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Relationship between microstructure, hardness, impact toughness and wear performance of selected grinding media for mineral ore milling operations

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Abstract

Investigations were conducted to determine the microstructure–property–wear performance relationships of five selected commercial grinding mill ball types in laboratory scale milling experiments. The results obtained show a general increase in hardness and wear resistance of the grinding media with an increase in carbon content reflecting a transition from a wholly pearlitic structure in steels to one dominated by hard carbides in a pearlite and retained austenite matrix in cast irons. The impact toughness of the medium chromium cast iron as indicated by the drop test results improve significantly after the heat treatment. This is attributed to the disruption of the crack sensitive continuous carbide network leaving behind discrete carbides surrounded by a tough matrix comprising pearlite and retained austenite. Medium chromium cast iron ball type in the heat-treated condition has the desired microstructure–mechanical property–wear performance combination. Economic consideration and the ease of production favour the use of unalloyed white cast iron, particularly in the grinding of abrasive mineral ores.

Keywords: Microstructure; Heat treatment; Wear

1. Introduction

Increasing scales of mining operations in the second half of the last century, in particular the introduction of large diameter ball mills, is often cited as the main reason for the intensive research that was carried out not only to improve the quality, but ultimately the performance of grinding media [1–4]. Much of the research was directed towards modifying existing materials and selected variations of high manganese steel. Because of its ability to withstand the severe impact conditions such as those experienced in the large diameter ball mills, the high manganese steel became the focus of many of the early investigations [5,6]. The steel, which has a low initial hardness (approx. 200 BHN) is also expensive to produce. High chromium cast irons, which also came into prominence around the same time, have remained the choice grinding media for soft materials such cement [7,8]. Their use has since been extended to include the production of liner materials for the mining industry [9–11].

Most commercial grinding media today is produced from martensitic low alloy steels. Both forged and cast grades are available. The main advantages of these steels are their adaptability to most milling conditions and the favourable cost to wear ratios. While the world-over has all but stopped the production of unalloyed white cast iron due to its rather average resistance to abrasion and insufficient impact toughness when used in modern large diameter mills, it remains the most popular grinding media in some countries, including Zimbabwe [12]. The wide range of balls available on the market today make it difficult for the end user to select grinding media for optimum performance in a cost effective manner. A detailed comparison of these balls under identical conditions is not always available. Consequently, the use of cost price rather than cost effectiveness, as the criterion for grinding media choice

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Table 1
Chemical composition of selected grinding media (wt.%)

Type of ball	C	Mn	Si	Cr	S	P
Low alloy steel	0.50	1.07	0.43	1.15	0.02	0.02
Eutectoid steel	0.85	0.65	0.69	<0.15	0.01	0.01
Medium chromium cast iron	3.00	0.57	0.61	17.81	0.04	0.02
Un alloyed cast iron	3.00	0.55	0.62	0.58	0.02	0.02
Cast semi-steel	2.18	0.68	0.87	<0.15	0.02	0.02

is widespread leading to the high grinding media costs being incurred. The aim of the present investigation is to compare the relative performance of different ball materials under identical conditions.

2. Experimental methods

2.1. Materials

The materials used in this investigation comprised five ball types whose designations and chemical compositions are listed in Table 1. The balls, which measured 60 mm in diameter, were produced in a 400 kg induction furnace and sand cast. The eutectoid steel, cast semi-steel and medium chromium cast iron ball types were further subjected to a heat treatment schedule in which they were heated for 3 h at 750 °C, 850 °C and 1050 °C, respectively, followed by cooling in still air.

2.2. Metallography

Samples for metallographic examination were cut from each of the ball types and prepared following standard procedures. Polished specimens were etched using 3% Nital and the microstructures viewed under a Zeiss MI15 optical microscope. A 35-mm camera attached to the optical microscope was used to take micrographs of the features observed. The volume fraction of carbides present in the unalloyed cast iron, cast semi-steel and medium chromium cast iron specimens was determined using an image analyser.

