POTENTIAL HEALTH EFFECTS OF LOCALLY-MANUFACTURED CORN-MILL GRINDING PLATES

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ABSTRACT

Laboratory tests were carried out on samples of some locally-manufactured corn-mill grinding plates to investigate the possible causes of their early wear and failure. Three different samples selected from the same local manufacturer were tested for chemical composition and micro-structural, as well as wear and hardness. Results show that, although the chemical compositions were similar, the hardness and wear resistance of samples were significantly different, suggesting that the samples were of different heats. A strong correlation exists between the wear rate and micro-hardness of samples, the wear rate decreasing linearly with hardness. Since the grinding/milling plates were from the same production shop and meant for the same purpose, these differences in hardness and wear resistance indicates non-reproducibility of products. The differences in hardness and wear resistance of the samples are explained in terms of chemical composition and/or microstructures of samples. The wear of these locally-manufactured corn-mill grinding/milling plates is discussed in terms of the possibility of consumption of iron into the human body and the health hazards associated with it.

Keywords: *Ghana; Casting; Maize (Corn); Locally-manufactured grinding/milling plates; Cast Iron; Wear; Iron Overload.*

INTRODUCTION

In Ghana a lot of casting activities are carried out on a small-scale basis. Large concentrations of such activities can be found in "Suame-Magazine" of Kumasi in the Ashanti region, "Kokompe" of Sekondi /Takoradi in the Western Region, and "Abossey Okai" of Accra in the Greater Accra Region, with smaller concentrations 'littered' all over the country. Although these small-scale activities support the economy in terms of (i) providing jobs for several hundreds of self-employed people and thus reducing the level of unemployment and (ii) contributing immensely in the manufacture of machine components or parts to replace worn-out ones, and thus help reduce the foreign exchange burden on importation, there is the need for their appraisal due to one or the other of the following reasons:

a) Most of the workers are semi-skilled artisans, with little formal education and having acquired experience only through several years of apprenticeship. Hence they have little understanding of the science of and metallurgy of casting and how these impact on the properties of their products.

b) Due to (a) above, the quality and integrity of their products are often far from satisfactory. Consequently, failure of products often occurs unexpectedly and rather early in their service life.

c) Most of the practices are indigenous and workers do not have any code of practice to follow. Hence, the quality and/or integrity of products depend solely on the skills of the worker.

d) There is no standardized means of testing for defective items or products, thus flooding the markets with inferior goods.

e) As a result of (a)-(d) above, the use of such products may present safety and/or health risks to consumers, most of whom may not be aware of such dangers anyway.

f) Consumers often have little choice in the use of these inferior products due to the fact that better quality products may not be on the market and, if available, may be very expensive.

A common casting product of interest manufactured by the small-scale artisans, which is the focus of the paper, is corn-mill grinding plates. They are produced by sand-casting method using old engine blocks and other scrap metals and castings. These locally-manufactured corn-mill plates have been observed to wear out very quickly lasting a maximum of four months. The wearing of these plates in service causes metal debris to mix with the ground corn and this could present health hazards to consumers. The seriousness of any possible health issue is underscored by the fact that maize (known locally as corn) is a staple foodstuff in Ghana and, more often than not, milled or ground for preparing various kinds of delicacies.

In this paper the results of chemical and microstructural analyses, as well as hardness and wear tests of some locally-produced corn-mill grinding plates are presented and discussed. The observed differences in hardness and wear resistance could be related to differences in microstructures. The significance of wear resistance of ferrous metallic material for use as corn-mill grinding plates is highlighted in terms of dietary iron overload and its associated toxic effects in the human body.

MATERIALS AND METHODS

Three different samples of corn-mill grinding plates were taken from a workshop in Suame-Magazine (Kumasi) for the analyses. These samples, herein labeled A, B and C were, according to the producer, supposed to be of the same quality and meant for the same purpose, i.e. grinding/milling of maize. The mode of selection of these samples was by visual inspection and sound tests. A piece of metal was used to strike the plates and their various sounds noted. The three samples chosen sounded differently, which suggested differences in some physical properties. The shape of the plates was in a form of a disc having a diameter of about 30cm and a hollow core diameter of about 11cm. The thickness of the plates was non-uniform ranging from about 10mm at the outer circumference and tapers down to about 1mm at the centre. In addition the plate surface has grooves/striations for effective grinding/milling operation while in service.

