OPPORTUNITIES FOR FERROUS ALLOYS USED IN COPPER MINING

V. Pérez and D. Villaseca

Corporación Nacional del Cobre (CODELCO), Chile

Keywords: Copper Mining, Ferrous Alloys, Grinding Balls, Liners, SAG Mills, Molybdenum, Cost Saving, Wear Rates

Abstract

A study of ferrous alloys used in the Chilean mining industry was conducted in order to determine potential opportunities for the development and introduction of new ferrous alloys where benefits far outweigh cost increases. Two criteria were defined for determining the alloys of interest: demand for the alloy reaches at least 15,000 tonnes per year within the Chilean copper mining industry, and improving the alloy properties would have a positive economic impact and therefore be of interest to other mining companies.

The copper production chain was examined to identify at which points conditions caused impact and abrasion wear, and where chemically aggressive conditions existed that could cause corrosion. As a result of this analysis, it was concluded that grinding balls and SAG mill liners constitute interesting opportunities. In the case of grinding balls, it is the second greatest expense of a concentrator plant, after energy. The estimated consumption by the Chilean copper mining industry is 445,000 tonnes of steel per year. Given the large volume involved, there is a significant direct economic benefit to users if the consumption of grinding balls is reduced. Based on treatment of 50 million tonnes of ore per year, it is estimated that improved alloy properties, sufficient to reduce ball consumption in the copper mining industry by at least 10%, would, even with an increase in alloy cost of 4%, produce savings of approximately US$1.56 million per year.

In the case of SAG mill liners, achieving an increase in liner service life is important, since downtimes of SAG mills have a direct impact on final production and thus on sales. It was estimated that, for plants treating 50 million tonnes of ore per year (estimated three SAG mills), the benefit stemming from a 5% increase in liner duration would be US$2.62 million per year, per plant.

Introduction

In analyzing an appropriate context in which to introduce new or improved ferrous alloy products, the Chilean mining industry emerges as an attractive area within which to seek opportunities. Given its great size, the fact that it is a completely globalized industry and that it is a world leader in copper mining, all potential innovations should have an impact both locally and globally.

This study aims to determine the types of steel (ferrous alloys in general) in greatest demand within the Chilean mining industry, and to evaluate the potential opportunities to introduce improved steel and/or iron products.

Identification was made of those points in the copper production cycle (from extraction to finished product) where it was estimated there is a high tonnage use of ferrous alloys. This preliminary evaluation was based on the experience of the investigators, secondary data sources, rates of consumption, direct inquiry with suppliers, etc.

During visits to mines, the preliminary critical point assessments were compared to the on-site users' assessments of consumption volumes and the impact that an improvement in the performance of the iron and steel involved would have.

The analysis that yielded the definitive critical points in the process was carried out using the information gathered from visits, available secondary sources, contacts and visits to suppliers, ongoing professional contacts with mining professionals, consultations with mining experts, etc. These critical points were evaluated from the standpoint of annual consumption and impact on the client's business.

Identification and Analysis of Preliminary Critical Points

The largest consumption of steel in copper mining occurs at those points where high abrasion and/or impact and/or pressure stresses occur. These conditions exist, to a greater or lesser extent, for all equipment that comes into contact with mined material from the drilling stage onwards.

After identifying these points, the next step was to estimate annual ferrous alloy consumption at each critical point to determine whether it met the established baseline consumption criterion of 15,000 tonnes per year. Table I is a summary of the preliminary critical process points identified.

Drilling

During the drilling process, the drilling components that are subject to the greatest stresses, and thus have higher consumption rates, are tricones and drill bits, adapters and extension bars. The steels used in these components are structural and specialized tool steels (SAE 4340, 4140, 4130, etc.).

Based on information gathered from visits to the main suppliers in Chile, (Drillco, Atlas Copco and Sandvik), national consumption of these components does not exceed 6,000 tonnes/year. This consumption level was corroborated by information from the mining companies visited.