2.3. Drop testing

Three balls from a batch of each of the ball types described in Table 1 were randomly selected for the impact toughness drop test. The balls were dropped from a height of 6 m onto a manganese steel anvil. The number of drops required to fracture each test ball type were recorded and the average computed. The extent of flaking and spalling of the balls was also observed and noted in both as cast and heat-treated samples.

2.4. Hardness testing

The hardness of the test balls including the heat-treated types was measured using a Rockwell Hardness Tester with a 'C' scale employing 30 and 10 kg as major and minor loads, respectively.

2.5. Abrasive wear tests

Milling tests to assess the wear behaviour of the grinding media were conducted in 0.45×0.45 m batch laboratory-scale ball mill. A ball and charge of 21 kg and 30 kg, respectively, was used. Each of the test balls was marked (for identification purposes) by means of differently oriented shallow notches, 25-mm long and 3-mm wide that were cut using an angle grinder. Granite stones with a bond work index (BWI) of 14.4 kW h/t (typical of ores found in Zimbabwe) represented the charge material. In preliminary tests, milling time was varied to obtain a product with an average harmonic mean size (HMS) close to 300 μm. Milling times of 3 h, 4 h and 5 h, for example, gave HMS values of 810 μm, 360 μm and 280 μm, respectively. Accordingly, a 5-h time interval was used in the subsequent tests.

Wet milling tests were carried out with 65% solids. Two wear-in 5-h runs were used to remove surface defects such as scaling and decarburisation. The marked balls were then weighed after these runs before being introduced into the mill for the actual milling test run. At the end of each test run, the marked balls were retrieved, cleaned with a soft brush and thoroughly washed with water, dried with compressed air and re-weighed. The average weight loss for three balls was recorded for each test run. A total of 16, 5-h milling periods were used in all the milling test runs.

3. Results and discussion

The microstructures of the test balls in both the as-cast and heat-treated conditions are shown in Figs. 1–6. Fig. 1 shows the microstructure of the low alloy steel balls. The structure is composed of very fine pearlite barely resolvable even at high magnification. Given the

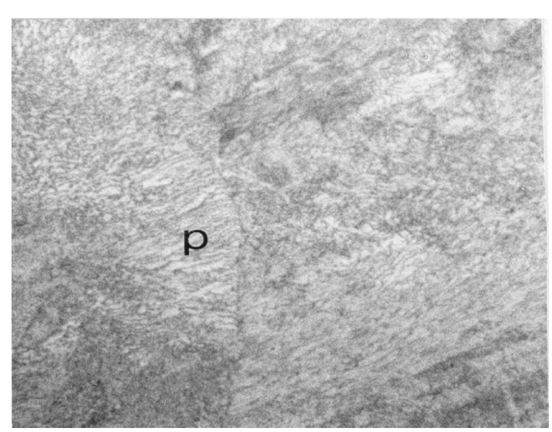

Fig. 1. Low alloy steel showing very fine pearlite, **1000×**.

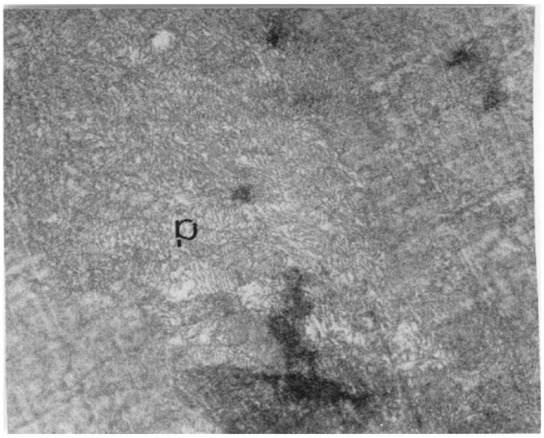

Fig. 2. Heated treated eutectoid steel showing a fine pearlitic structure, **500×**.