Specimens of dimensions 21x17x8.5mm were cut from each sample and analysed for chemical composition, microstructure, hardness and wear. Chemical analysis was performed using a Metal Scan (2500L) Spectrometer. The microstructures of polished surfaces were viewed off a Union Optical Microscope and micrographs taken using conventional 35mm film. The hardness was measured using a Galileo Hardness Tester, in accordance with the British Standard BS 240:1986 specification, with a 187.5kg load and a 2.5mm tungsten ball. Wet abrasion / wear tests were carried out using a rotating wheel at a speed of 100rpm. Silica slurry of 100g/litre was poured onto the wheel and a specimen pressed against the rotating wheel for a period of thirty (30) minutes. The weights of specimens before and after the wear test were noted. For each plate sample, four such specimens were tested for wear. The wear rate for each specimen is determined as loss in weight divided by the time of wear test (i.e. 30 minutes). The results of these tests are as given below:

RESULTS

Chemical Composition and Bulk hardness

The chemical compositions of the three samples are shown in Table 1, which shows that the materials of these samples are of unalloyed cast iron. The main elements of unalloyed cast iron are Carbon (C) Silicon (Si), Sulphur (S), Manganese (Mn) and Phosphorus (P). All other elements in unalloyed cast iron are considered as impurities in as much as they do not directly influence the properties of the material. The type and properties of cast iron depend on the amount of carbon and the form in which it exists. The carbon can exist either in the free form as graphite or in combined form as cementite, Fe_3C. Graphite is soft and weak, but cementite is hard and brittle. Other elements such as Si, S, Mn, directly or indirectly promote the formation of one form of carbon or the other. Since carbon is the main element that determines the type of cast iron it is often conventional to convert other elements into their carbon equivalent (CE) by a simple empirical formula. For example, the carbon equivalent (CE) of cast iron may be determined (Leslie and Hornbogen, 1996) as:

$$CE = \%C + 0.3\%Si + 0.33\%P - 0.027\%Mn + 0.40\%S \quad (1)$$

TABLE 1: Chemical Composition and Bulk Hardness of Plate Samples

Element	Composition in Mass %		
	A2	B2	C2
Carbon	3.15	3.28	3.17
Manganese	0.4	0.44	0.33
Sulphur	0.188	0.151	0.163
Phosphorus	0.061	0.058	0.348
Silicon	1.3	1.36	1.18
Chromium	0.69	0.4	0.25
Molybdenum	0.03	0.1	≤0.010
Nickel	0.18	0.07	0.05
Copper	0.35	0.21	0.07
Aluminium	0.01	0.013	0.013
Vanadium	0.011	0.011	0.015
Niobium	0.007	0.009	0.01
Boron	0.0092	0.0108	0.0105
Titanium	0.008	0.009	0.018
Iron	Matrix	Matrix	Matrix
Bulk Brinell Hardness	420-429HB	289-294HB	289-294HB

Using equation (1) the CE of samples A, B and C were determined as 3.64, 3.77 and 3.71, respectively. The carbon equivalent (CE) of cast iron helps to distinguish the grey irons which cool into a microstructure containing graphite and the white irons where carbon is present mainly as cementite (Yescas-Gonzalez and Bhadeshia, 2001). In general, a high cooling rate and a low CE favours the formation of white cast iron whereas a low cooling rate and a high CE promotes grey cast iron. Hence, all things being equal, the tendency of the samples to form white cast iron is sample A (CE=3.64), C (CE=3.71) and B (CE=3.77), in decreasing order.

Microstructures

Plate 1 shows a micrograph of Sample A at magnification 200X. The microstructure consists of an unalloyed *chill-cast* white iron structure of coarse lamellar pearlite in a matrix of iron carbides (cementite), with the latter phase accounting for approximately 55% of the total structure. The microstructure of Sample B is shown in Plate 2, also at magnification of 200X. The microstructure consists of an unalloyed *partially chill-cast* white iron structure containing Type A Size 5 graphite flakes (Graphite-Bearing) in a matrix consisting of coarse lamellar pearlite and cementite, with the cementite phase accounting for approximately 30% of the total structure. The microstructure of sample C is shown in Plate 3, at magnification 200X. The microstructure consists of an unalloyed *chill-cast* white iron structure of fine lamellar pearlite and ferrite in a matrix of iron carbide (cementite), with the latter phase accounting for approximately 60% of the total structure.

