no bolting requirement. As such, the lining is leak-proof and no re-tightening of bolts is required.
7. The metal magnetic mill liner is the only magnetic lining that successfully covers the entirety of the interior of the ball mill, including the mill end caps.
8. The metal magnetic mill liners can be installed in ball mills up to 18'-0" diameter.

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