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(Research Article)

Tribology in mining: Highlights in iron ore abrasiveness

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Abstract

This article aims to present results on research, recently developed, and related to wear of equipment to meet the challenges of the mining industry. Emphasis is done to iron ore mining in Brazil due to the relevance of the sector for its economy and the relevance of tribology for assets and productivity. Results and considerations cover wear of equipment (conveyor belts, ore pipelines) and development of high chromium cast iron (HCCI) microstructures to face the wear.

Under wet erosive wear caused by pumped slurries with different compositions of solid particles the wear of samples tested follows a trend in which those with higher silica contents provided greater mass losses of high chromium cast iron (HCCI) samples.

On the other hand, when surface protection against wear of components is the objective, the presence of niobium in a hardfacing coating contributed to increase resistance to abrasion, due to the presence of niobium carbides (NbC).

It was also demonstrated that there is a positive correlation between the degree of metamorphism of iron ore throughout its genesis and evolution in relation to the abrasiveness.

Keywords: Iron ore; Conveyor Belts; Slurry pumps; Wear tests; Abrasion; Erosion

1. Introduction

Tribology is defined as the science and technology of the interaction between surfaces in relative motion and wear is understood as the progressive loss of substance from the surface of a body as a result of the relative motion between the parts involved. This article aims to present an overview on the main research recently developed to meet the challenges of the mining industry.

As pointed by Hutchings & Shipway [1] the surfaces of solids represent a complex form of organization of matter because they contain a variety of defects, distortions and irregularities in various orders of magnitude, from macroscopic to atomic order, which exert great influences on friction, wear and lubrication. The characteristics and imperfections of a real surface are close related to the chemical reactions that can occur from contact with fluids, lubricants or other surfaces. Roughness controls the contact mechanisms between solids resulting in the wear process. In addition, the surface characteristics of a solid affect its thermal, electrical, optical performance and the appearance of the finished product (Hutchings & Shipway) [1].

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Stachowiak and Batchelor [2] emphasizes the role of surfaces in two different scales, both affecting the wear mechanisms and friction: atomic-scale defects in a smooth surface provide a catalytic effect for lubricant interactions with the wear surface while roughness restricts contact between solid surfaces to a fraction much smaller than the actual surface area.

According to Blau [3], as there are several factors that influence the tribological behavior between bodies in contact with respect to friction; attention should be paid to the right choice in order to select variables and their levels for experimentation. It is stablished that friction, in a tribological system, can be influenced by: contact geometry (roughness and ripples), the type of relative motion, applied forces, contaminating particles at the contact interface, physicochemical properties of the lubricants, temperature, vibrations, damping, among others.

A mine industry incorporates equipment and structures covering activities as;

- Ore crushing and milling,
- Ore transportation of solid particles by conveyor belts and pipelines for slurry with high ore concentration. Mining waste (tailings) are also transported by similar installations,
- Heavy pumping systems are necessary to transport ore slurry over long distances, sometimes several hundred kilometers. In this case wear of pumps parts are of great importance as well as the wear of pipes.

Considering the importance of the mineral sector in the Brazilian economy it is conveniently to highlight or to comment some data. World Bank data for the year 2019, comparing countries with populations above 140 million inhabitants, country area greater than 3 million km^2 and GDP greater than US$ 1.2 trillion, indicate that four BRICS countries (Brazil, Russia, India and China) and the United States combine the best conditions for the mineral economy scenario: population and GDP allied to the surface of the territory. (Source: World Bank 2019, prepared by IBRAM - Publications - IBRAM . https://ibram.org.br/) [4].

The mining sector's share in Brazil's GDP is approximately 4%, as data from the SGM (Secretary of Geology, Mining and Mineral Transformation of the Ministry of Mines and Energy) and the IBGE (Brazilian Institute for Geography and Statistics). Considering only the extractive mineral industry, excluding oil and gas, the share is approximately 2.3% (data referring to 2018 - Source: IBRAM, SGM, IBGE) [4].

Currently, the development of engineering solutions in the most varied fields of activity is, necessarily, scrutinized by the correlations – existing and inseparable – that connect the themes Energy, Materials and the Environment. In view of this, we consider it is important to highlight the influence that Tribology has on global energy consumption, CO_2 emissions and associated costs. Economic losses due to friction and wear as well as the potential gains that advances in Tribology can bring is well perceived in the article published in 2017 by Holmberg, K. & Erdemir, A. [5], among others.

According to Holmberg K. and Erdemir A. [5], currently, the activities that consume the most energy are represented by the transport, manufacturing, energy generation and residential sectors. In the 2017 publication, Holmberg, K. and Erdemir, A. [5] state that ~23% of global energy consumption is due to tribological contacts; ~20% of the world's total energy consumption is spent on overcoming friction and ~3% on remanufacturing worn parts and spare equipment. Also, according to the same authors, the new technologies made available by Surface Engineering, combined with new developments in "lubrication", can provide gains of up to 40% in energy in the long term (15 years) or up to 18% in the short term (8 years).

In mining – a sector dedicated to the extraction, processing and transport of rocky materials – 40% of energy consumption is aimed at overcoming friction. In mining, energy loss due to wear is 43% of that due to friction (Holmberg K., Kivikyto-Reponen P., Harkisaari P., Valton K. and Erdemir A.) [5]. Wear-related energy losses include the energy required to produce new replacement parts and maintenance downtime. The set of studies mentioned above indicate that, in mining, the cost of worn parts is on the same order as the cost of maintenance.

It is estimated that a third of the energy resources used in the world are spent to overcome losses caused by friction. Thus, tribology is a field of Science that also seeks for solutions to operational problems of great economic and energetic importance, acting on reliability, maintenance and equipment wear (Stachowiak and Batchelor) [2].

Focusing on mining, slurry pumps represent a heavy-duty, robust version of a centrifugal pump, intended to handle tough jobs by pumping mud, clay, sludge, sand, ores and tailings in the solids size range up to 2 mm. This equipment is widely used for the hydraulic transport of solids over short and medium distances through pipelines (Tarodiya) [6].