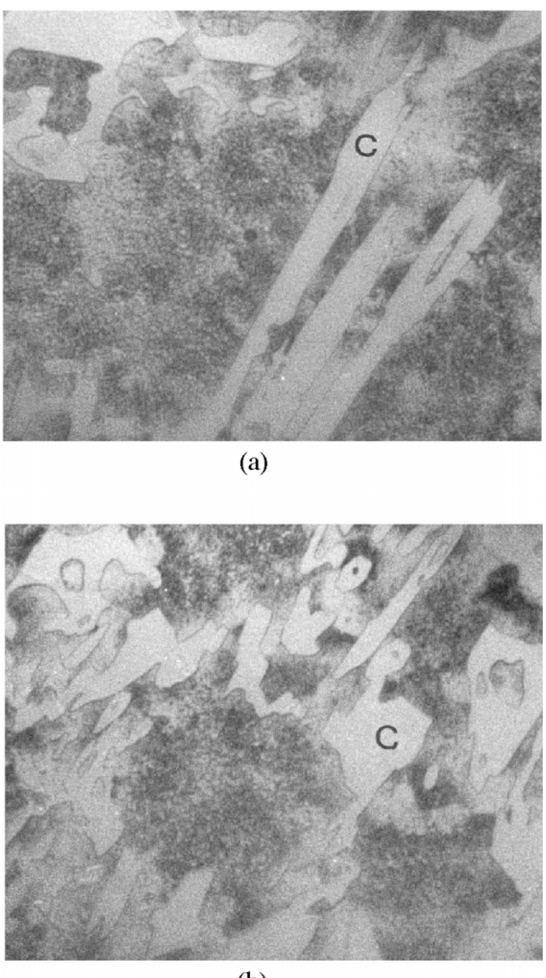

Fig. 3. (a) Medium chromium cast iron in the as cast condition showing coarse carbides in a pearlitic matrix, **500×** and (b) Heated treated medium chromium cast iron showing refined carbides in a pearlitic matrix, **500×**.

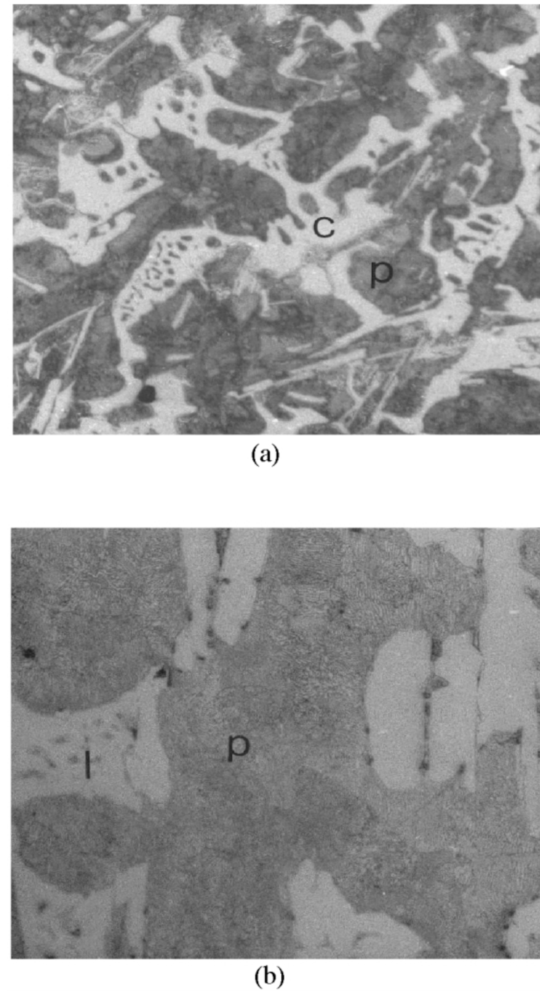

Fig. 4. (a) Unalloyed cast iron showing pearlite (P) formed from primary austenite dendrites with a continuous network of eutectic carbides (C), **200×** and (b) A high magnification of unalloyed cast iron showing ledeburite (l) and some slightly resolved lamellar pearlite, **500×**.

carbon equivalent for the material is 0.91, the presence of ferrite in the microstructure should not be expected [13,14]. A typical microstructure of the as cast and heat-treated eutectoid steel is shown in Fig. 2. The structure comprises fine pearlite in which the lamellar are difficult to resolve, as was the case with the low alloy steel.

