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Investigating grinding media differences in microstructure, hardness, abrasion and fracture toughness

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ABSTRACT

It is recognised that grinding media wear can represent up to 50% of the operating costs of a given tumbling mill. Over the years, a number of works have explored the development of different ways and means to both understand grinding media wear as well as model and predict it. The focus of the present work is to examine the differences in microstructure, hardness, abrasion and impact toughness of grinding media from eight different manufacturing sources. Results will be presented for 125 mm diameter media typically used for SAG mills. A discussion will address any issues highlighted by the results than may contribute to predictive wear model development as well as indicate possible directions for future research.

1. Introduction

In mineral processing, the two main operating costs are related to energy consumption and wear. Energy consumption in comminution processes especially as it related to efficiency has been the focus of much research and application. Current efforts aim at developing guidelines and potentially standards for energy based grinding performance metrics (McIvor, 2015) and benchmarks (Ballantyne and Powell, 2014; Nadolski et al., 2015). On the other hand, with respect to wear and particularly grinding media wear, there are still a few different schools of thought (Bond, 1963; Benavente, 2007; Gates et al., 2008; Chenje et al., 2009) all of which converge on the general notion that wear in comminution processes is a function of three main components which are the energy involved in wear, the chemical and mechanical properties of the media as well as the chemical and mechanical properties of the ore or slurry.

The focus of the present paper will be to examine the components related to the mechanical properties of the media. Specifically, the focus will be on 125 mm diameter grinding media and will investigate the differences in microstructure, impact toughness, abrasion and hardness of grinding media from eight different manufacturing sources. Following a presentation of the results, a discussion will explore any possible relationships as well as possible avenues for future research.

2. Sample preparation

Ten different SAG mill 125 mm diameter media samples from eight different manufacturing sites was collected for this investigation. The different media sampled are randomly listed as illustrated in Table 1. With respect to chemical composition, it should be noted that the standards ASTM E1479 (2011) and ASTM E1019 (2011) were followed. The chemical analysis indicated the percent weight results for aluminium, arsenic, carbon, cobalt, chromium, copper, manganese, molybdenum, niobium, nickel, phosphorus, silicon, sulfur, tin, tantalum, titanium, vanadium, zirconium and tungsten. Table 2 provides the percent weight results for chemical components common to all media sampled, while Table 3 indicates that number of media samples that contained the chemical components not common to all samples tested along with their range.

Subsequently, the media samples were then prepared in order to accomplish the different tests for microstructure, impact fracture toughness, abrasion testing and hardness. All samples were cut under wet conditions such that a number of samples were obtained without microstructure modification including three from different radial positions in the ball as illustrated in Fig. 1. In the case of impact toughness, samples were prepared according

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Table 1
Selected grinding media with the corresponding codes (125 mm media).

Coded provider	Coded provider
A5	F5
B5	G5
C5	H5
D5	I5
E5	J5

to the requirements of the Charpy V-notch specifications defined by the ASTM E23 (2002).

The hardness profile was achieved by conducting a series of tests along the center line of the 125 mm media slice from which Charpy test specimens were machined from. Samples for abrasion wear test did not have any special preparation other than meeting the required sample size and shape for use in steel wheel abrasion test as described by the ASTM G65 (2015) and ASTM B611 (2013) standards. Chemical analysis was completed on the fractured halves produced by the Charpy impact test. Surfaces were prepared in the typical fashion required for metallographic analysis. This includes sample mounting in Bakelite, mechanical grinding, abrasion and polishing, etching followed by microscopic analysis (Modin and Modin, 1973; ASM, 1985; Vander Voort, 2007).

3. Results

The results are presented in the following order: microstructure, impact toughness, abrasive wear and hardness.

3.1. Microstructure

The microstructures of all grinding media investigated in this work are shown in Figs. 2–15. All appear to be quenched and tempered martensite, with two exceptions: (i) C5, the high C and high Cr alloys, which reveals a microstructure that is not readily identifiable (Fig. 15); (ii) J5 sample reveals the cast structure of dendrites with what appears to be a matrix of ledeburite i.e. the eutectic formed at the final stage of liquid solidification, which should be a mixture of white cementite and transformed austenite (Figs. 14 and 15). Apart from the white cementite matrix, the darker areas could be tempered martensite. Higher magnifications are required to clarify this.