Table I. Preliminary Critical Process Points, their Characteristics and Estimate of Annual Consumption

Critical points (process)	**Component**	**Equipment**	**Alloy**	**Microstructure**	**Estimated steel consumption (tonne/year)**
Drilling	Tricone/drill bit	Drill	Low-alloy steel (4340-4140-4130-3310-3315)	Various	<6,000
	Adapter				
	Bar				
Loading	Wear protections	Rope shovel	Low-alloy steel	Martensitic	9,080
		Bulldozer			
		Wheeldozer			
		Front-end loader			
	Crawler shoes	Rope shovel	Low-alloy steel		530
			Mn steel	Austenitic	3,000
Transport and Haulage	Anti-wear plates	Truck-hopper, chutes, etc.	Low-alloy steel	Martensitic	NA
Primary crushing	Concaves and mantles	Primary crusher	Mn steel	Austenitic	2,360
			Cr-Mo steel (concaves)	Martensitic	650
Secondary and Tertiary crushing	Mantle and concave	Cone crusher	Mn steel	Austenitic	6,800
SAG grinding	Liners	SAG mill	Cr-Mo steel	Pearlitic	20,500
	Balls		Low-alloy Cr steel	Martensitic	167,000
Ball grinding	Liners	Ball grinder mill	High Cr white iron	Martensitic	7,520
			Cr-Mo steel	Pearlitic	3,500
	Ball		Low-alloy Cr steel (forged)	Martensitic	278,000
			Low-alloy Cr steel (cast)		
Pumping	Volutes	Slurry pump	High Cr white iron	Martensitic	2,600
	Feeding plates				
	Impellers				
Transport	Anti-wear plates	Conveyor belt, chute, feeder, etc.	Low-alloy steel	Martensitic	NA
Electrowinning	Cathode	Electrowinning cell	316L	Austenitic	1,600

NA – Not Available

Loading

In the loading category, the anti-wear elements utilized in shovels, bulldozers, wheeldozers, front loaders, etc. are, for the most part, associated with low-alloy cast steel parts used to protect buckets and dozers attached to the equipment. The parts are mainly teeth, tooth adapters, lateral shields, blades, rippers, etc.

It is estimated that 20% of these components are forged (mainly tips and adapters) or fabricated from plates of 500 HB hardness (mainly blades and rippers). These types of parts have a wear-consumption rate of 3.2 grams of steel for each tonne of material moved. Assuming a total of 810,592,000 tonnes per year of ore processed and a sterile-ore ratio of 2.5:1, the total tonnage moved in the open pit copper mines would be 2,837,072,000 tonnes per year. This figure, multiplied by the material loss rate of 3.2 grams per tonne, yields an approximate consumption of 9,080 tonnes per year for these types of alloys.

This consumption figure was confirmed by comparison with information gathered from field visits.

Primary Crushing

This process point mainly focuses on rotary crusher concaves and mantles which are the types primarily used in large-scale copper mining. Manganese steel consumption is low at around 2,300 tonnes per year.

SAG (Semi-Autogenous Grinding)

SAG mills generate significant consumption of grinding balls and liners which is proportional to the tonnage treated in the mills. Table II shows the tonnage of ore treated per plant in the large-scale Chilean copper mining industry. This point will be discussed in detail in later sections.

Ball Grinding

In ball grinding, as well as SAG grinding, significant consumption of the relevant balls occurs and this point will be analyzed further in the subsequent stages of this study.

In the case of high-chrome white iron liners, consumption amounts to 7,520 tonnes annually. This was calculated based on the total tonnage passed through ball-grinder mills at concentrator plants in the mining sector, 522,133,000 tonnes per year, multiplied by the wear rate of 12 g/tonne and adding 20% to cover vertical mills, medium and small mining mills and mainly, gold and iron treatment mills. This tonnage, combined with the 3,000 tonnes/year estimated as the consumption of slurry pump replacement parts, does not reach the minimum value of 15,000 tonnes per year set as the required minimum for further consideration.

