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Wear characterization from field and laboratory tests of pearlitic steels used for SAG mill liners

J.I. Pereira [a,*], P.C. Machado [a,b], J.J. Penagos [a,c], A. Sinatora [a,c]

[a] Surface Phenomena Laboratory, Department of Mechanical Engineering, University of São Paulo, São Paulo, Brazil
[b] Department of Mechanical Engineering, Federal University of Pará, Brazil
[c] ITV – Instituto Tecnológico Vale, Av. Juscelino Kubitschek, 31, Bauxita, 35400-000 Ouro Preto, Brazil

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ABSTRACT

This work characterizes the wear behavior of pearlitic SAG Mill liner material for in-service and laboratory worn samples. The abrasion tests (Dry Sand/Rubber Wheel Abrasion Test – DSRW) were carried out on samples removed from the undeformed region of the same liner – applying different normal loads (from 22 N to 380 N). The electron microscopy techniques (FEG-SEM, FIB-SEM) were used to characterize the microstructural and wear micromechanisms. A cross sections analysis of both samples highlighted the presence of a deformed layer. The hardness of the original microstructure (undeformed pearlite) was 360 HV_{10}, however, this work shows that the typical operational conditions in the mining process increased the hardness in a sub-superficial layer up to 580 HV_{10}. The thickness of the deformed layer was determined to be approximately 300 μm and 3 μm in-service and laboratory worn samples, respectively. The in-service worn samples showed scratches and micro-indentations along the surface. For the laboratory tests, the predominant wear mechanisms were micro-cutting with and without micro-ploughing and micro-indentation. It was shown that the normal load in the laboratory abrasion tests did not significantly affect the deformed layer formation. For the various normal loads applied, the thickness of deformed layer remained practically constant, around 3 μm. On the other hand, regarding wear mechanisms, a change in the normal load affected the indentations/cutting ratio: for lower loads micro-indentations prevailed whereas increased loads (above 130 N) indicated the presence of micro-cutting. Therefore, on the basis of these observations, it was possible to conclude that the DSRW represented a suitable alternative to simulate the abrasion component occurring in liners for SAG Mills once a higher load was applied (200 N to 280 N).

1. Introduction

Abrasion resistant materials are of great importance and interest within the mining industry. High rates of wear to their equipment are observed in many of the processes of mining e.g. the grinding of iron ore [1]. Traditionally pearlitic steels have been used for the manufacturing of liners for Autogenous and Semi-Autogenous (AG/SAG) Mills, where the operational conditions cause wear in particular by abrasion, impact and corrosion.

The sub-superficial microstructure formed after a range of wear mechanisms is usually called either hard or white layer in a number of ferrous materials. The WEL (White Etching Layer) is associated with a high etching resistance to Nital etchant (Nital: 2–10 vol% HNO_3 in ethanol). This layer has been systematically studied because of its relevance for different processes (e.g. mechanical milling and superficial heat-treatment processes). The mechanisms of WEL formation have been widely studied in wheel-rail contact and were associated to a martensitic transformation by cyclic shear deformation [2], transformation from pearlite to a nanostructured Fe–C alloy layer [3]; and the austenization (by flash temperature in the contact zone) followed by martensitic transformation during rapid cooling [4,5].

To understand the abrasive wear mechanisms it is necessary to analyze all elements of the tribosystem but also to look at the dynamic processes of any transformation in the subsurface resulting from the plastic material deformation during the abrasion process. Bakshi et al. [6] presented in their analysis of the abrasive behavior of pearlite, bainite and martensite microstructures the WEL formation in DSRW for all materials. These findings stand in contradiction to the work of Xu et al. [7] who were not able to produce the transformed layer. The authors associated their result to the ability of DSRW to remove such layer. Hence the mechanism of WEL formation remains a highly controversial issue.

The current study presents the characterization of the sub-surface

* Corresponding author.
E-mail address: jipagudelo@usp.br (J.I. Pereira).

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Table 1
Dry sand/rubber wheel abrasion test parameters.

Number of samples	3 for each normal load
Hardness of rubber	Durometer A-60
Abrasive	Silica sand
Abrasive size (mean)	0.20 ± 0.07 mm
Abrasive sphericity (SPHT=$4\pi A/P2$)	0.790
Abrasive aspect ratio (b/l)	0.701
Loads	22, 35, 50, 75, 105, 130, 1501 180, 200, 250, 320 and 380 N
Sand flow rate	200 g min^{-1}
Total sliding distance	1436 m
Test time	10 min

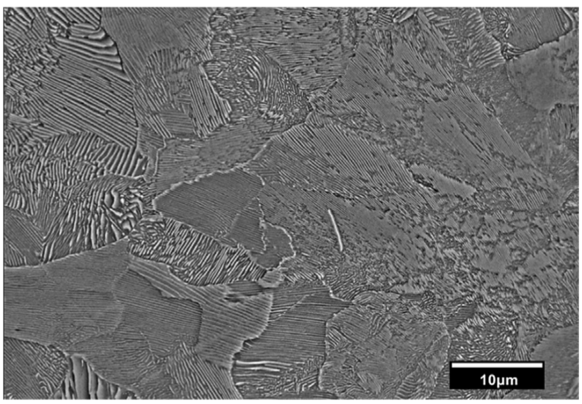

Fig. 1. Secondary electron SEM image of the undeformed pearlitic microstructure.