At optical microscopy magnifications, it is extremely difficult to differentiate between the characteristics of quenched and tempered martensite. Only the martensite laths can really be resolved, but it is still difficult to differentiate between martensite morphologies. Carbides and retained austenite cannot be resolved. These characteristics need to be defined by electron microscopy and X-ray analysis, if necessary. A literature review is required to ascertain whether the degree of tempering, or changes in martensite morphology, affect wear. Certainly the degree of tempering affects toughness, and is well documented. There appears to be inclusions (black particles) in all the grinding media samples.

Table 3
The chemical composition results common to all media samples (%wt).

	No. of samples	Range (wt.%)
% Aluminium	8	0.02
% Arsenic	0	<0.01
% Cobalt	1	0.01
%Molybdenum	6	0.01–0.06
% Niobium	1	0.08
% Tin	3	0.01–0.08
% Tantalum	1	0.08
% Titanium	2	0.01
% Vanadium	1	0.03
% Zirconium	0	<0.01
% Tungsten	0	<0.01

These need to be quantified at some point since these may affect the toughness of the grinding media.

A5 media: The microstructure of A5 media consists of tempered martensite but retained austenite was difficult to find in the microstructure (Fig. 2). Although this is a hypo-eutectoid structure, no pro-eutectoid ferrite was observed at grain boundaries. This may explain the high toughness for this media sample as compared to other samples tested. As the hardness is comparable with other, this could be as a result of good heat treatment or performing forging treatment.

B5 media: The microstructure is composed of lath martensite and small islands (5–10 μm) inclusions of irregular shape. With regards to the ball application and measured hardness, the martensite seems to be slightly tempered in order to increase toughness and decrease retained austenite. The brighter area in Figs. 3 and 4 could be tempered retained austenite.

C5 media: Based on the composition and in terms of the carbon content it is a hyper-eutectoid structure. The microstructure shows chromium carbides in a matrix of untempered martensite, which should lower dramatically the toughness (Fig. 5). There should be relatively high amount of retained austenite (not resolved with Nital etchant).

D5 media: This grinding media sample is composed of tempered martensite, retained austenite and inclusions. The martensite looks to be a mixture of lath and needles due to the carbon content of this structure. The lamellar style of microstructure implies deformed structure due to forging treatment (Fig. 6). The inclusions were also elongated as a proof of forging. Precipitated ferrite was observed in this steel due to its pro-eutectoid characteristics. The relatively good toughness can be attributed to the forging treatment applied on this media sample despite of the presence of detrimental ferrite at primary austenite grain boundaries (Fig. 7).

E5 media: The composition is almost the same as D5 media (Fig. 8), however, this sample showed lower hardness and higher toughness. Ferrite at the grain boundaries was observed in limited areas as compared to D5. The presence of this ferrite may contribute to lowering the impact toughness as compared to the D5 sample.

Table 2
The chemical composition results common to all media samples (wt.%).

	A5	B5	C5	D5	E5	F5	G5	H5	I5	J5
% Carbon	0.551	0.623	2.10	0.577	0.524	0.669	0.764	0.572	0.608	1.97
% Chromium	0.78	0.98	18.61	0.64	0.63	0.33	0.75	0.68	0.96	12.68
% Copper	0.10	0.15	0.05	0.05	0.03	0.25	0.21	0.02	0.15	0.06
% Manganese	0.69	0.72	0.31	0.97	0.96	0.85	0.85	0.99	0.72	1.04
% Nickel	0.05	0.08	0.11	0.03	0.03	0.14	0.14	0.02	0.13	0.14
% Phosphorus	0.012	0.011	0.020	0.016	0.015	0.012	0.016	0.015	0.013	0.036
% Silicon	1.75	0.73	0.38	0.42	0.43	0.19	0.16	0.42	0.77	0.72
% Sulfur	0.003	0.025	0.041	0.010	0.004	0.028	0.027	0.005	0.021	0.031

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