Table II. Ore Treated per Plant in Large-Scale Chilean Copper Mining

Plant		Ore treated			
		Total (tonne/day)	**Per SAG mill (tonne/day)**	**Total (tonne/year)**	**Per SAG mill (tonne/year)**
Concentrated Ore Plants	Minera Escondida	225,000	225,000	82,125,000	82,125,000
	Los Pelambres	180,000	180,000	65,700,000	65,700,000
	Codelco Norte	171,000	60,000	62,415,000	21,900,000
	Collahuasi	140,000	140,000	51,100,000	51,100,000
	El Teniente	123,000	85,000	44,895,000	31,025,000
	Caserones	100,000	100,000	36,500,000	36,500,000
	Esperanza	98,000	98,000	35,770,000	35,770,000
	Andina	95,000	36,000	34,675,000	13,140,000
	Candelaria	75,000	75,000	27,375,000	27,375,000
	Los Bronces	56,000	56,000	20,440,000	20,440,000
	Carmen de Andacollo	55,000	55,000	20,075,000	20,075,000
	División Ministro Hales	50,000	50,000	18,250,000	18,250,000
	El Salvador	33,500		12,227,500	
	El Soldado	18,000	18,000	6,570,000	6,570,000
	Mantos Blancos	11,000		4,015,000	
Oxidized Ore Plants	Radomiro Tomic	160,000		58,400,000	
	Gabriela Mistral	130,000		47,450,000	
	El Abra	114,000		41,610,000	
	Spence	55,000		20,075,000	
	Zaldivar	55,000		20,075,000	
	Minera Escondida	55,000		20,075,000	
	Cerro Colorado	48,000		17,520,000	
	Lomas Bayas	36,000		13,140,000	
	El Tesoro	26,000		9,490,000	
	Manto Verde	25,000		9,125,000	
	Quebrada Blanca	21,000		7,665,000	
	Codelco Norte Mina Sur	19,000		6,935,000	
	Doña Inés de Collahuasi	17,300		6,314,500	
	Minera Michilla	16,000		5,840,000	
	Mantos Blancos	13,000		4,745,000	

Slurry Pumping

Large-sized slurry pumps use high-chromium white iron replacement parts, alloys similar to those used in ball-grinder mill liners. Based on contact with personnel from Weir Minerals Chile, the leading national provider of slurry pumps, the consumption of high-chromium white iron pump replacement parts was estimated at 2,600 tonnes/year.

The estimate takes into account the existence of 50 large-sized slurry pumps, with an impeller (the main wearing part) lifespan of 3 months on average. This means an annual consumption of 200 impellers for these pumps, with an approximate weight of 7 tonnes/impeller. These large-sized pumps would thus generate a consumption of 1,400 tonnes/year. To this is added 400 tonnes for consumption of volutes. It is considered that this amount represents 70% of the total national consumption of slurry pump parts, so the overall total is estimated at approximately 2,600 tonnes/year.

Secondary and Tertiary Crushing

During the steps of secondary and tertiary crushing, manganese steel is consumed as the main alloy used to manufacture crusher mantles and concaves. Additionally, manganese steel is also consumed in the primary crushing stage and the loading stage, as the alloy is used in the manufacture of shovel crawler shoes. Accounting for these applications, the total sum for manganese steel consumption reaches 12,160 tonnes per year, which is insufficient to be considered for further analysis.

Electrowinning (EW)

In the electrowinning process, permanent cathodes of stainless steel grade AISI 316L are used. Based on information from available technical literature [1] and corroborated by contacts in the mining industry, it was established that in Chile there are 350,000 operating cathodes, each with an average lifespan of six years. This would generate a replacement consumption of approximately 58,000 cathodes per year. The weight of each cathode is 28 kg, generating an annual consumption of approximately 1,600 tonnes, which is far below that required for further analysis in the current study.

Transport

Ore transport is required at all stages of copper mining extraction and comminution, and each phase, to a greater or lesser extent, has associated abrasion and impact stresses. Plates with a hardness of approximately 500 HB are widely used for structural protection for equipment involved in ore transportation.

Critical Analysis and Identification of Opportunities

The preliminary analysis of the critical process points led to the selection of SAG Grinding and Ball Grinding as worthy of further analysis. Since the general aim of the study is "to determine potential opportunities for the development and introduction of new ferrous alloys where benefits significantly exceed cost," the analysis of the opportunities was made based on alloy type. Therefore, the opportunities to be analyzed are:

- Low-alloy Cr steel used in grinding balls;
- Cr-Mo steel used in SAG mill liners.

The remaining points were discarded as final critical process points since ferrous alloy consumption for each was below the 15,000 tonnes/year criterion. Additionally, insufficient interest was shown by mining companies' operational managers who were visited during the execution of this project.

Table III shows the final critical process points and the annual consumption of different types of parts and alloys in each, along with their estimated 2014 tonnage totals.