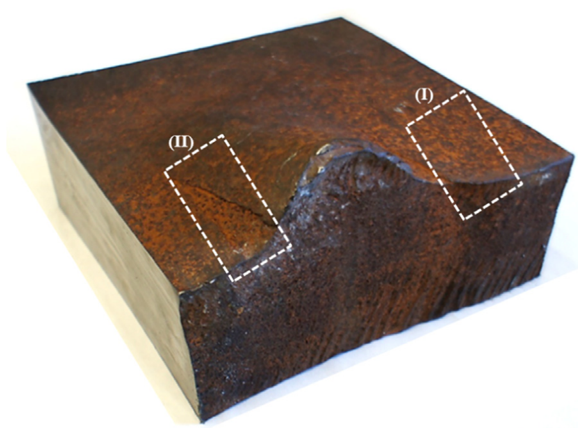

Fig. 2. Macro scale image of lifter exhibiting abrasive wear surface (marked as “I”) with detachment of material “II”.

deformed layer (of a pearlitic steel) resulting from two abrasive wear processes: in-service (SAG Mill Liner) and laboratory (Dry Sand/ Rubber Wheel Abrasion Test – DSRW) [8]. The relationship between the normal load and the wear mechanism as well as the microstructure transformation in DSRW was analyzed.

2. Experimental procedure

2.1. Materials and test conditions

A commercial pearlitic steel with chemical composition: 0.75C, 2.00Cr, 0.76Mn, 0.76Si (wt%), was studied. The surface of an industrial mill liner worn in-service was analyzed (SAG mill with a capacity of 1,8 t/h and half-life in service in a cooper mine with a production up to 400,000 t per year). Samples for laboratory abrasion tests were removed using wire electro-discharge machining. Metallographically polished (MD-System – Struers) samples were etched with 5% nital reagent and examined using scanning electron microscopy (SEM) for microstructural characterization and for measurements of the pearlite interlamellar spacing (ILS). Pearlite “ILS” measurements were made using the intercept method according to Eq. (1).

$$ILS=\frac{L}{n} \tag{1}$$

where, the number n of interceptions with cementite lamellae yields in a size line L.

It was determined the Vickers hardness profile for in-service worn samples with a load of 0.1 Kgf, accompanied by the analysis of sub-superficial layer using nanoindentation (TI 950 TriboIndenter® – Hysitron) with Berkovich tip and 7 mN of normal load. Abrasive wear tests were carried out according to the procedure described in ASTM G65 standard, Dry Sand/Rubber Wheel Abrasion Test – DSRW (Table 1).

2.2. Sample characterization

Test pieces were cleaned in an ultrasonic bath (99% Ethylic alcohol), dried using compressed air and weighed before and after wear tests. Scanning Electron Microscope (SEM – JEOL JSM-6010LA) was used to identify the wear surface micromechanisms in both conditions. Cross-sections of wear samples were analyzed using FEI – Inspect 50 FEG with EDAX camera (Field Emission Gun) and FEI – Quanta 3D FEG/FIB (Focused Ion Beam). The milling process was operated at 30 kV and 30 nA to open a cavity of 30 μmx20 μm. The finishing proceeded in two steps: i. 30 kV and 5 nA, and ii. 30 kV and 3 nA. The image was captured with 30 kV and 30 pA.

3. Results and discussion

3.1. Microstructure

Fig. 1 represents a typical SEM micrograph of the sample in an undeformed region, showing a fully pearlitic microstructure i.e. the lamellar arrangement of the ferrite (α-Fe) and cementite (Fe_3C) phases. The average value of ILS was measured as to be 0.18 ± 0.02 μm.

3.2. Characterization of in service wear

The milling process occurs from the landing of larger rocks on smaller ores, with an energy level high enough to cause fractures. Fig. 2 shows the in-service worn surface of a SAG lifter. The regions marked as “I” and “II” correspond to the analysed areas of abrasive wear (I) and to the particular event of a material fracture (II).

A typical abrasion surface is shown in Fig. 3. It is possible to observe: a) grooves and b) indentations caused by the mill charge impact. According to Napier-Munn et al. [9], any lifter damages caused by the impact of balls or rocks are essentially the same, however, the impact forces of rocks are deemed to be lower and therefore less detrimental.

The cross-section analysis shows the deformation profile of the microstructure characterized by the changes in the pearlite morphology (Fig. 4a). The thickness of this sub-superficial layer is 300 µm and characterized by a smaller than 0.18 µm interlamellar spacing measured in the undeformed pearlite colonies (Fig. 4b). A transitional region (Fig. 4c) located deeper in the sample and characterized by the combination of deformed zones and typical