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The Relative Importance of Erosion and Corrosion
on Metal Loss in Ball Milling

by

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Introduction

Wet milling has been described as "The most expensive single step in processing minerals"¹. At normal operating levels, the North American mining industry consumes more than 400,000 tons of grinding media and liners in wet milling at an annual cost in excess of \$300 million. Wet milling consumes up to ten times as much metal as dry grinding the same ore, and this has often been attributed to the effects of corrosion^{2,3}. Laboratory scale ball mill tests by Hoey et al^{4,5} indicated that between 28-60% of the ball wear could be attributed to corrosion, lending support to the belief that corrosion is a major cause of metal loss in wet milling. Remark and Wick⁶ calculated from their corrosion studies, covering a wide range of ores and mill environments, that the use of inhibitors could lead to savings of between \$36,500 and \$73,000 per annum for a 10,000 tpd mill. If the results of those and similar investigations are valid, much of the effort expended on the development of harder grinding media and harder liner plate materials has been misdirected and attention should now be focused on means to reduce corrosive rather than abrasive wear. There is, however, a vast wealth of data in the mining industry which demonstrates that harder abrasion resistant materials have progressively reduced milling costs in primary grinding mills which consume by far the largest tonnage of grinding media and liners. Data collected at the Climax and Henderson mines is presented, which indicates that in the primary grinding of molybdenite ore, abrasive wear is the major cause of metal loss. Thus, it would appear that the rapid loss of metal in many primary wet milling operations is unlikely to be affected significantly by corrosion control measures.

Climax Mill Tests

(a) Effect of Hardness and Alloy Content

The Climax and Henderson molybdenum mines have served an invaluable role as test sites for the development of improved abrasion resistant material. Variations in mill operating conditions have been undertaken over the years to help in continuous programs to reduce the metal loss and cost of wet milling and to indicate the direction research should take in developing improved corrosion-erosion resistant alloys. Table 1 shows the results from a marked ball wear test on 5" diameter balls with varying hardnesses and chromium contents from 2.8 up to 13.9%. No difference was observed in metal loss between the balls with the highest and lowest chromium content, whereas there was a marked increase in the metal loss as the ball hardness decreased. Metal loss in this 9' x 9' Marcy grate discharge mill at a pH of 8 appeared to be governed more by hardness than resistance to corrosion.

(b) Effect of Inhibitors

Development of a new level at the Climax mine introduced more acid mine waters into the milling circuits. After operating at pH levels in the mills between 4 to 7 for some 36 months, quicklime, soda ash and sodium silicate additions were initiated specifically to obtain higher flotation efficiency. Grinding media consumption over a further period of 26 months, operating at a controlled pH of 8, showed only a modest reduction of some 3%. See Table 2⁷. While this data does not prove that corrosion is not important, the effects of the change in pH and the use of sodium silicate, a known inhibitor, were, at the best, minimal.

(c) Effect of Mill Diameter and Feed Size

Marked ball wear tests were run on 5" diameter forged steel balls in a 28' diameter semiautogenous mill and in a 9' Marcy mill⁷. The water chemistry, mineralogy of the ore and work index were similar in the two mills, but the feed to the semiautogenous mill was -7" whereas the feed to the 9' mill was -3/8".

Table 3 shows that the abrasion factor for soft and hard balls was the same in the two mills, although the metal loss in the semiautogenous mill was some four times greater. No evidence of pitting or general corrosion could be found on sections cut from grinding media and liner plates removed from these mills⁸. This example demonstrates the dramatic differences in metal loss rates which can occur in primary milling without marked differences in the corrosive environment. No measurements were made of the real surface area of the hills and valleys of the scored and worn grinding balls which may have affected corrosion rates, and there could have been some differences in the availability of oxygen at the metal surfaces in the two mills. This test by itself can hardly be considered conclusive; however, none of the innumerable investigations carried out at the Climax mills have yielded data which might suggest that corrosion could be responsible for a major proportion of the metal loss in wet milling. On the other hand, measures taken to increase the hardness of both grinding media, see Table 4, and liners have consistently reduced metal losses^{7,9}. This is not only true of the Climax and Henderson mines, but is true of many other primary grinding installations.