As a consequence, the conventional design of a centrifugal pump is continuously modified to meet the requirements of slurry pumping. Among the main components of slurry pumps, the impellers are the ones that generally have the highest rates of wear during operation. Wear occurs mainly by erosion due to the impact of solid particles, but cavitation and corrosion processes can also occur as a result of localized changes in rotor surfaces and geometry as wear progresses. The direct costs related to the wear of these equipment components are significant for the mining industry and reduce these costs requires a better understanding of pump wear patterns and wear rates produced by different slurries on different impeller geometries (Walker [7]).

In recent decades there has been a robust development in the search for new tribological solutions to reduce friction and wear whose implementation has been very fast in the automotive sector – passenger vehicles, public transport and trucks (Holmberg K., Kivikyto-Reponen P., Harkisaari P., Valton K. and Erdemir A.) [5] (Holmberg K., Andersson P. and Erdemir A.) [8] (Holmberg K., Andersson P., Nylund PO, Makela K. and Erdemir A.) [9].

Thus, at present, there are numerous innovative technologies that improve the tribological properties of machine components. The mining industry is a complex arrangement of heavy machines facing heavy tribological conditions: huge mechanical loads, extreme friction conditions and aggressive environment where dust, moisture and chemicals are always present.

Contributions of Tribology to environmental protection means: less material consumption as a consequence of better performance of machines/components thanks to well adapted microstructures of materials: better combination of ductile matrix and disperses hard particles in alloys, controlled grain size and volume fraction of reinforcing particles, carbides, for instance, bringing more resistant materials against wear and less lubricant consumption; all this contributing to energy saving.

In order to develop innovations Materials Science Engineering (MSE) provides a large spectrum of test in which operational conditions may be reproduced to approach field conditions to controlled laboratory parameters. In all of them the main mechanisms are reproduced so that wear ratio and microstructural events can be observed in different dimensions ranging from nano to millimeter scale [10].

2. Methodology

The studies were conducted using several standardized tribological tests that will be detailed throughout the text. Results arising from research at Ouro Preto School of Mines and ITV – Vale Technological Institute. These results cover a wide range of studies in search for understand the role played by characteristics and properties of abrasive particles on the wear behavior of materials, elastomer and metallic alloys, for instance. Two main wear mechanisms were in focus: abrasion and erosion.

3. Results and Discussion

3.1. Abrasion of an Elastomer

When the transport of ore is done by conveyor belts the most useful test is based on the dynamic contact that a wheel (covered by an elastomer) acting as the counter body can provide when rotate against a sample (body) accordingly to a specific design. A lot of research has been done under the ASTM G65 – 04 - 2010 Standard recommendations (Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus) [11]. Sometimes the recommendations are adapted to the research needs [10]. One of the most common modifications relies to changes in the suggested tribosystem: instead of Polymer – Abrasive – Metal arrangement, the metal sample is replaced by polymer when the material of interest belongs to this family. This is the case of the work done by Nins, B. [12]. This work compares the abrasiveness of four types of Run of Mine (ROM) iron ores: Jaspelite (JP), Friable Hematite (FH), Hydrated Iron Ore (HO) and Compact Hematite (CH) (Figure 1). The four types of iron ores were dried, crushed and classified into size classes of 0,30-0,15 mm and 0,60-0,30 mm, equivalent to IPT (Technological Research Institute of São Paulo, Brazil) standard sand NBR-7214 Nº 100 and Nº 50, respectively. The author, considering the literature review, done tests following the application of the ASTM G65 recommendations for rubbers. The procedure selected was also used by Molnar et.al. [13] to study rubbers.

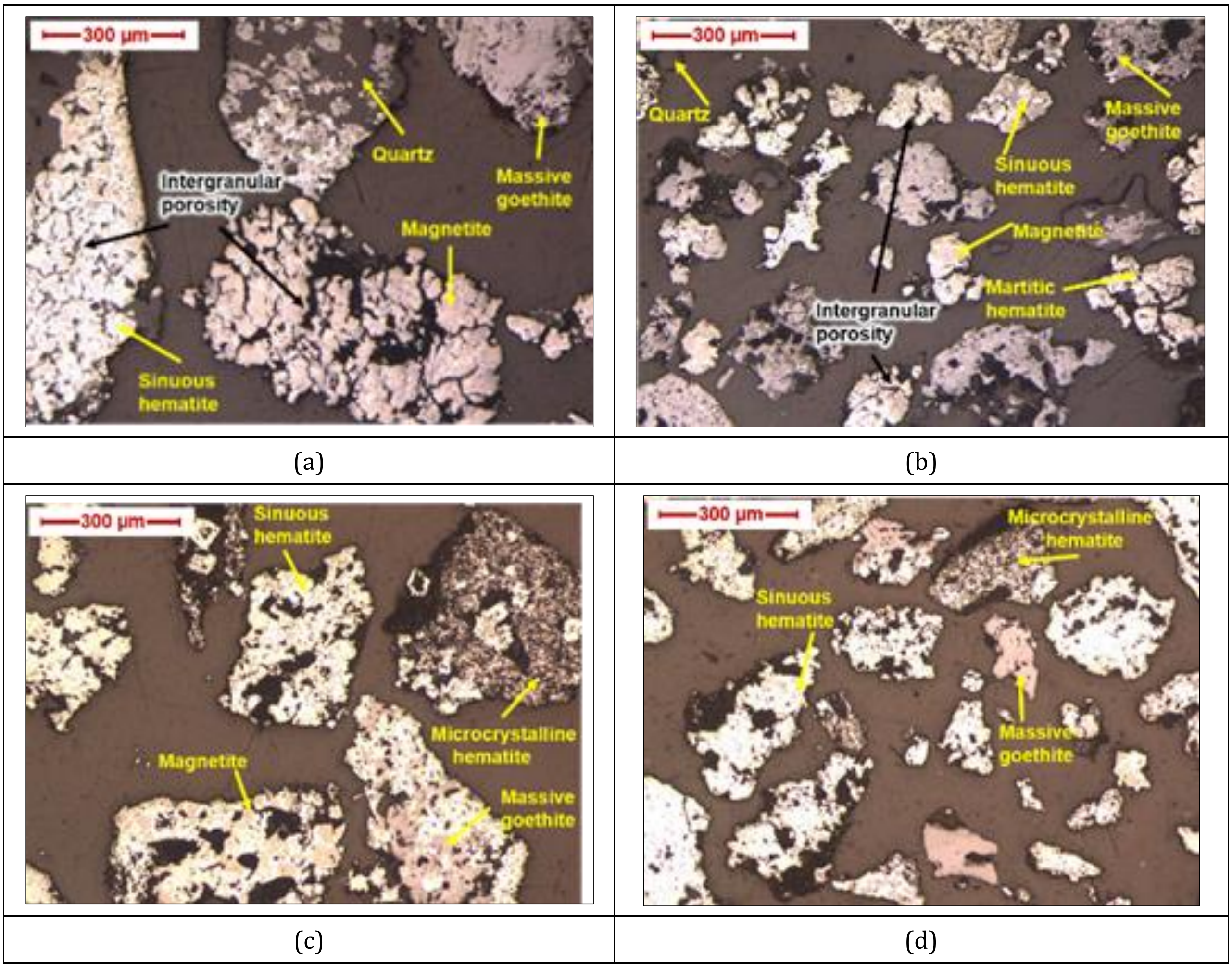
The main objective of Nins, B.`s [12] work was to compare the worn surfaces features of samples from unused (as provided by manufacturer) conveyor belt and field conveyor after long usage. The experiments were conducted in order to validate laboratory protocol to simulate wear of conveyor belts in laboratory conditions. The main conclusions of Nins, B. [12] can be summarized:

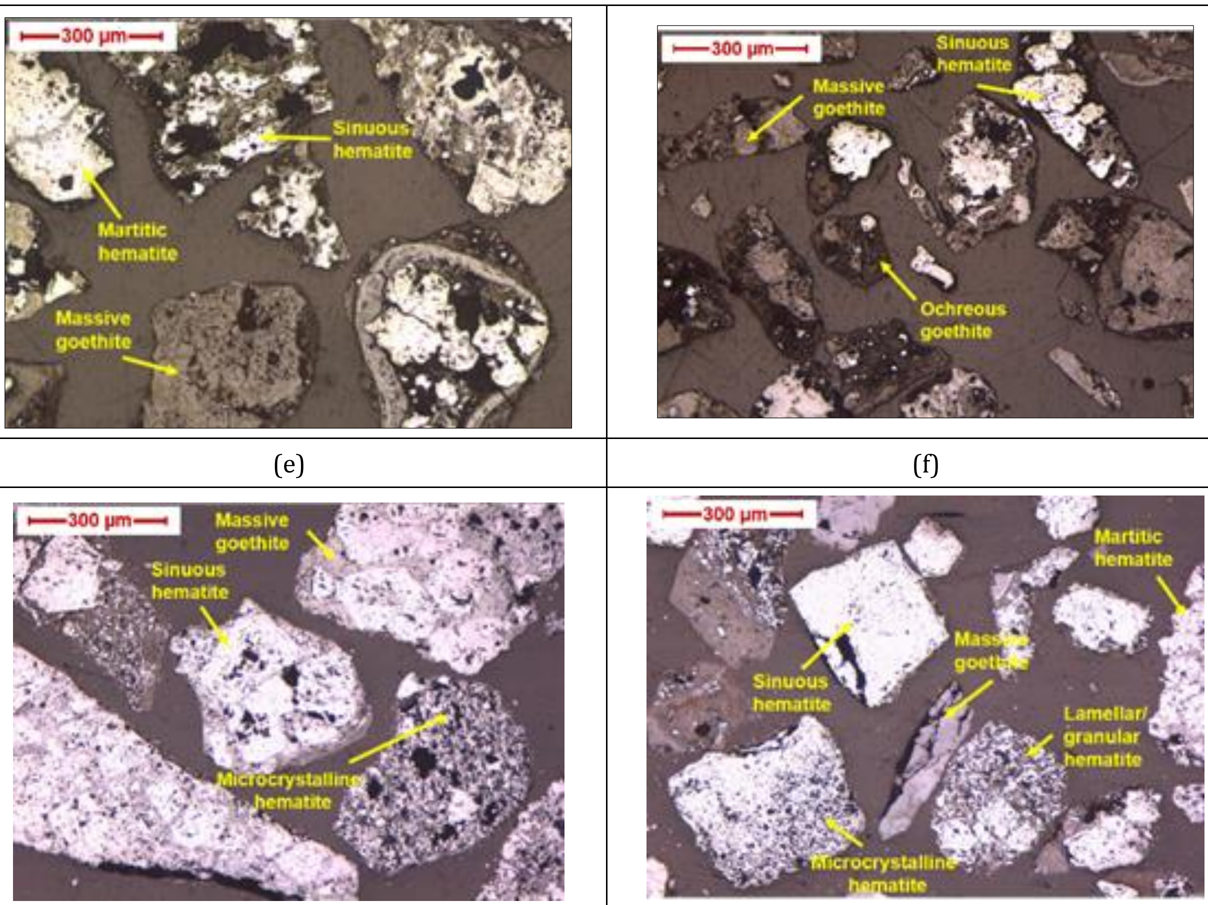
- The mineralogical composition is the most relevant fator in the whole abrasiveness;
- The Friable Hematite samples showed higher abrasiveness than the others, due to the large presence of sinuous and microcrystalline hematite minerals;
- The predominant wear mechanism in the field and laboratory sample revealed the formation of Schallamach waves as a consequence of the wear process;

The distance between the waves is possibly related to the size of the abrasive particle, being a directly proportional relationship.

The chemical analysis of the samples highlights the differences in composition of iron oxides and silica. As expected, Friable and Compact Hematites have the highest iron content and Jaspelite the highest silica content.

Petrographic analysis presented in Figure1 to show the diversity of microstructures under which iron ores may be organized has also been obtained. There is a clear distinction of the mineralogical assembly between the four types of iron ore.