Table III. Final Critical Points and Estimated Consumption of Alloys that Exceed the 15,000 tonne/year Threshold. Estimates are for 2014

Opportunity	**Annual consumption by critical points – tonnes**			
	Primary crushing	**SAG grinding**	**Ball grinding**	**Total**
Cast and forged grinding balls Low-alloy Cr steels	-	166,600	277,900	444,500
Cast liners Cr-Mo steels	650	20,500	3,500	24,650

Low-Alloy Steel Used in Grinding Balls

Description of Use

Balls are grinding bodies whose function is to reduce, or help to reduce, the size of the ore that passes through the mills. They are used in both SAG mills and Ball mills:

SAG MILLS: Large mills, ranging between 28 and 40 ft in diameter, which mainly use forged balls with diameters between 5.0 and 6.0 in, whose function is to use impact and abrasion to reduce the size of the ore. As the mill turns, some of the balls and ore are lifted and dropped on the rest of the load, which generates high impact and abrasion stresses.

BALL MILLS: These mills are of smaller diameter, although they are now reaching sizes of up to 26 ft. They employ mostly 3.0 in diameter (1.0 in for regrind mills) forged or cast balls. Their primary function is to reduce the ore size by abrasion, and therefore the primary ball stresses are those caused by abrasion.

Characterization of Balls

Typical chemical composition ranges of grinding balls are shown in Table IV. This information was taken from the suppliers' websites. The molybdenum content in the 5.5 in diameter forged balls was less than 0.08% according to chemical analyses done on locally manufactured and imported balls in 2013. Niobium was not found in any of the ball compositions.

Table IV. Typical Chemical Composition Ranges of Both Types of Grinding Balls

Ball type	**Mill type**	**Chemical composition (wt.%)**				
		C	**Mn**	**Cr**	**Si**	**Mo**
Forged balls	SAG and Ball mills	0.55 - 0.90	0.70 - 1.25	0.37 - 1.20	0.18 - 0.70	0.00 - 0.20
Cast balls	Ball mills	0.75 - 0.95	0.40 - 1.10	0.20 - 1.10	0.30 - 0.60	residual

Table V shows the property characteristics normally offered by suppliers, as product specifications, to their clients, which are available on their websites.

Table V. Available Grinding Ball Characteristics

Ball type	**Mill type**	**Features**			
		Microstructure	**Hardness HRC**	**Diameter (in)**	**Mechanical requirements**
Forged ball	SAG mill	Tempered martensite with retained austenite	55 - 63	5 - 6	High impact, moderate abrasion resistances
Forged ball	Ball mill		55 - 65	2 - 3	High abrasion, moderate impact resistances
Cast ball	Ball mill		60 - 66	1 - 3	High abrasion, moderate impact resistances

In general, the forged ball has a tempered martensite microstructure with retained austenite present throughout the entire section thickness. The hardness profile is fairly even with no more than a 4 point HRC (Rockwell Hardness) variation between the ball's center and surface. They have practically no internal discontinuity defects since they are manufactured from laminated bars that are cut and hot forged.

The cast grinding ball has a similar microstructure, but with all of the characteristics of a cast section; chemical segregation and presence of discontinuities (pores, shrink holes, etc.). This results in the cast grinding ball having inferior mechanical properties, making it unsuitable for use in SAG mills where, due to high impact stresses, failure by fracturing would occur.

Reason for Ball Replacement

In the case of SAG mills, the replacement balls are added at the same rate they leave the mill, ie. when they reach an internally specified size. Normally this size is between 2 and 3.5 in. In Ball Grinding, the grinding media leave the mill when of a size capable of being carried off by the slurry. In this case, there is no classification and the slurry runs off through a spillway.

Ball consumption is mainly due to wear in ball grinder mills and also due to fracturing in SAG mills (approximately 10%) [2]. In large size, 38 to 40 ft diameter SAG mills, ball fracturing can account for a higher percentage of consumption due to increased impact energies. In these cases the quality of the ball becomes more important.

Ball Consumption

It is commonly accepted practice in concentrator plants to measure the consumption of grinding media in grams per tonne treated (g/tonne); that is to say, the weight of the balls, in grams, that is consumed to treat one tonne of ore at the plant. Also it is known in mining circles that the average value for SAG mills is around 390 g/tonne, and for ball grinder mills around 535 g/tonne. These figures were corroborated by site visits to plants and through consultation with national experts [3]. The figures shown in Table VI are based on these rates and the tonnage treated annually at the concentrator plants.

