Minerals Engineering 65 (2014) 9–16

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

A process mineralogy approach to geometallurgical model refinement for the Namakwa Sands heavy minerals operations, west coast of South Africa

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A R T I C L E   I N F O

Article history:
Received 4 February 2014
Accepted 7 April 2014
Available online 4 May 2014

Keywords:
Heavy minerals
Geometallurgy
Ore characterisation
Quantitative mineralogy
Mineral processing

A B S T R A C T

The original geometallurgical model for the Namakwa Sands deposit was modified to accommodate ore blends in addition to the various single ore types. A process mineralogy approach was followed in a structured and systematic manner to evaluate the integrity of the adjusted model, particularly for ilmenite and zircon, the minerals of highest intrinsic value. This study reproduced recovery relationships predicted by the geometallurgical model for each of the key process functions, and as a result the integrity of the geometallurgical model is validated. Overall, the recovery potential determined for ilmenite and zircon are well adjusted to model estimates. Poor mineral liberation, an anomalously high abundance of garnet and pyroxene and variation in particle chemistry are recognized as the key recovery penalties. The gangue content is the most significant constraint to ilmenite recovery, whereas zircon chemistry is the most important negative factor in the production of a premium quality zircon product. Results of this study contributed to the refinement of the current geometallurgical model and also identified opportunities to optimise mineral resource utilisation in the future.

1. Introduction

Tronox Mineral Sands is presently operating the world-class Namakwa Sands heavy minerals deposit which is located along the west coast of South Africa. Estimated pre-mining mineral resources are in excess of 1 100 Mt of ore with in situ grades of 7.9 wt.% total heavy minerals, 3.16 wt.% ilmenite, 0.85 wt.% zircon, 0.50 wt.% leucoxene and 0.21 wt.% rutile. The bulk of this mega-deposit represents cemented high-grade ore that hosts a diverse heavy mineral suite.

Geometallurgical challenges related to the heterogeneity of the ore prompted systematic intervention, endeavouring to improve mineral resource intelligence (Philander and Rozendaal, 2008, 2009, 2011). As a result, a geometallurgical template model was developed for the Namakwa Sands deposit (Philander and Rozendaal, 2013). This model demonstrated a promising ability to predict the valuable mineral recovery potential for the seven ore types individually, but was not previously evaluated for *ore blends*. Since then Namakwa Sands abandoned ore-type campaigning in favour of consistent blending, which provides a greater balance between life of mine sustainability, mine development, throughput, mineral recoveries and product quality.

The primary objective of this study was to modify this 'starter' geometallurgical model in order to quantitatively evaluate its ability to determine mineral recovery potential for *ore blends*. In addition, it was envisaged that the outcomes of this study would help to refine the geometallurgical model and highlight opportunities to improve mineral resource utilisation. A process mineralogy approach was preferred since mineralogy denotes an integral building block of the original geometallurgical model (Adams, 2007; Evans et al., 2011; Lotter, 2011). In the current study emphasis is placed on the minerals of greatest economic interest, namely ilmenite ($FeTiO_3$) and zircon ($ZrSiO_4$).

2. Methodology

The original geometallurgical model describes selected relationships between ore characteristics and mineral recoveries that were determined from controlled sample populations. These ore characteristics manifest as bulk properties, for example oversize contents (+1 mm particle size), fines contents (−45 µm particle size), mineral grade and heavy mineral composition, or as particle attributes such as size, shape, density, surface exposure, mineral liberation and particle chemistry. Model indications are that these mineral

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http://dx.doi.org/10.1016/j.mineng.2014.04.006
0892-6875/

characteristics control mineral recoveries to variable degrees depending on the ore type processed. Mineral grades and the particle chemistry of the valuable fraction were identified as the key recovery drivers. All seven ore types are individually accounted for in the original geometallurgical model, but for this study the model was statistically transformed in an attempt to accommodate specific *ore blends*. As a consequence, all the recovery relationships that were established in the 'starter' model were copied into the current blend model.

The ore type compositions of monthly ore blends were determined from geological block model depletions and used as inputs in the geometallurgical model to calculate the mineral recovery potential at key processing stages over an 18 month period.

Monthly composite samples representing key sampling points at several processing stages were collected with automated samplers. Samples were investigated using a variety of analytical techniques. Optical microscopy assisted with mineral typification, X-ray fluorescence spectroscopy provided bulk chemical assays, QEMSCAN quantified mineral composition, and electron microprobe and laser ablation techniques were employed to determine the chemistry of selected heavy minerals.

3. Process mineralogy

The Namakwa processing flow sheet starts with two primary concentrators, PCP East and PCP West, which are fed by separate mining operations (Fig. 1). Their resulting heavy mineral concentrates are blended into the Secondary Concentration Plant (SCP) where magnetic and non-magnetic concentrates are produced. At the Mineral Separation Plant these concentrates are further upgraded by removing unwanted contaminants to produce the saleable products. In the following sections the adjusted geometallurgical model is systematically evaluated with respect to the relevant process.