Hardness and Wear

Table.1 shows the Bulk Hardness of the three sample plates. It is observed that sample C has the highest Brinnel hardness number (BHN) followed by sample A, with sample B having the least. That is, sample C is hardest, followed by

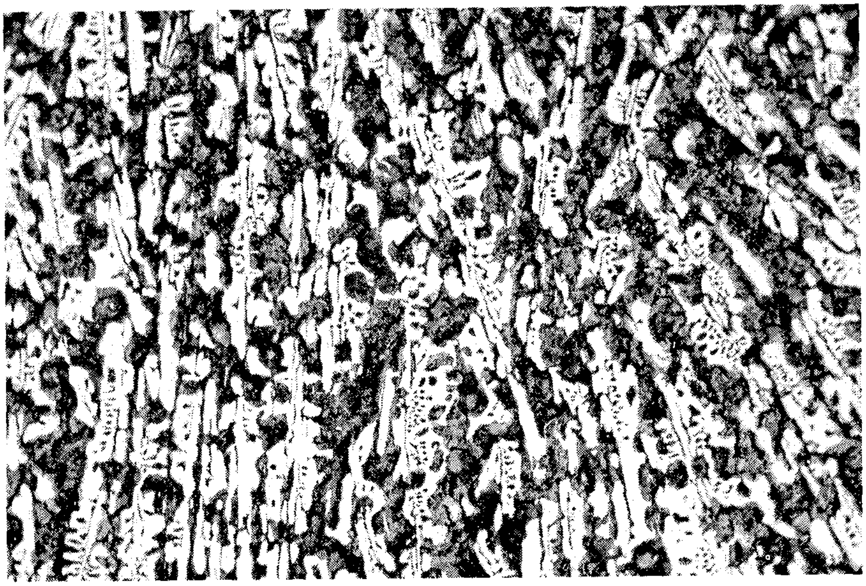

Plate 1. *Microstructure of sample A consisting of coarse lamellar pearlite in a matrix of cementite (Fe_3C), with the latter phase accounting for about 55% of the total structure (200X)*

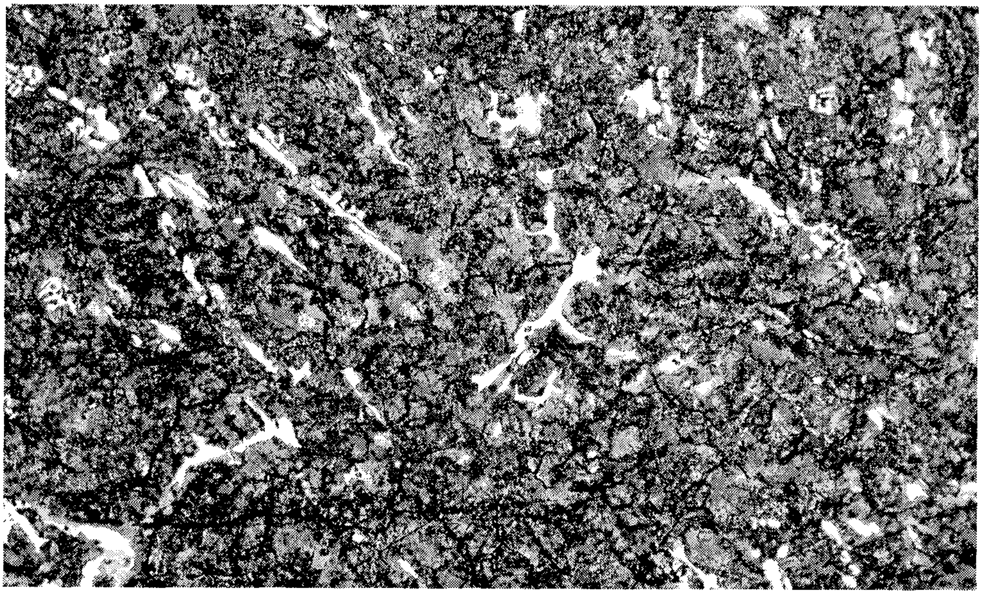

Plate 2. *Microstructure of sample B consisting of Type A size-5 graphite flakes(Graphite Bearing)in a matrix of coarse lamellar pearlite and cementite(Fe_3C), with the latter phase accounting for approximately 30% of the total structure(200X)*