(e) (f)

(g) (h)

Figure 1 Photomicrographs [12] under reflected light of: a) Jaspelite 0.60-0.30mm, b) Jaspelite 0.30-0.15mm, c) Friable Hematite 0.60-0.30mm, d) Friable Hematite 0.30-0.15mm, e) Hydrated Ore 0.60-0.30mm, f) Hydrated Ore 0.30-0.15mm, g) Compact hematite 0.60-0.30mm, h) Compact hematite 0.30-0.15mm

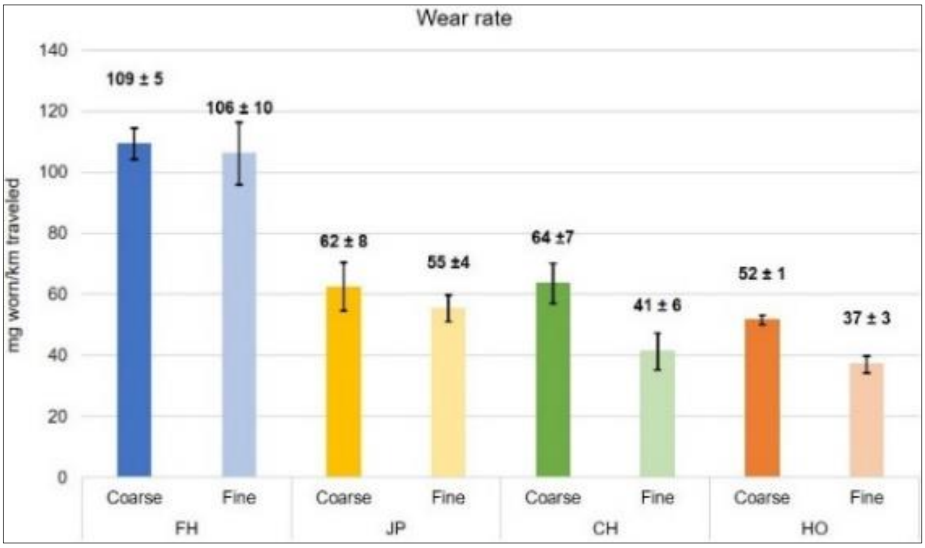


Figure 2 Rubber wear caused by iron ores in the ASTM G65 laboratory test. Loss of mass X ore type (FH; JP; CH; HO).[12]

Wear tests results, as shown in Figure 2, reflects the relationship between the microstructures and the abrasiveness of iron ore particles.

To interpret this behavior the author considered the others parameters influencing the abrasiveness: the morphology of the particles and the chemical composition especially the silica content as well as the morphology of grains. The size distribution of each sample also influences the wear response of rubber, the lowest the grain size the loss of mass decreases.

3.1.1. Wear Mechanisms of Belt

The field-worn belt was probably subjected to high severity conditions, which caused different serious damage to the upper rubber layer. The predominant feature found in the field-worn rubber sample is also the presence of Schallamach waves. These waves are a succession of leaning ridges formed perpendicular to the abrasive's sliding direction [12]. Parallel to the waves, cracks were also observed between the ridges.

In the field the belt is submitted to a combination of loads: static by the ore being carried and dynamic by the movement of ore particles due to the light and continuous vibrations transmitted to the conveyor from the other components of the conveyor belt. The abrasive wear of rubbers generates microcracks on the surface as pointed by Y. Fukahori, H. Yamazaki [14]. The return of the belt on the drum imposes compressive and tensile stresses (the upper side of the belt is under tensile stress while the other side is under compressive stress). This repeated condition is responsible for fatigue microcracks generation and propagation [15].

The abrasion pattern of Schallamach waves was also observed in the laboratory-worn rubber. Also, in the laboratory, the distance between waves appears to be related to the size of the abrasive particle. This fact would also explain the greater distance between waves in field-worn rubber compare to that issued from laboratory tests. As a contribution one may consider that these laboratory tests were able to reproduce, to some extent, the field conditions.

3.2. Erosion of High-Chromium Cast Iron

Wet erosive wear is defined as the progressive loss of material from a solid surface caused by the mechanical action of the impact of a liquid containing solid particles forming an abrasive slurry. A slurry is generally defined as a heterogeneous mixture of a liquid and one or more types of solid particles being classified as a highly viscous liquid. It can also be defined as a mixture of liquid and solid transported by pumping. In mining, the transport of ores in the form of slurry presents itself as an economically viable and environmentally friendly alternative (Budinski [16]). Al-Bukhaiti et al. [17] investigated the influence of slurry concentration on the erosive behavior of high chromium white cast iron. Ductile materials tend to present higher rates of erosive wear at small angles (<30º), being more susceptible to micro-cutting and grooving mechanisms. As the angle increases, the volume loss decreases approaching a minimum at 90º. The impact angle is of great importance in erosive wear (Frosell T, Fripp M, Gutmark, E.) [18]. As a general rule ductile materials have the ability to absorb the impact energy exerted by erosive particles, preventing material loss. On the other hand, fragile materials tend not to have the ability to absorb the impacts generated by erosive particles, presenting higher rates of erosive wear at angles close to 90º with the mechanisms of microcracks and fatigue. At smaller angles, the high hardness, characteristic of brittle materials, is very effective to withstand the micro-cutting action caused by the particles (Chung [19]).

From detailed studies (Stachowiak and Batchelor [2]) confirm that impact angle, impact velocity and flow rate are also factors that modify erosive wear mechanisms. The impact angle refers to the angle between the surface and the particle's trajectory just before impact. Materials with ductile behavior generally show maximum erosive wear at angles close to 20º-30º, while brittle materials show greater wear at normal angles (Stachowiak and Batchelor [2]).

Generally, with an increase in the ratio between the hardness of the erosive particle and the hardness of the eroded material, the total erosive wear increases to a certain value after which a further increase in hardness has little effect. Erosive wear resistance has a strong relationship with the hardness and toughness of the material; if two materials have similar hardness values, the material with higher toughness may offer better resistance to erosive wear under the same conditions. (Divakar [20]).

Experimentally speaking, equipment for wet jet erosion tests allows simplified control of test parameters such as particle velocity, flow, angle and impact distance. Furthermore, due to high erosion rates, the test time usually does not need to be long (Frosell et al. [18]).

Roco [21] analyzed the erosive wear of a slurry pump by applying a thin layer of polyamide and epoxy resin to the internal components subject to wear. It was observed that the total wear of the internal components is a result of the cumulative effects of directional impacts, random impacts and the sliding of solid particles.