Table VI. Estimated Ball Consumption in Large-scale Chilean Copper Mining, 2014

Process	**Ore treated**	**Ball consumption**	
	(tonne/year)	**(g/tonne)**	**(tonne/year)**
SAG grinding	429,970,000	390	167,688
Ball grinding	522,132,500	535	279,340
Total ball consumption			447,028

Considering that Chile is responsible for one-third of the global copper mining production [4], the total market for balls could reach figures of close to 1.35 million tonnes annually, in this industry alone.

Economic Impact for Abrasion and Impact Resistant Grinding Balls

The economic impact on companies can be estimated in terms of direct and indirect benefits. The direct benefits are related to lower annual costs, from the reduced need to renew grinding balls in this case. The indirect benefits are those generated as a result of using a new, higher-performance product, for example, increased plant availability, lower operating costs, increased safety, reduced environmental impact, etc.

In order to obtain a direct benefit (savings due to reduced ball consumption), the potential price increase due to higher alloy content or change in manufacturing route must be offset by reduced consumption from the improved performance of the new alloy balls.

In consultations, concentrator plant managers and superintendents agreed that a 5% cost decrease in grinding media would be of interest to them, especially considering that grinding balls are the second highest cost item in a concentrator plant, after energy. This equates to an overall cost saving of 5% over and above any additional costs incurred due to a change in alloy composition and/or change in process route to manufacture the grinding balls. As an example, for a SAG plant treating 50 million tonnes of ore per year and assuming a ball wear rate of 390g/tonne this indicates a ball consumption of 19,500 tonnes per year. Typically, ball cost is currently US$1250/tonne which equates to an annual ball consumption cost of US$24.38 million. If the ball parameters changed such that cost increased to US$1300 per tonne but the ball consumption reduced by 10% (due to improved wear and impact performance) then the annual direct costs due to ball consumption would be US$22.82 million. This represents a potential saving of 1.56US$ million/year which is greater than a 6% saving on ball consumption costs. The above simple cost analysis serves to illustrate that the potential savings from improved ball wear and impact resistance are significant and that improving ball properties is a goal worthy of further research.

Indirect benefits, as listed below, are difficult to quantify and their magnitude depends on individual companies:

- Better resource usage owing to longer ball service life (less loss of material due to wear);
- Decreased materials handling cost owing to reduced consumption;
- Decreased occupational risk from materials handling;
- Environmental and sustainability benefits through reduced transportation, reduced energy consumption generally, smaller carbon footprint, etc.

Key Business Players

The Chilean grinding ball market is dominated by Moly-Cop, a national manufacturer of forged balls, which holds approximately 39% of the market. Table VII shows the participants in this market, comprising 100% of the supply.

Ball manufacturers are significant players because they manufacture the final product, have extensive market knowledge and have a commercial relationship with the client. The key players in the Chilean market are Moly-Cop and Elecmetal (Changshu Longteng).

Table VII. Major Suppliers of Mill Grinding Balls

Suppliers	Company	Ball type	Diameter (in)	Domestic market share (%)
National	Moly-Cop	Forged	1 - 6	39
	Sabo Chile	Forged	1.25 - 6	10
	Proacer	Forged	2 - 4	18
Foreign	Changshu Longteng	Forged	1 - 6	30
	Others			3

Bar manufacturers are important in this market as well because the performance of the forged ball depends to a large degree on the quality of the bar and because any study related to changes in chemical composition of the ball will affect the bar production process. In Chile, the only bar supplier is the Huachipato Steel Company (Compañía Siderúrgica Huachipato).

Cr-Mo Steel Used in SAG Mill Liners

Of the total amount of Cr-Mo cast steel used in mining, 81% is used in SAG mill liners, 16% in large ball grinder mill liners and 3% as primary rotating crusher concaves. Given this distribution, the analysis will focus on SAG mill liners.

SAG mills play a key strategic role in those mining sites that use this type of equipment, because between 50% and 100% of processed ore flows through these mills depending on plant configuration and existing operating lines. This means that most or all the plants' production depends on their smooth functioning, as any stoppage of the mill leads to a total or partial shutdown of the mine.