Plate 3. *Microstructure of sample C consisting of fine lamellar pearlite and ferrite in a matrix of cementite (Fe_3C), with the latter phase accounting for about 60% of the total structure (200X)*

sample A with sample B being the softest. The result of the wear test for the three samples is shown in Table 2. For each of the samples, for example sample A, four specimens were tested for wear over a period of about thirty (30) minutes each. The wear rate (gramme/minutes) for each specimen is estimated as the weight loss divided by 30. That is, the wear rate R_i (i =1, 2, 3, 4) for the ith specimen was estimated as

$$R_i = (W_b - W_f)/T \qquad (2)$$

Where W_b and W_f are the weights of specimen before and after the wear test, respectively, and T is the period of wear test, which in this case is 30minutes. It is observed that for specimens of the same sample the wear rate varies by a factor of about 2, 2.5 and 2.6 for samples A, B and C, respectively. Since no homogenization heat treatment is performed by the local manufacturers, the difference in wear rate of specimens of the same sample could be due to chemical composition segregation since the solidification process occur over a range of temperature. It could also be due to the uneven section thickness of the plates resulting in non-uniform cooling rates during the solidification process. Hence, for each sample, say sample B, the average wear rate R is taken as the mean of the wear rates of its specimens, i.e.

$$R = (R_1 + R_2 + R_3 + R_4)/4 \qquad (3)$$

Using equation (3) it is found that sample C has the lowest average wear rate followed by sample A, with sample B having the highest rate of wear. In other words, Sample C, relatively, has the highest wear/abrasion resistance followed by sample A, with Sample B having the lowest and rather poor wear/abrasion resistance.

Figure 1 shows the relationship between the wear rate R, determined according to equation (4) and the bulk hardness value. It indicates that

Table 2: Wear data for the various plate samples

Specimen	Initial Weight, W_b (g)	Final Weight, W_f (g)	Weight Difference (W_b-W_f) (g)	Wear rate $R_i=(W_b-W_f)/30$ (g/min)
A1	14.2769	14.2588	0.0181	0.603e-3
A2	14.3676	14.3490	0.0186	0.620e-3
A3	14.4989	14.4635	0.0354	1.180e-3
A4	14.2856	14.2603	0.0253	0.843e-3
Average	**14.3573**	**14.3329**	**0.0244**	**0.8115e-3**
B1	14.0802	13.9825	0.0977	3.257e-3
B2	13.9851	13.9337	0.0514	1.713e-3
B3	14.0747	13.9456	0.1291	4.303e-3
B4	14.0655	14.0018	0.0637	2.123e-3
Average	**14.0514**	**13.9659**	**0.0855**	**2.849e-3**
C1	13.6811	13.6764	0.0047	0.157e-3
C2	14.6082	14.6029	0.0053	0.177e-3
C3	14.5997	14.5874	0.0123	0.410e-3
C4	14.6181	14.6058	0.0123	0.410e-3
Average	**14.3768**	**14.3681**	**0.0087**	**0.289e-3**