Erosion and abrasion or a combination of both mechanisms are well reproduced in wet jet slurry erosion test ASTM G40-17 [22] and also in Miller/SAR essays [23]. In this last case abrasion is prevalent and sometimes improvements in the standard equipment allows the detection of synergic interactions between abrasion and corrosion, if the chemical characteristics of the slurry fill the basics conditions to interact chemically with samples. Erosion studies done by Chaves R.P. et al. [24] showed the relevance of silica content on erosion caused by iron ore slurry in High Chromium Cast Iron (HCCI) samples. This alloy is widely used in slurry pumps parts, mainly in pump rotors because of its properties, i.e., high hardness, due to the nature and arrangement of microconstituents: elongated primary and hexagonal carbides; eutectic carbides have been revealed in optical micrographs of the HCCI shown in Figure 3.

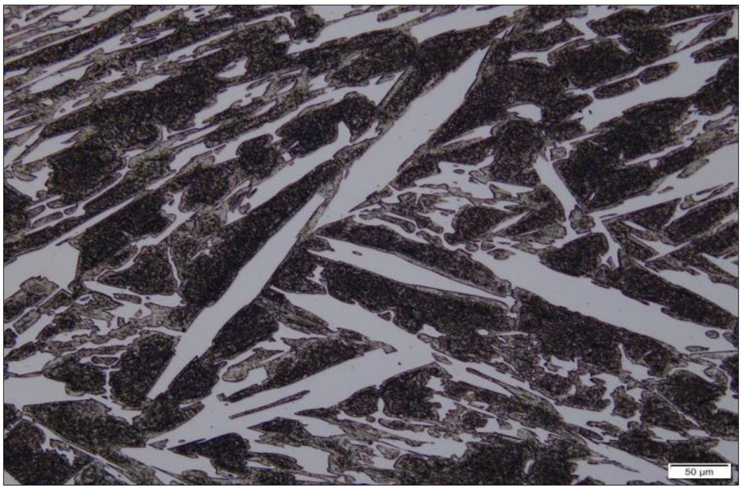


Figure 3 Optical micrography of HCCI [24]. Elongated primary carbides and eutectic carbides. Vilela Reagent (200x)

As shown by Chaves R.P. et al. [24] there was an increase in the rate of wear with increasing angle until reaching the peak of greatest wear at 45º, followed by a continuous decrease until the angle of least wear (90º). The wear surface of the eroded samples presented different topographies starting from a circular cap at a 90º angle followed by more elongated craters, the smaller the slurry jet impact angle (Figure 4(a, b)).

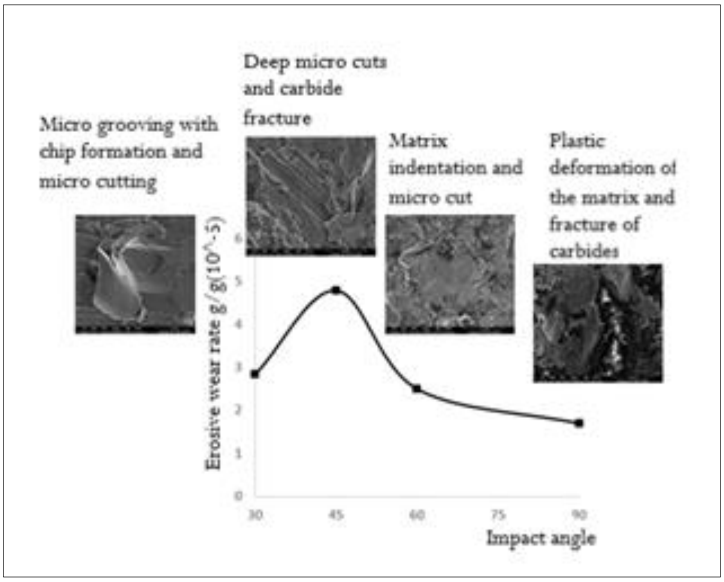
Figure 4a illustrates the differences of the wear mechanisms in function of the impact angle.

All conclusions drawn from this study are in accordance with results presented by other authors studying other metallic materials [25-26-27].

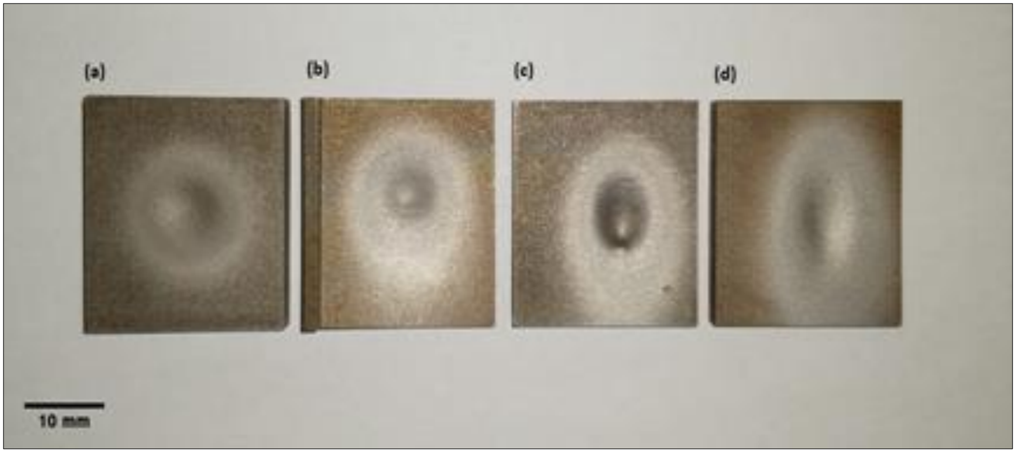
Table 1 presents the proportion of the mixtures of the constituents of the different slurries used in the erosive wear test of samples of high chromium cast iron (HCCI). (Percentage by mass of silica sand and hydrated iron ore mixtures). Figure 5 illustrates the total mass loss of samples eroded with these slurries for 8 minutes.