Correlation Between Laboratory and Full-Scale Mill Data

There have been many attempts to obtain quantitative data in small-scale tests which might be helpful in reducing the enormous cost of metal losses in wet milling. Ellis¹⁰ used small jar mills and demonstrated that wear caused by the removal of oxide film was a dominant factor, and additions of chromium to his steel and changes in mill atmosphere and alkalinity were very effective in reducing loss of weight. Norman¹¹ found that similar changes in environment had a much smaller effect in a 3' diameter pilot scale mill. Removal of oxide film was considered to represent a much smaller proportion of the total weight loss in the pilot scale mill than in the small jar mills. Norman concluded that most of the metal loss in full-scale operations investigated was by the removal of metal particles. Table 5 shows that even in much more recent investigations^{4,5,6,12}, the amount

of metal removal in laboratory tube mills is small compared with metal lost in primary wet milling¹ and is less than that incurred in many regrind operations. Remark and Wick⁶ developed an abrasive lap test in which corrosion currents can be measured and from which corrosion rates can be calculated by application of electrochemical principles. In a test on a sample from a 3" diameter forged steel grinding ball using Climax molybdenum ore ground to a -20 mesh in a solution of pH 9, a corrosion current of 30mA/in² was recorded at a corrosion potential of -0.45 volts versus a saturated calomel electrode. This is roughly equivalent to a corrosion rate of 2.1 in/year or approximately 2/3 of the observed rate in a Climax mill grinding -3/8" ore. Unfortunately, no attempt was made by Remark and Wick to measure the total metal loss in their abrasive lap test. The corrosion rate of 2.1 in/year is also probably considerably higher than would be expected in a full-scale mill since the test was deliberately designed to ensure complete continuous removal of the surface of the specimen, whereas this may not occur in practice. When the available data from laboratory ball mill tests is examined, it is clear that the total metal loss is low compared with most primary wet grinding operations and it is not surprising that some 50-70% of the loss in laboratory mills has been attributed to corrosion. In primary mills grinding much coarser ores in which there are much greater abrasive effects due to the coarseness of the feed and the difference in the available energy, see Table 6, it would be reasonable to assume that corrosion plays a much smaller role. Using the Remark abrasive lap data, corrosion could only account for some 16% of the metal loss in the Henderson 28' semiautogenous wet mill.

Development of Materials for Wet Milling

Development of improved materials to resist corrosion-erosion in wet milling would be easier if it were possible to quantify the many parameters which affect cost and service life of liner plates and grinding media. Dunn⁷ and Arnson¹³ have recently reviewed the interrelationship between mill operating conditions, liner designs and the development of improved materials in papers

which served to demonstrate the complexity of the task. Both authors recognize that corrosion contributes to metal loss in wet milling but do not overemphasize its importance. A similar viewpoint is expressed by Moroz⁹ and Sailors¹⁴ in recent papers describing the development and use of improved grinding media. Wilson¹⁵ has shown that an increase in the hardness of the long established "Pearlitic-Chromium Molybdenum" steel liner plates from 340 HB min. to 380 HB min. has resulted in an increase of life between 16-20%. Martensitic steels have been developed with adequate toughness at hardness levels in excess of 500 HB for use in the high impact semiautogenous mills. Arnson¹³ shows that such steels can have 44% better life than 400 HB castings in wet mills. Examples are also quoted of improvements in resistance to corrosion-erosion by using composite liner plates with a steel body and high chromium molybdenum alloy iron inserts with a hardness of 700 HB. All of these recent papers, which are based on a wealth of practical experience in the supply and use of materials in wet mills, demonstrate that the development of harder and more abrasive resistant liner materials and grinding media has been the most effective method of reducing metal loss in wet mills to date.

Although the major thrust in developing new materials has concentrated on higher hardness and toughness, there has also been a systematic effort to identify wet milling operations in which more corrosion resistant alloys could be cost-effective¹⁴. High chromium molybdenum alloy iron/^{balls} containing up to 35% Cr and up to 3% Mo have been tested in wet mill applications where there has been clear evidence of some corrosion. These more expensive alloys can be cost-effective in mills where the abrasion is relatively modest. In more abrasive applications, the improvement in life over forged or cast low alloy steel balls may not justify the additional cost. Recent research by the Climax Molybdenum Company, see Table 7, indicates that high chromium molybdenum alloy irons, with somewhat lower carbon content and higher chromium content than are in general use in liner plates and grinding media, may be of value in the more corrosive environments encountered in

some regrind mills. Alloy irons of this type have been used in abrasion resistant pumps for some ten years with good results in pH levels as low as 3.5^{16,17,18}.

Conclusions

1. Substantial progress has been made particularly over the past decade in improving the performance of alloys used to resist corrosion-erosion in wet milling. This has been achieved by developing irons and steels with more suitable metallographic structure, generally with higher hardness and with adequate toughness to withstand service conditions.
2. Massive savings in primary wet milling costs have been achieved without resorting to the use of high alloy contents to enhance corrosion resistance.
3. Further investigations would appear necessary to quantify the importance of corrosion in specific full-scale wet milling operations to determine whether higher hardness or more corrosion resistant materials would be more useful in reducing metal loss.
4. In wet milling operations where corrosion is found to be the major cause of metal loss, martensitic high chromium molybdenum alloy irons with a high chromium carbon ratio may prove to have the required combination of corrosion-erosion resistance, particularly at pH levels in the range of 4-12.

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Tables

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