Description of Use

Liners are used in a mill's interior to protect the structure and to shape the motion of the load. They can be classified as cylinder liners and cover liners:

CYLINDER LINERS: consist of a lifter and plates. The lifter is responsible for lifting the load in order to generate the impact energy necessary to reduce the ore size. The cylinder lifters are the heaviest parts, weighing as much as 4.5 tonnes;

COVER LINERS: also made up of a lifter and plates. In this case, the lifter is intended to provide wear protection more than to lift the load. Grates are used in the discharge cover to classify the ore's output size.

The main function of a SAG mill is ore size reduction, achieved through the impact produced by the grinding balls and from the large-dimension rocks that feed the mill and fall on the internal load. This is the reason for the large diameters seen in this equipment, which currently stand at 40 ft in the largest mills. The liners are subject to high impacts, produced mainly by grinding balls of up to 6 inches in diameter and they must be sufficiently tough not to fracture under normal operating conditions.

Additionally, abrasion stresses produced inside the mill load are significant; therefore, wear resistance is also a required property of these alloys.

Characterization of Cr-Mo Steel

The chemical composition of the Cr-Mo steel used in liners does not adhere to any particular standard. However, the large majority of the suppliers manufacture their products in a composition range as shown in Table VIII. When requested, this information is delivered to customers. In some cases it is also available on the supplier's website.

It is important to note that there has been virtually no change in these types of alloys in the last 20 years, which suggests that there is little applied research on the topic.

Table VIII. Typical Chemical Composition Ranges of Cr-Mo Steel Liners

Application	**Chemical composition (wt.%)**				
	C	**Mn**	**Cr**	**Si**	**Mo**
SAG and Ball mill liner	0.50 – 0.75	0.75 – 1.00	2.00 – 2.50	0.40 – 0.60	0.30 – 0.45

Table IX shows the information about characteristics and mechanical properties which is normally delivered by the suppliers to their end-use customers (when requested). Only some of it is published on their websites. In general, this is information that suppliers provide only selectively.

Table IX. Typical Microstructural, Mechanical and Stress Characteristics of the Cr-Mo Steel Used in Mill Liners

SAG mill liner features					
Microstructure	**Hardness HB**	**Tensile strength (kgf/mm^2)**	**Yield strength (kgf/mm^2)**	**Resilience (lbf/ft^2)**	**Mechanical requirement**
Pearlitic	300 - 400	110 - 135	85 - 115	35 - 100	High impact, high abrasion resistances

In general, these castings seek to obtain a fine pearlite microstructure since this offers a better toughness vs. hardness balance for this application. In the case of very thick parts, such as cylinder lifters for example (over 14 in), the microstructure varies greatly across the thickness of the part. On the surface, martensite, bainite and fine pearlite can be found. Then fine pearlite becomes predominant and finally at the center of the part coarse pearlite is found. The hardness gradient is high in these parts, with differences of up to 50 HB between core and surface. Thinner parts, such as plates for example (6 to 8 in) are more microstructurally homogeneous and the hardness gradients are lower.

Grates, being mechanically less resistant to impacts, are manufactured in lower hardness ranges (290 to 340 HB) in order to increase toughness and prevent fracturing during operation. Naturally, decreased hardness means higher wear rates.

Reasons for Liner Replacement

Replacement is carried out owing to wear and/or fractures in liners. Replacement owing to wear is carried out during planned stoppages, whereas liner fracturing causes unforeseen stoppages, accounting for about 10% of the replacements required. Although in both cases production stops, the annual plan only considers scheduled maintenance, which means that unplanned stoppages have the additional effect of jeopardizing the achievement of company goals. Because high percentages of plant production pass through the SAG mill, any stoppage leads to significant revenue loss for mining companies. Therefore, SAG mill liners are considered to be strategic items.

For purposes of scheduling liner changes, an empirical determination is made as to what the minimum liner thickness can be without affecting production, without risk of breakage or structural damage. From this point of view, liners are designed to cause the fewest stoppages and to take the least possible time to replace. This is due to the fact that an increase in mill availability means increased plant availability and thus increased production.