Fig. 3 shows the microstructures of the as-cast and heat-treated medium chromium cast iron balls. The structures are basically the same comprising mainly carbides which are surrounded by pearlite and retained austenite. In the as cast material, many of the carbides are coarse and elongated (Fig. 3a). There is considerable refinement of the carbide structure when the as-cast balls are heat-treated (Fig. 3b). The amount of retained austenite following heat treatment appears somewhat reduced. The volume fraction of the carbides was estimated by image analysis to be 28% and 31% in the as cast and heat-treated medium chromium balls, respec-

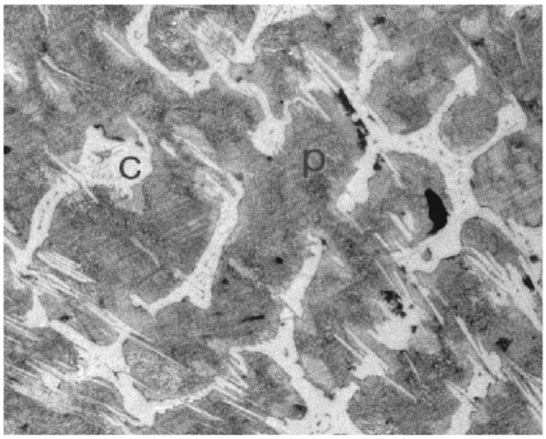

Fig. 5. As cast semi-steel showing pearlite (P) formed from primary austenite dendrites with continuous network of eutectic carbides (C), **200×**.

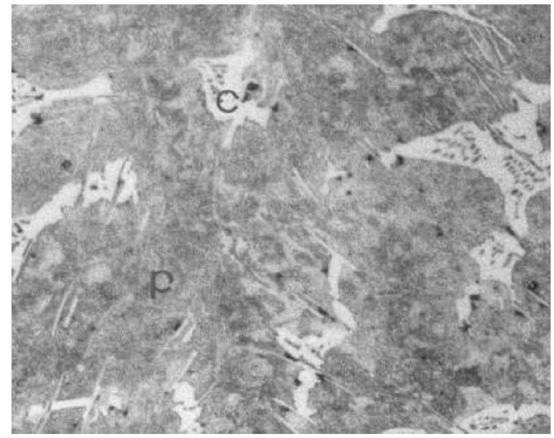

Fig. 6. Heat treated semi-steel showing pearlite (P) formed from austenite dendrites with a discontinuous carbide (C) network, **200×**.

tively. These values are averages of measurements taken from different areas on the microstructures.

Minkoff [8] was able to demonstrate that the carbide phase in medium and high chromium cast irons is of the type M_7C_3 where M is chromium and iron. Using the Fe–Cr–C ternary diagrams, a relationship between the chromium and carbon content that would be required to establish a completely eutectic structure in both medium and high chromium cast irons was developed:

$$\text{Total\% Carbides} = 12.33\text{C} + 0.55\text{Cr} - 15.2. \quad (1)$$

The application of this formula to the medium chromium cast iron balls (Table 1) gives a total carbide content of 31.6%. This compares favourably with the values of 27.85% and 30.97% for the as cast and heat-treated balls, respectively, obtained by volume fraction calculations based on image analysis.

The microstructure of the as-cast unalloyed white cast iron is shown in Fig. 4, and basically comprises primary dendrites of austenite, which on cooling transformed to a mixture of pearlite and eutectic carbide. The eutectic carbides form continuous networks, and have a volume fraction of 22%. At higher magnification, a slightly resolved pearlitic structure as well as ledeburite can be seen. While the as-cast semi-steel ball structure (Fig. 5) is very similar to that of unalloyed cast iron, it contains in addition Widmanstatten cementite, which is not present in the former (Fig. 4). The carbide network becomes less continuous when the cast semi-steel is heat-treated (Fig. 6) with considerably reduced Widmanstatten cementite. The heat treatment temperature, which lies in the intercritical region of the iron–carbon phase diagram facilitates the transformation of pearlite and a little of the cementite to austenite, resulting in a reduction of the carbide network and the evolution of a finer structure. The volume fraction of the carbides as measured by image analysis were found to be 25% and 15% for the as-cast and heat treated semi-steel, respectively.