Table 1 Proportion of abrasive mixtures (% by mass)

% by mass	S1	S2	S3	S4	S5
Silica	100	70	50	30	0
Hydrated Iron Ore	0	30	50	70	100



(a)



(b)

(a) 90º; (b) 60º; (c) 45º and (d) 30º. (b)

Figure 4(a, b) Variation of wear mechanisms and erosion rate with impact angle for the HCCI (a); Erosive wet wear test. Macroscopic wear surface (craters) of the tested samples [24]

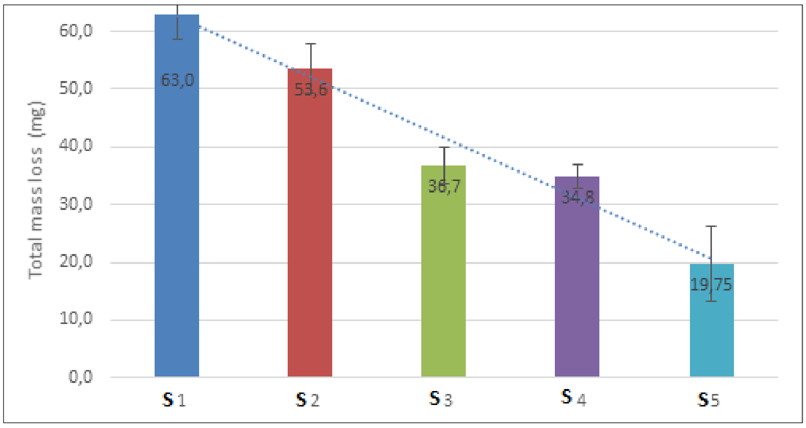


Figure 5 Wet erosive wear test [24]. Total mass loss of samples eroded with Slurries S1, S2, S3, S4 and S5 for 8 minutes

3.3. Erosion and Abrasion

Testing the same HCCI under abrasive wear, using the Miller test [23], a similar trend of higher abrasiveness was observed: slurries that contained higher silica were more aggressive than the hydrated ore one.

The Miller abrasiveness index presented the number 92.7 for slurry S1, which was 1.65 times higher than that for slurry S5 (56.1). The other slurries showed intermediate abrasiveness.

If one compares the behavior of HCCI tested under erosive wet jet with Miller graphics the same trend is observed. This kind of behavior is that proposed by Archard`s Equation. This model was proposed for pure abrasion condition but, in many cases, it match with results issued from tests in which pure abrasion conditions are not predominant (Figure 6).

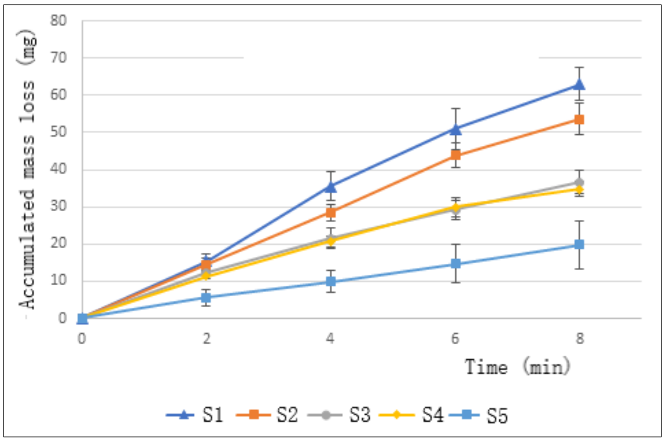


Figure 6 Mass loss as a function of test time. Wet erosive wear at normal angle. [24]

Also, when ore slurry transportation wear studies are the objective, Kalber et al. [28] have explored the possibilities offered by Miller/SAR test (ASTM G75 - 2001) [23] to provide data for the understand of wear in API steel pipelines dedicated to iron ore slurry transportation performed by brazilian mining industries. Accordingly to results the evidence of the influence of the geological history of the mine in ore abrasiveness is experimentally demonstrated.

As an overall conclusion Kalber et al. [28] points that not just one property has an effect on the abrasiveness of the slurry. All properties act together.

3.3.1. Geology and Abrasiveness

Searching for evidences in relationship between geology and abrasiveness of iron ore Barbosa et al. [29] realized experimental studies in order to correlate geological history of iron ores and its effectiveness in damage API steel samples by means of Miller/SAR test.

Samples of iron ore slurries and iron ore tailings slurries from Quadrilátero Ferrífero (QF) Minas Gerais (Southeast region of Brazil) and Carajás mines (CJ) (Pará State in Amazon region) were tested according to the Miller method for slurry abrasive wear measurements. Samples from these regions were named QF and CJ, respectively. The aim of the study was related to the characterization of the abrasiveness of these slurries against API X70 steel samples. API X70 steel pipes are used to transport ore slurries over long distances from mines to pelletization plants. The main objective of the work has been to investigate the existence of correlation between the geological history of the deposits (from which these slurries have been prepared to transport) and their absolute abrasiveness (Miller and SAR index). The geological processes involving crust deformation by strong stresses coupled with high temperatures and further geochemical processes (metamorphism) to generate ore deposits are very different and complex depending on the region of the planet [30]. Results point to a correlation from which one concludes that iron ores from Carajás mines (CJ) are less abrasive in comparison with Minas Gerais State iron ores (QF). These differences in abrasiveness could be explained taking in account features as morphology, chemical composition, mineralogical organization of samples components (texture), hardness and microstructure.

In addition, Barbosa`s et al. [29] experiments had also it focus on relevant aspects concerning the wear of pipelines transporting slurry, especially in mining industry. The goal is to contribute to the understanding of which properties of slurries influence the abrasive behavior in which way. Results point to positive correlation between abrasiveness and mean grain size, concentration of slurry (dilution) and silica content as shown in Figure 7.