Improving liner performance would require: increasing abrasion resistance while maintaining toughness, increasing toughness while maintaining abrasion resistance, or improving both properties at the same time. The effect of improving liner alloys is highly valuable to company revenues, primarily as a function of increased equipment availability, as this is where the majority of production comes from.

SAG Mill Liner Consumption

Total consumption was calculated based on wear-rate parameters in grams of steel per processed tonne (g/tonne). The value used, 40 g/tonne, is an average estimate for the domestic mining industry. This parameter is known for each mine and was corroborated during visits and consultations with experts carried out during this study. The value of the tonnage processed by all SAG plants operating in copper mining in Chile was determined based on the tonnages processed by each establishment that operates with SAG mills (Table II). The estimated total Cr-Mo steel consumed in SAG mill liners is shown in Table X.

The value of "Consumption due to other factors" is related to unplanned changes, for SAG mill consumption in gold mining and in small plants, for obsolete designs, etc. This value was estimated at 20% of wear consumption.

Table X. SAG Mill Liner Consumption Estimated Based on Average Wear Rate

Annual tonnage processed by SAG plants in Chilean Copper Mining (tonne/year)	**Average wear rate for SAG mill liner (g/tonne)**	**Estimated total consumption for wear (tonne/year)**	**Consumption due to other factors (tonne/year)**	**Estimated total consumption (tonne/year)**
429,970,000	40	17,199	3,470	20,669

Economic Impact on Mining Companies

To obtain a direct benefit, the increased price of any new alloy developed (due to higher alloy content or change in process route) must be offset by the lowered costs from reduced liner consumption and a longer service life.

To make a direct-benefit analysis, a hypothetical mill that consumes mill linings at a rate equivalent to the average SAG mill rate will be considered. The estimates are:

- Total annual mill lining consumption in Chile: 20,669 tonnes/year (Table X);
- Total mills considered: 24 [5];
- Average annual SAG mill lining consumption: 860 tonnes/year;
- Current average spending per SAG mill: US$2,580,000 At an average liner price of US$3,000/tonne.

As an example of a cost analysis and using the figures above for liner consumption and cost, if the liner cost increased by 5% and the liner life increased by 10% (due to improved wear resistance) then the annual liner consumption cost would be US$2.438 million which represents a saving of US$142,000. This represents a small saving and much less than that associated with the savings possible from improved ball performance.

The principal indirect benefit from an increase in liner service life is from increased mill availability, as there is always a potential bottleneck at this point in the process, and time spent on liner changes is the main variable controlling the number of SAG mill downtime hours. In other words, if liner durability is improved, mill availability increases, thereby raising plant productivity.

A hypothetical SAG mill operating under average market conditions (same assumption as made to estimate direct benefits) will be used in estimating indirect benefits. The assumed conditions are:

- Daily SAG mill treatment average is 49,086 tonne/day;
- Average hourly treatment of 2,045 tonne/hour;
- 0.86% Cu average ore grade [6];
- Copper price of US$2.57/pound, US$5.65/kg [7];
- Average SAG production income of 99,556 US$/hour;
- A six month liner service life (assuming a constant tonnes per day figure);
- Average downtime due to complete liner change is 92 hours;
- Average total weight for all parts is approximately 410 tonnes;
- A complete liner kit has an average cost of US$1,230,000;
- The alloy price increases proportionally to the increase in service life duration.

Under these assumed conditions, Table XI shows the benefit estimates from increased availability under different increments of liner durability.

Table XI. Indirect Annual Benefits from Plant Availability as a Function of Increased Service Life and Price Increases for a SAG Mill that Meets the Conditions Specified Above

Estimated annual benefits of increasing availability			
Increase in new alloy liner lifespan (%)	5	10	15
Duration for base alloy liner (months)	6	6	6
Duration for new alloy liner (months)	6.30	6.60	6.90
Time for saving one change (months)	126	66	46
Time for saving one change (years)	10.5	5.5	3.8
Time for change (h)	92	92	92
Additional time available for production, per year (h)	8.76	16.73	24.00
Additional income from additional hours (US$/year)	872,111	1,665,572	2,389,344

As can be seen, the benefits are significant. In the case where there is a 5% service life increase, (where the direct financial benefit is zero), the indirect benefit is US$872,111 per year.