Table 2 gives a summary of the microstructures of the ball types as described in Figs. 1–6. The cast irons

Table 2
Summary of microstructural features observed in the grinding media investigated

Type of ball	Microstructural features	Carbides observed
Low allow steel	Very fine pearlite	No carbides
As-cast eutectoid steel	Fine pearlite	No carbides
Heat treated eutectoid steel	Fine pearlite	No carbides
As cast medium chromium cast iron	Primary carbides (Cr, Fe)$_7$C$_3$ and (Cr, Fe)C$_3$ in a pearlite matrix	Fine discontinuous carbides
Heat treated medium chromium cast iron	Primary carbides (Cr, Fe)$_7$C$_3$ and (Cr, Fe)C$_3$ in a pearlite matrix	Fine discontinuous carbides
As-cast semi-steel	Pearlite, and grain boundary Widmanstatten cementite (FeC$_3$)	Continuous grain boundary carbides
Heat treated semi-steel	Pearlite, and grain boundary Widmanstatten cementite (FeC$_3$)	Discontinuous grain boundary carbides
Unalloyed cast iron	Pearlite and massive cementite (FeC$_3$)	Continuous massive carbides

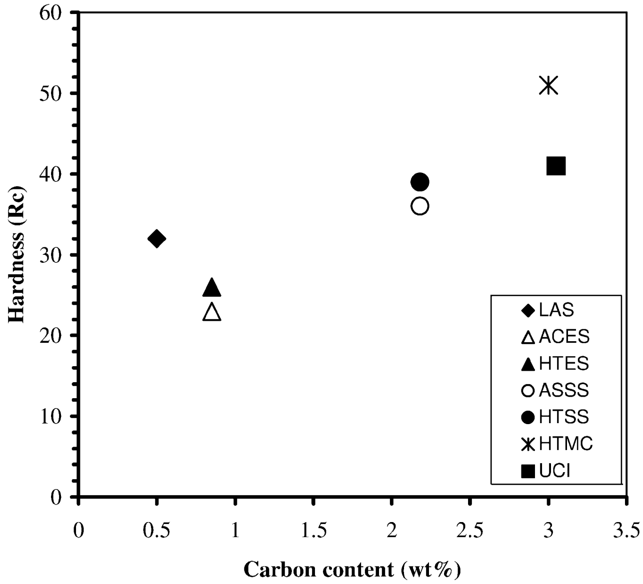

Fig. 7. Effect of carbon content of grinding media type on hardness.

with relatively high carbon contents have corresponding high hardness values (Fig. 7). This is generally attributed to the formation of carbides, which are relatively hard compared with the fine pearlitic structure that is typical of low alloy and eutectoid steels. The rather high hardness values exhibited by the medium chromium balls is basically due to the presence of carbides of the type $(Cr,Fe)_7C_3$ and $(Cr,Fe(C_3)$, which are harder (1200–1800 HV) than the FeC_3, cementite phase (840–1100 HV) associated with both unalloyed cast iron and the cast semi-steel. Heat-treatment, which in the main serves to improve properties of the materials by altering the microstructure was found to greatly increase the hardness value in medium chromium cast iron and only marginally in eutectoid and semi-steels.

The eutectoid and low alloy steels with relatively low carbon content, hence reduced hardness values performed exceptionally well in the impact toughness drop test (Fig. 8). After 3000 drops, the eutectoid steel in the as cast and heat-treated conditions had not broken. This excellent performance is attributed to the fine structure, which is completely pearlitic. Some flaking was, however, observed on the surface. The performance of the medium chromium cast iron balls improved markedly with heat treatment with the drop count increasing from 1344 in the as-cast condition to 2627 after heat treatment. There was, however, extensive spalling of the balls before fracture, particularly in the as-cast condition. A decrease in the extent of spalling with increasing number of drops to fracture of the heat-treated balls is attributed to reduced retained austenite effect. The latter undergoes a strain-induced transformation to martensite, which is brittle leading to the spalling. The spalling is also a result of the volume increase resulting from the transformation. It follows, therefore, that the high quantity of austenite that is present in the as-cast balls naturally should result in massive transformation to martensite, and consequently a high degree of spalling. In contrast, the unalloyed cast iron and cast semi-steel balls simply fractured at relatively low drop counts without showing any signs of spalling or flaking. A major constituent of the microstructure of these balls, the carbide phase, is characteristically hard and brittle. Because it is present in continuous networks, this greatly facilitates crack propagation. Heat treatment of the cast semi-steel slightly improves the impact toughness due to a reduction in the continuous nature of the carbide networks.