3.1. Primary concentration

The key purpose of the primary concentration process is to remove the low density minerals from a dressed ore (45–1000 μm fraction). PCP West houses a semi-autogenous mill that mills the cemented ore to −1 mm. Conventional wet spirals are used in a four stage duty to recover the heavy minerals (density greater than 29 g/cm^3). The starter geometallurgical model relates zircon and ilmenite recoveries mainly to their spiral feed grades, because the zircon grades of both the concentrate and tails are stringently controlled within fixed specifications. By comparison, particle characteristics such as size, shape and liberation were previously determined to have lesser effects on ilmenite and zircon recoveries (Philander and Rozendaal, 2013).

Actual grade-recovery data traverse the model grade-recovery curves relatively well (Fig. 2). Zircon recoveries for PCP East are markedly better than for PCP West across a wide feed grade range. Ilmenite recoveries for the two primary concentrators mirror the zircon recovery trends, although at lower levels because the current mine grade control philosophy targets zircon. PCP East recoveries remain consistent across a broad feed grade range, but by comparison, the extensive spread in zircon recoveries at a fixed feed grade effectively implies that feed grade is not the only driver of PCP West recoveries (Fig. 2). Therefore, the recovery performance of the two primary concentrators was systematically reassessed with reference to the basic fundamentals of spiral separation.

Theoretically, the recovery of heavy mineral particles on a spiral is dependent on their hydraulic behaviour, which is mainly a function of their particle density (Pascoe et al., 2007; Grobler and Bosman, 2011). A density cut-point of 3.4 g/cm^3 is in use at the two primary concentrators (Fig. 3). Mineral particles with greater densities, such as zircon (ρ = 4.7) and ilmenite (ρ = 4.7) would essentially report to concentrate (Fig. 3). Valuable mineral losses to tail would be limited, yielding ilmenite and zircon recoveries typically approaching 98% as achieved by PCP East. The inconsistent zircon losses to PCP West tails, which is an order of magnitude greater by comparison, prompted further investigation.

Previous studies showed that wet spirals have limitations in recovering heavy minerals reporting to the −45 μm and +250 μm fractions and that spiral separation is particularly hampered by polymodal particle size distributions (Burt, 2000; Richards et al., 2000; Mohanty et al., 2002; Pascoe et al., 2007; Walklate and Jeram, 2007). All seven ore types that constitute the Namakwa Sands deposit exhibit unimodal particle size distributions for all the heavy minerals analysed, although there are slight differences in median particle sizes amongst ore types (Table 1; Philander and Rozendaal, 2013). In addition, the total proportion of ilmenite and zircon in the −45 μm and +250 μm fractions constitute less than 5 wt.% in both the tails and concentrates of PCP East and PCP West. In agreement with the previous study, the current findings confirm that the particle size distribution of valuable heavy minerals has no meaningful bearing on their recovery in the current primary concentration process.

Detailed QEMSCAN analysis revealed that up to 35% of the zircons reporting to PCP West tails are poorly liberated. Evidently, the cemented nature of the ore fed to PCP West reduces the effective particle density of the heavy minerals, resulting in increased losses of valuable minerals to tailings (Laplante and Spiller, 2002). Poor liberation impairs the recovery of zircon to a lesser degree compared to ilmenite, because the latter has a more conducive surface template for the cementing agent to interlock. The geometallurgical model imposes a linear penalty on total zircon recovery to account for liberation effects (Fig. 4). Actual data straddle the calculated line prominently, which confirms that recovery penalties owing to poor liberation could be as high as 10% for zircon and even greater for ilmenite.

The balance of the zircon and ilmenite in PCP West tails is properly liberated, but are notably finer compared to zircon and ilmenite reporting to concentrate (Table 1). This is a clear indication of entrainment. Unlike PCP East, PCP West treats ore blends with a variable heavy mineral composition that could contain more than 50% gangue of which garnet and pyroxene constitute the major part (Fig. 1). The abundance of garnet, a silicate mineral that reports essentially to the heavy mineral concentrate, because it has a density (ρ = 4.3) above the density cut-point complicates primary concentration and other processes downstream.

Wet spirals appear particularly effective in rejecting the bulk of lower density gangue heavy minerals such as pyroxene (ρ = 3.4), apatite (ρ = 3.2) and aluminosilicates (ρ = 3.2). This however comes with an inadvertent penalty as it appears that pyroxene facilitates the entrainment of zircon and ilmenite to tails, due to its comparatively larger particle size (Table 1). The data suggest that the recovery of valuable heavy minerals is strongly a function of the pyroxene feed grade, which could impose recovery penalties of up to 20% for ilmenite and zircon (Fig. 5). Ilmenite and zircon feed grades, which are inversely correlated with the pyroxene grade ($r > 0.9$) however, remain good predictors of mineral recoveries.

The present study indicates that the starter geometallurgical model incorrectly highlighted feed grade as the chief recovery driver for the primary concentration process. Instead, the recovery of ilmenite and zircon appears to be related to their degree of liberation and the pyroxene feed grade (Table 2). These two recovery drivers have a significant impact on the recovery performance of PCP West, which treats variable ore blends that exhibit striking variations in the degree of cementation and heavy mineral compo-