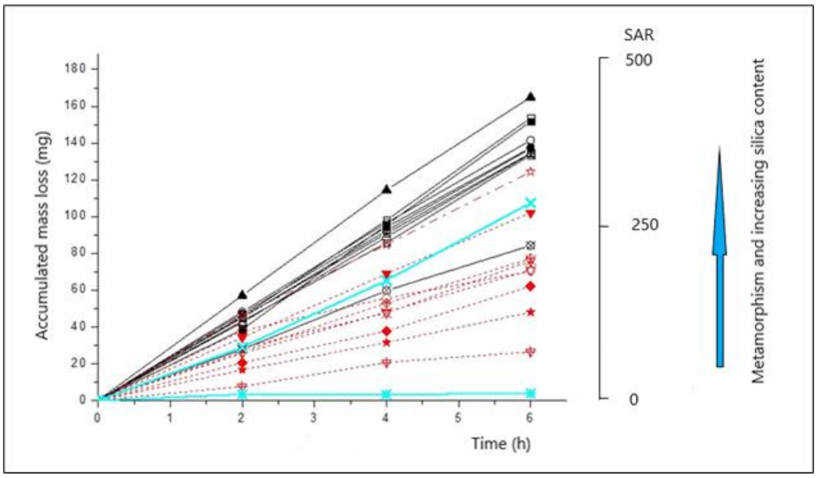


Figure 7 Comparison between the abrasiveness of the tested iron ore. Red discontinuous lines refer to CJ`s samples and black ones to QF`s. Light blue lines refer to equipment calibration test. [29]

Results demonstrated that two main conclusions can be drawn:

- There is a positive correlation between the degree of metamorphism of iron ore throughout its genesis and evolution in relation to the abrasive indices MN and SAR, influencing properties such as hardness and morphology, thus resulting in greater abrasiveness of ores that came from regions with more intense metamorphic events.
- The amount of silica present in iron ores also influences the MN and SAR abrasiveness indices, having a positive correlation, that is, the greater the amount of silica, the greater the abrasiveness of this ore tends to be.

Generalizing the observations, abrasion appears as the main mechanism acting during slurry transportation. This way slurry samples, covering a wide variety of iron ore mixtures, were tested accordingly to ASTM G75 [23] by da Costa, A. R. et al. [31]. Compiling over 100 results it has been shown that the abrasion phenomenon is prevalent: samples extracted from mud, tailings, feed for flotation, concentrated from flotation and combinations of magnetite with ROM (Run Of Mine) have been tested in order to measure the dimensionless wear coefficient (k) [32]. These coefficients, arising from Archard`s Equation and SAR indexes were organized in Figure 8 by Type of slurry. This Figure shows that Miller/SAR indexes fit the range that characterizes “abrasive wear in metals in a two-body configuration of the tribosystem”, as proposed by Hutchings et al. [1].

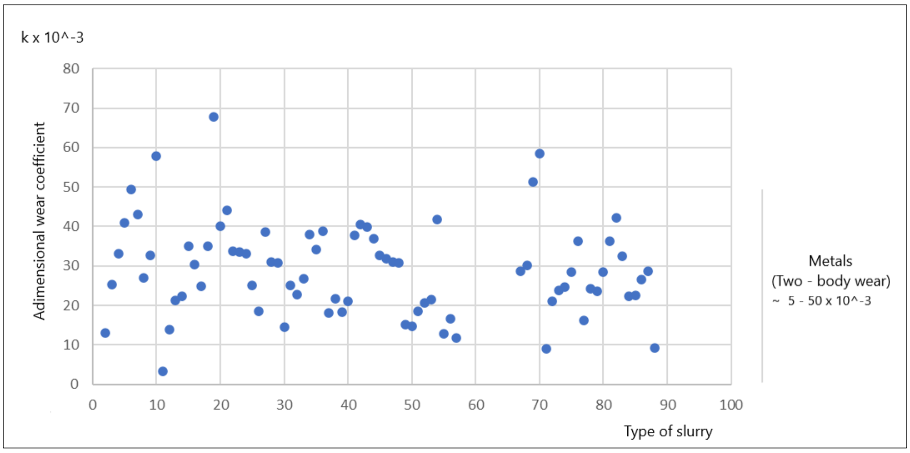


Figure 8 Dimensionless wear coefficient (k) and Type of slurry [31]

3.4. Microstructure and Wear

The excellent wear and corrosion resistance of high chromium cast irons is strongly related to its microstructure, which generally has a hard second phase composed of high hardness primary or eutectic M_7C_3 carbides (where M represents Fe, Cr or any other forming element alloy constituent carbide) present in a martensitic or austenitic matrix or a product of the transformation of these microconstituents.

With increasing Cr content, the structure and property of chromium carbides varies between types M_3C, M_7C_3 or $M_{23}C_6$. M_7C_3 carbides can solidify to form isolated carbides like primary carbides, or they can also form a continuous network within interdendritic spaces like eutectic carbides. In addition, M_7C_3 has the highest hardness among chromium carbides ranging from 1.200 – 1.800HV, being effective in increasing wear resistance. Coronado [33]; Bedolla-Jacuinde [34]; Yaer et al. [35], Liu et al [36], compared the erosive wear of a high chromium 26Cr-6Mo cast iron for the manufacture of slurry pump impellers with an AISI 316l stainless steel, an FC20 cast iron and alumina. For this, a wet erosion test with a rotating arm was used, varying the size of the silica abrasives. The wear resistances of all materials varied with particle size. Larger particles (d=600µ) caused greater wear on all materials. Alumina had the lowest wear rate followed by high chromium cast iron. For high chromium cast irons, the content and distribution of carbides are important factors that influence the fracture toughness and hardness of these materials and thus determine the erosive wear resistance of these materials.

Heino et al. [37], state that the abrasive wear resistance of white high chromium cast irons can be controlled by adjusting the size, distribution and volumetric fraction of the carbides present and the wear resistance is directly related to the hardness of the material. The study evaluated samples of white high chromium cast iron of approximately 27 to 28%Cr submitted to different heat treatments under high abrasive conditions. In conclusion, they showed that the size, shape and orientation of the carbides present affected the wear resistance under high abrasive conditions. According to Penagos et al. [38], when high chromium cast iron is used in the manufacture of parts with irregular geometries, such as in pump rotors, the component may present different levels of microstructure refinement, between thin and thick regions due to variations in the cooling rates and thus concluded that the wear-related properties of this material are not exclusively dependent on hardness, but on the refinement of the microstructure when subjected to two and three-body abrasion.

De Mello et al. [39] analyzed the effect of the microstructure of multicomponent white cast irons on micro abrasive wear using fine abrasive particles in the free sphere micro abrasion test.