Wet milling test results are shown in Fig. 9. The slope of the lines in the mass loss vs. milling time is considered an indication of the wear rates for the different ball types. Generally, the ball types exhibiting low hardness values (Fig. 10) and high drop count (Fig. 11) performed rather poorly in milling tests as indicated by the high wear rates, a reflection perhaps of the carbon content effect (Fig. 12) on the evolution of microstructural constituents that impart wear resistance (Table 2). The eutectoid balls were, however, an exception in that the heat-treated variety with a slightly superior hardness had a wear rate that was considerably higher than that of the as-cast form with a similar microstructure. Soft grinding media may at times be coated by the abrasive material, which becomes embedded in the soft matrix of the ball. This effectively reduces the balls interaction with other abrasives in the mill, hence the wear that the ball material would be expected to experience [15,16]. In the currently reported work, the wear performance of medium chromium cast iron in the as cast condition has

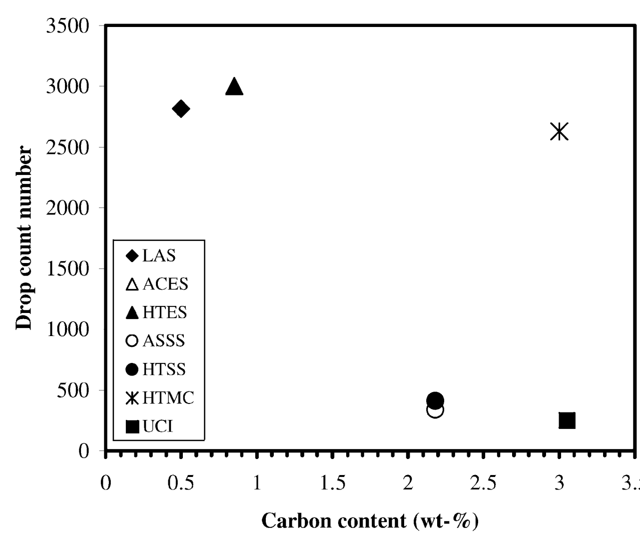

Fig. 8. Effect of carbon content of grinding media type on toughness (as indicated by the drop count number).