In the case of a plant that treats 50 million tonnes per year (three SAG mills estimated), the indirect benefit stemming from increased availability from a 5% increase in liner life would be US$2,616,333 per year, per plant. This is the same order of magnitude as the possible direct benefits estimated for the grinding balls. Thus, the indirect benefit that comes from increased plant availability is valuable to the mining industry and possible developments in this area should strongly arouse their interest. In fact, plant availability is an important benefit indicator for mills.

These benefits are not sensitive to the price of the alloy. The benefit estimates assume percent price increases for the alloys commensurate with their service life increases. Thus, alloy price increases of the order of 10% to 15% will not significantly affect the overall benefit to the customer.

Other indirect benefits stemming from increased abrasion and/or impact resistance are safety associated with less downtime and operational versatility, and better reliability.

Liner changes pose potential risks to worker safety, given the weight of the parts involved, working conditions, etc. A reduction in the number of hours spent on liner changes due to longer liner service life, and/or avoiding having to change liners due to fracturing, reduces exposure to risk, which is always valued by mining companies.

As an alternative to increased availability, increased abrasion resistance from the alloys could be used to manufacture thinner liners while maintaining service life duration. Operationally, this decreased weight would allow for an increased percentage of grinding balls which raises production capacity. Moreover, an increase in liner toughness could lead to an improvement in impact resistance, which could be exploited operationally by using greater mill spin velocity without fear of direct load impact causing liner fracturing. This could mean an increase in production without an increase of the downtime due to liner breakage.

Key Players for Mill Liner Supply

The manufacturers of mill liners are ferrous foundries which specialize in these types of mining parts. In Chile there are two manufacturing companies, Elecmetal and Aceros Chile. Elecmetal has the larger market share (around 60%) and is a Chilean-owned international company with plants in the USA. They are a major player nationally and internationally. Other participants in the domestic market are shown in Table XII.

All the foundries achieve the desired steel composition by the use of classified scrap steel as the raw material and then make adjustments to the composition using ferro- and virgin alloys. Therefore, manufacturing a new alloy depends exclusively on them and not on third parties as is the case with grinding balls.

Table XII. Major Mill Liner Suppliers

Country	Company	Estimated market share
Chile	Elecmetal	60%
	Aceros Chile	20%
Indonesia	PT Growth	20%
Canada	Norcast	

Conclusions

Faced with the overall objective of finding opportunities for the introduction of new or improved ferrous alloy products in mining operations, the study concluded that:

1. Two types of alloy could provide an opportunity for new products: low-alloy steel for use in grinding balls and Cr-Mo steel used as SAG mill liners.

2. Material consumption for balls, 445,000 tonnes/year in the Chilean copper mining industry, is an order of magnitude greater than for any other alloy used in mining operations.

3. For a SAG mill plant that processes 50 million tonnes of ore annually, the benefit of a 10% extension of grinding ball life, given a 4% increase in cost due to extra alloy content and/or change in process route, is estimated as US$1.56 million per year.

4. SAG mill liners do not represent such a large volume of steel usage as grinding balls. However, alloy development leading to an increase in liner life, and thus reduced downtime for liner changes, would have a significant beneficial economic impact which justifies the alloy development investment. It was estimated that, for plants treating 50 million tonnes of ore per year (estimated 3 SAG mills), the benefit stemming from a 5% increase in liner duration would be US$2.62 million per year, per plant.

5. New product development should result in a strong competitive differentiation for any new player in the market since alloys for balls and liners have shown little evolution over the last 20 years.

References

1. Portal Minero, Guía de Ingeniería en Operaciones Mineras. 2005/2006.

2. J.E. Sepúlveda, “Criteria for the Selection, Application and Evaluation of Grinding Mill Media” (Paper presented at the First International Ore Processing Meeting, Antofagasta, Chile, 26 – 28 July, 2006), 20.

3. Luis Magne, private communication with authors, Universidad de Santiago, August 2014.

4. Comisión Chilena del Cobre, Yearbook: Copper and Other Mineral Statistics, 1993 – 2012, 2013, 137.

5. Editec, Catastro de Equipamiento Minero 2013-14, Febrero 2015.

6. Consejo Minero, Gran Minería en Chile: Desafíos de Productividad, Agosto 2013, 16.

7. Comisión Chilena del Cobre, Informe Semanal del Mercado Internacional del Cobre, Semana del 16 al 20 de Marzo de 2015.