Albertin and Sinatora [40] studied the effect of the volumetric fraction of carbides present in high chromium cast iron on wear resistance. Samples with martensitic, pearlitic and austenitic matrix with carbide concentrations varying between 13 and 40% by mass were evaluated. The tests were carried out in a ball mill using the following abrasives: iron ore-hematitic (400-600Hv), phosphate rock-apatite (300Hv), quartz (1000Hv) and also in the pin-on-disk test using SiC and alumina abrasives. An improvement in wear resistance was observed with increasing percentage of carbides using hematite and apatite abrasives; the opposite was observed when quartz was used as the abrasive.

The development of wear resistant microstructures is well demonstrated by Oliveira T.G. and Costa, A.R. [41]. This work shows how the arrangement (volume fraction and distribution) of carbides in a ductile matrix enhances the wear performance of Fe-C-Cr-Nb alloys. This kind of material is well adapted to build tools and parts for a great variety of equipment whose components operate in heavy abrasive conditions. The work also shows the ball abrasion test capabilities to fast characterization of wear resistance in abrasion and the mechanisms involved [42].

The evaluation of the influence of chromium content and the blend of chromium and niobium in Fe-Cr-C hardfacing alloys on the microstructure was the aim of the search. These alloys associate carbides with a metallic matrix giving them high hardness and mechanical resistance [43-53].

For the realization of the experiments, commercial Fe-Cr-C alloys were obtained in the form of consumables (electrodes and wire) and applied as coatings on ASTM A36 carbon steel by means of SMAW and GMAW welding processes, respectively. In this case, two electrodes with addition of 25 and 45 percent by weight of chromium and a wire with 20 and 5 percent by weight of chromium and niobium, respectively, were used. For chemical composition see Table 2 [41].

Table 2 Chemical Composition of the Electrodes

		C	Mn	P	S	Si	Cr	Nb	Fe
ASTM A36	Substrate	0.25	0.80 1.20	0.04	0.05	-	-	-	Balance
Fe-Cr-C	Alloy A	5.30	0.85	-	-	1.25	45.00	-	Balance
Fe-Cr-C	Alloy B	4.10	0.40	-	-	1.42	25.00	-	Balance
Fe-Cr-C-Nb	Alloy C	5.00	2.00	-	-	1.00	20.00	5.00	Balance

The micro abrasion wear test was performed using the fixed rotating ball method and, as an abrasive, a diamond suspension of 3μm mean grain size. For this, four test specimens were used for each alloy. In order to calculate the wear coefficient, the average loss in volume was determined at pre-established time intervals, relating the result to the sliding distance.

Analyzing the obtained results, it was verified that the alloy that presented the combination of chromium and niobium in its composition had better wear resistance results, although it showed lower values of hardness and volume fraction of carbide in comparison to the other two alloys (Figure 9). Such result evidences the possibility of using such alloy in applications that require high performance in relation to wear resistance.

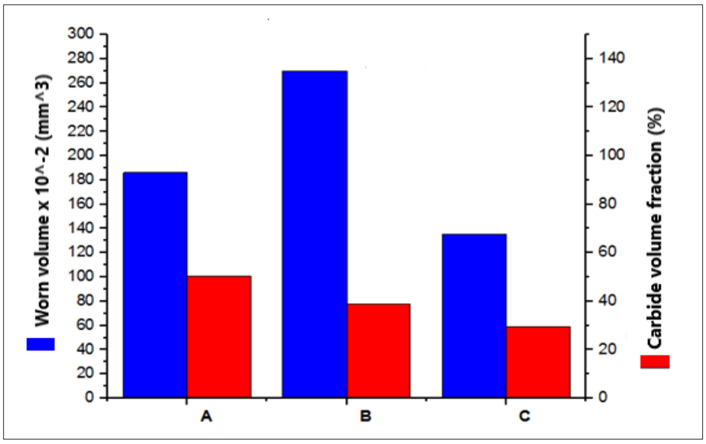


Figure 9 Effect of the percentage of carbides on the volume loss of the coatings of alloys A, B and C. [41]

The percentage of carbides is an important factor in the analysis of wear resistance; however, it must be evaluated together with the morphological and dimensional characteristics of these particles. Alloy A presented the highest percentage of carbides, followed by alloy B and C; however, the wear resistance of alloy A was lower than that presented by alloy C, due to the carbides existing in A being coarser, which may have facilitated the plucking or fracture of these particles.

4. Conclusion

Abrasion studies of conveyor belt showed that it was possible to characterize an in-service worn belt and to reproduce, with limitations, the in-service wear mechanisms in the laboratory. In this study, the morphology of the particles and the chemical composition, especially the silica content, did not play a dominant role in the wear process of the analyzed rubber.

The Friable Hematite samples showed higher abrasiveness than the others, possibly due to the large amount of hard hematite minerals, mainly sinuous and microcrystalline hematite, contributing to wear.

The predominant wear mechanism in service and in the laboratory sample was the formation of Schallamach waves. The distance between waves had a positive correlation with the size of the abrasive particle.

The complete reproduction of in-service conditions in the laboratory is limited by different factors, including different environmental conditions, mechanical stresses and varying sizes of abrasive particles.

Wet erosive wear caused by slurries with different compositions of solid particles followed a trend in which those with higher silica contents provided greater mass losses of high chromium cast iron (HCCI) samples.

Results showed point to a correlation from which one concludes that iron ores from Carajás mines (CJ) are less abrasive in comparison with Minas Gerais State iron ores (QF). These differences in abrasiveness could be explained taking in account features as morphology, chemical composition, and mineralogical organization of samples components (texture), hardness and microstructure.

There is a positive correlation between the degree of metamorphism of iron ore throughout its genesis and evolution in relation to the abrasive indices MN and SAR, influencing properties such as hardness and morphology, thus resulting in greater abrasiveness of ores that came from regions with more intense metamorphic events.

The amount of silica present in iron ores also influences the MN and SAR abrasiveness indices, having a positive correlation, that is, the greater the amount of silica, the greater the abrasiveness of this ore tends to be.

The presence of niobium in a hardfacing coating contributed to the greater resistance to abrasion, due to the presence of niobium carbides (NbC), which showed strong adhesion, making it difficult to pull them out during the wear process. In addition, niobium, due to its greater affinity for carbon, may have contributed to the formation of a matrix richer in chromium and, therefore, more resistant to wear.

Compliance with ethical standards

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