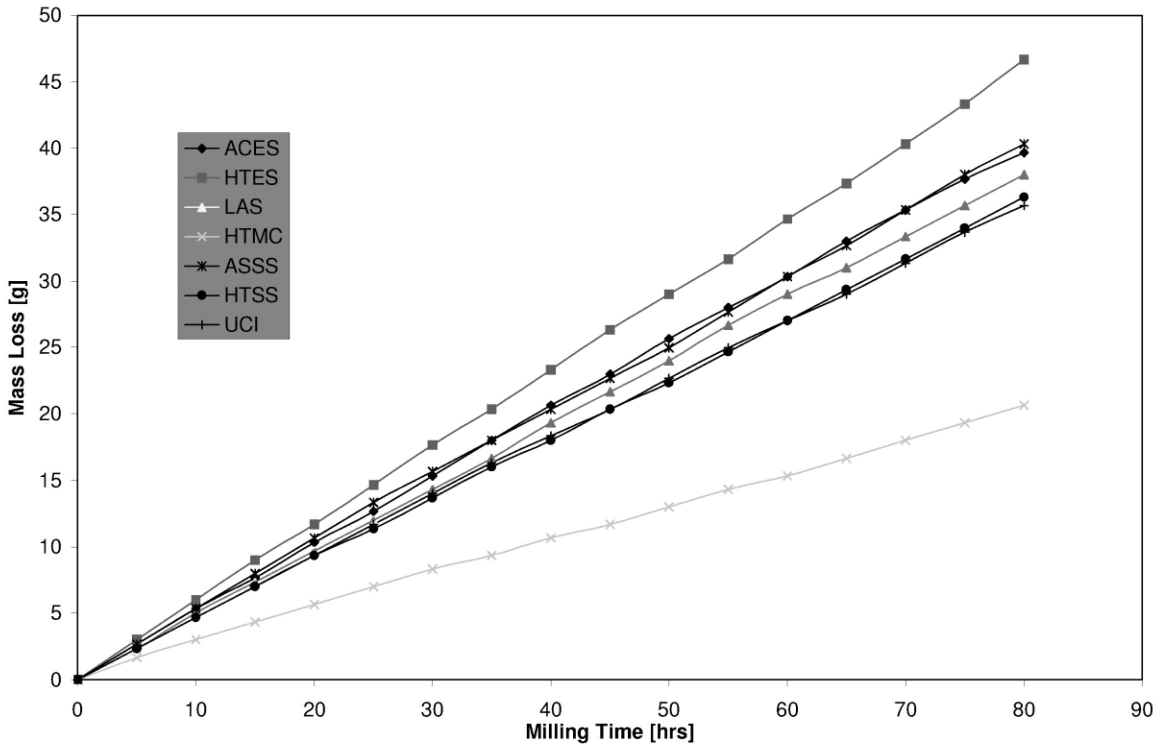

Fig. 9. Variation of mass loss of grinding media type with milling time.

not been studied. Traditionally, the material has only been used in milling operations in the heat-treated condition.

Ball wear in ore milling operations occurs by the removal of material from the surface of the ball as metallic particles [17–20]. As would be expected, the characteristics and distribution of the micro-constituents of the ball material become the dominating factors in determining wear resistance. Heat treatment that is sometimes applied (at an increased cost of the grinding media) has the overall effect of producing the desired

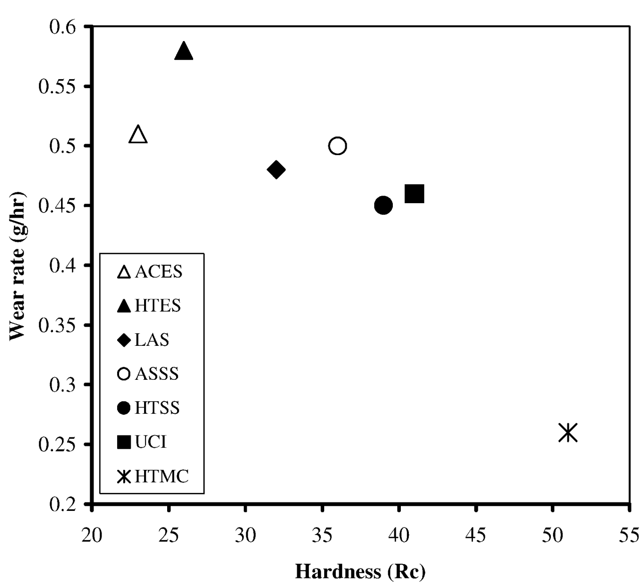

Fig. 10. Correlationship between wear rate and hardness of selected grinding media.

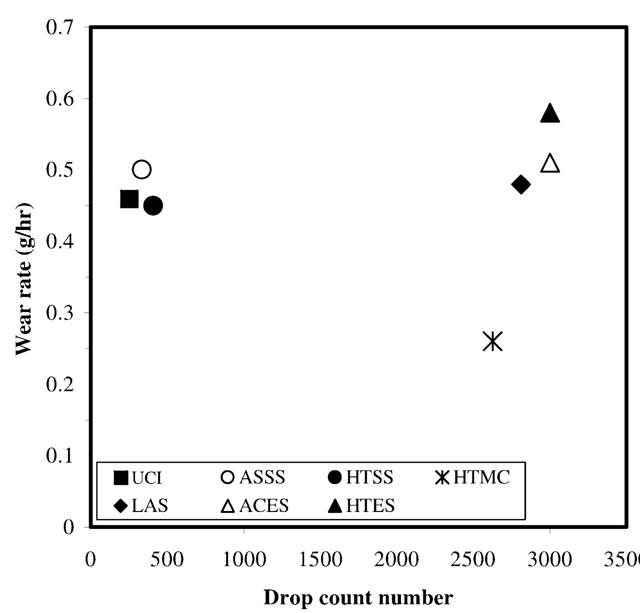

Fig. 11. Correlationship between wear rate and toughness of grinding media (as indicated by the drop count number).

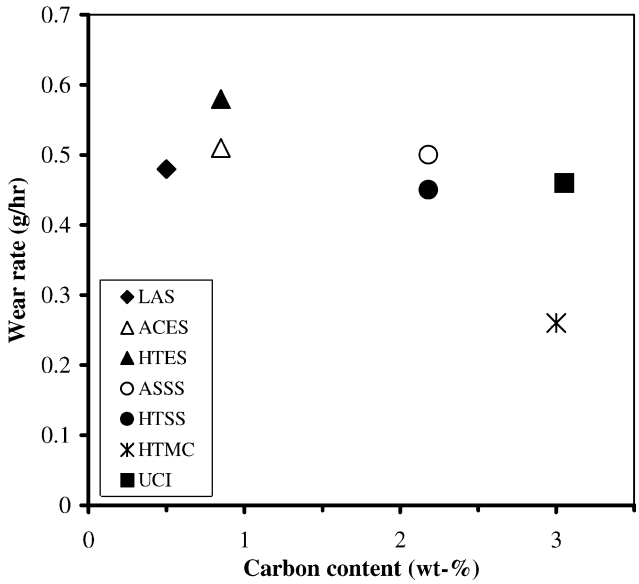

Fig. 12. Effect of carbon content of the grinding media type on the wear rate.

microstructure. While it is well established that hard particles such as carbides greatly improve wear resistance this is very much dependent on the characteristics of the matrix. The latter holds the carbides, which are responsible for improving, wear resistance in place.

Generally, the hardness, and hence the wear resistance can be improved by heat-treating materials, with the additional cost being passed on to the consumer. By introducing sufficient carbon to cause the formation of primary massive carbides in the structure, both the hardness and wear resistance are improved without necessarily performing any heat treatment (Fig. 4). The wear rate is reduced from 0.51 g/h in as-cast eutectoid steel to 0.46 g/h in unalloyed white cast iron but this is often achieved with much sacrifice of the impact resistance.

Economic consideration would seem to favour the use of unalloyed white cast iron as grinding media for the rather abrasive ores with bond work indices of 13–18 kW h/t. The ease with which unalloyed cast iron can be made compared to other ball types is an added advantage. However, because of the poor impactive wear properties, their use would be limited to milling operations in small to medium diameter ball mills. The heat treated semi-steel seem to offer the best alternative to the unalloyed white cast iron, but the additional cost incurred due to heat treatment and closer carbon content control during production would make them more expensive. The medium chromium cast irons with the best results in milling tests would also prove undesirable due to their higher cost price, although they would be advantageous in milling softer ores.

4. Conclusions

a. The hardness and wear resistance of the grinding media investigated were generally found to increase with increasing carbon content from steels to cast irons. The performance of the ball types in milling tests were as follow:

   Heat-Treated Medium Chromium
   $>$ Heat-Treated Semi-Steel
   $\geq$ Unalloyed Cast Iron $>$ Low Alloy Steel
   $>$ As-Cast Semi Steel
   $\geq$ As-Cast eutectoid Steel
   $>$ Heat treated Eutectoid Steel

b. Steels with purely pearlitic structures possess excellent impact toughness, but have inferior hardness. Their milling performance is, however, very good in conditions which should yet be studied in more detail. It seems that when used to mill very hard charge material, especially in large ball mills, these steels may prove to be very useful.
c. By increasing the carbon content to produce cast irons, both the hardness and wear resistance are improved significantly. The effect on impact toughness is, however, very negative, and is attributed to the presence of continuous networks of hard and brittle primary carbides in a pearlitic matrix. The impact resistance can be improved by appropriate heat treatment to produce discontinuous carbide networks.
d. Although heat-treated medium chromium cast iron has the desired combination of microstructure–mechanical property–wear performance, economic considerations and ease of production favour the use of unalloyed cast iron as the grinding media of choice particularly for abrasive mineral ores.

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