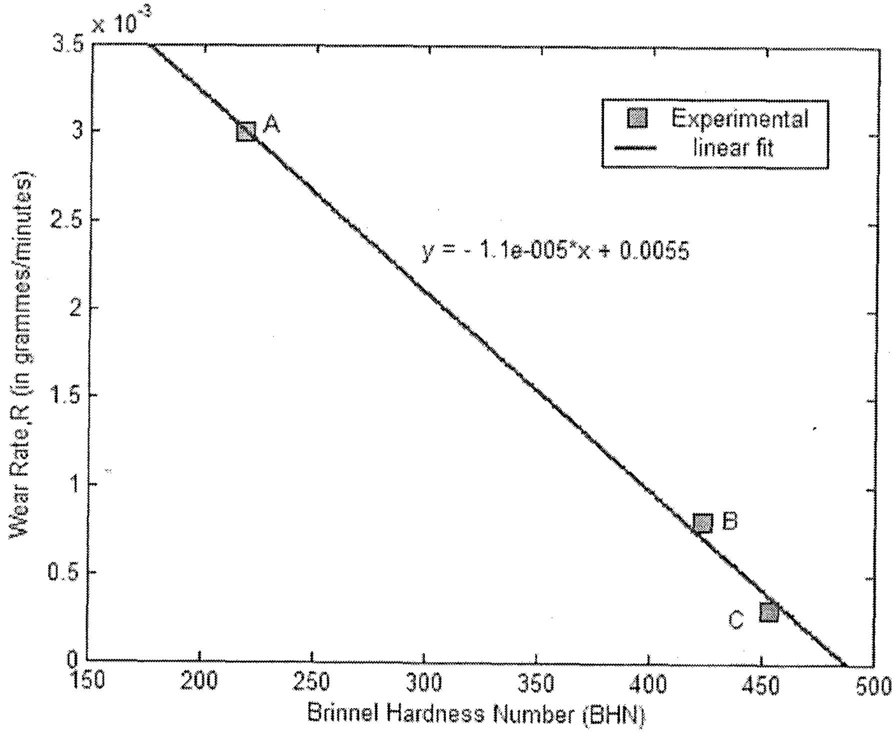

Fig 1: Effect of hardness on wear of the sample plates

the rate of wear of the plate is strongly dependent on its hardness, with the former decreasing linearly as the latter increases. That is, the rate of wear is inversely proportional to hardness of the plate material. From the result of this work, the average wear rate R (in gramme per minute), of cast iron may be estimated from the Brinnel hardness number (BHN) as:

$$R = 0.0055-0.000011(BHN) \qquad (4)$$

where the constants 0.0055 and 0.000011 are obtained from linear fit to experimental data.

DISCUSSION

Three samples (A, B and C) of cast material used for grinding/milling maize (corn) were taken from the same local shop and analyzed for chemical composition, micro-hardness, microstructures and wear/abrasion resistance.

The chemical compositions of the three samples show that they are unalloyed cast iron. All three samples, A, B and C have similar compositions, with carbon equivalent, CE of 3.64, 3.77 and 3.71, respectively. The average bulk hardness was determined as 424.5HB, 291.5HB and 454HB, respectively. The carbon equivalent indicates *hardenability* which is the depth to which the material can be hardened, but *hardness* on the other hand, is resistance to indentation or penetration. Thus, the hardness does not necessarily depend on CE, but on the microstructure and/or phases present. The wear/abrasion test shows wear rates (in g/minute) for A, B and C of about 0.0008, 0.0028 and 0.0003, respectively. Thus, the ratio of wear rates of A:B:C=2.67:9.33:1.

In general cast iron may be termed as *Grey* cast iron or *white* cast iron, depending on the form in which the carbon exists. In grey cast iron carbon exists mainly in the free-state as *graphite*, whereas in white cast iron carbon exists in the combined form as cementite (Fe_3C). Graphite is soft, low in strength with poor wear/abrasive resistance. Cementite (Fe_3C) on the other hand is hard and brittle with good wear resistance.

The properties of cast iron depend on chemical composition, rate of cooling from the melt and subsequent heat treatment on the material. The main elements in unalloyed cast iron are Carbon, Silicon, Sulphur, Manganese and Phosphorus. Carbon tends to increase the hardness of the material. It goes into solid solution to increase the strength of the iron and also combines with Fe to form cementite (Fe_3C). Silicon is a strong graphitizer, breaking down cementite into iron and graphite according to the following reaction:

$$Fe_3C \rightarrow Fe + C \text{ (graphite)} \qquad (5)$$

Sulphur, on the other hand stabilizes cementite and thus enhances the formation of cementite.
Manganese directly tends to stabilize cementite but indirectly promotes graphitization (i.e. breakdown of metal carbide to form graphite) by combining with Sulphur to form MnS. To a rough approximation one atom of manganese may be regarded as neutralising one atom of sulphur, so that by a weight percentage basis, it is only if the Mn:S ratio is less than about 1.7 that Sulphur exercises a marked effect in producing a white iron structure (Hume-Rothery, 1966). From Table.1, the Mn:S ratios for the specimens A, B and C are 2.13, 2.91 and 2.02, respectively. Thus, the tendency of the samples to form white cast iron structure is, in decreasing order, C, A and B. Phosphorus does not have effect on the form of carbon but improves fluidity. In general the silicon composition for achieving white cast iron castings does not exceed 1.3% (Hume-Rothery, 1966). This composition limit is satisfied by samples C (1.18%Si) and A (1.3%Si) but not by Sample B (1.36%Si), although the excess of 0.06% may be considered to be marginal. Thus, it appears that the presence of graphite in sample B may be due mainly to the high Mn:S ratio of 2.91 and to a lesser extent by the relatively high silicon content (1.36%), resulting in the breakdown of cementite during the solidification process.

The rate of cooling also determines whether grey or white cast iron would be formed. Higher cooling rates promotes the formation of white iron while slow cooling gives enough time for equation (2) to take place. In general thicker/ larger sections cool more slowly than thinner/smaller sections. As may be observed from the microstructures it appears that high cooling rates may have been employed which resulted in chilled castings. During the casting process, the solidified metal is not allowed to cool slowly to room temperature but quenched in water while still very hot. The temperature at which quenching is done is not known for certain, nor is it fixed. This could have effect on the final microstructure and hence on the hardness and wear values. Microstructures of samples A and C are fully chilled while sample B is partially-chilled. Sample C has fine pearlite (alternate lamination of ferrite and cementite), while sample A has coarse pearlite, which indicates that the rate of cooling of sample C is higher than that of A, which in turn is higher than that of B. The higher hardness/wear resistance of sample C is obviously due to its finer cementite (Fe_3C) and pearlite phases and, and more especially, the higher proportion of the cementite phase (~60%) in the structure.

Subsequent heat treatment of material can modify the structure of the cast iron. In general the rate of cooling of sand castings is low, especially for large section thickness, and may produce coarse grained structure. Further heat treatment may therefore be necessary to refine the grains. The differences in properties of these samples produced by the same shop and meant for the same job/service shows that the three samples are probably of different heats and that there is non-reproducibility of products. This is the result of the absence of quality control and assurance procedures in the manufacture of such products. It is important to mention that, in practice, the rate of wear could be much higher than indicated in Table 2 as a result of corrosion of the grinding plate. Grinding of maize may be done either dry or wet. Unalloyed cast iron has low corrosion resistance, forming rust which is non-adherent and easily rubbed off the surface by the corn or maize, thus exposing new surfaces for corrosion to continue. In such cases the wearing of plates would be accelerated by the corrosion action.

For use as grinding media for maize (corn) it is obviously clear that the cast iron material must have a high wear/abrasive resistance to minimize the amount of metal debris that might contaminate the ground product. This requires an iron casting of chilled white cast iron with fine microstructure consisting of high proportion of Fe_3C carbide in fine matrix of pearlite. Debris from worn-out plates is very fine and mixes with the ground corn.

In general, the ground/milled corn is used to prepare various kinds of dishes without prior separation process to rid the Fe-containing foodstuff off the metal debris. Such unintended consumption of iron into the human body may result in dietary iron overload (Strachan, 1929), (Bothwell *et al.*, 1964) and (Bothwell *et al.*, 1965). The presence of increased amounts of iron in the human body appears to facilitate infection, as evidenced by the increased risk of persons with hemochromatosis to certain infections, and by the fact that patients with lesser amount of hepatic iron appear to respond better to interferon therapy for chronic viral hepatitis than those with larger amounts of hepatic iron (Rubin *et al.*, 1995). In general iron overload causes major health consequences worldwide, since toxic effects of excess iron affects a large number of people with primary or secondary iron overload (Stal, 1995). The liver is a major target organ of injury in iron overload diseases, reflecting its central role in iron storage and metabolism (Deugnier *et al.*, 1992). In genetic hemochromatosis, excess iron absorbed from the gut is transported through the portal vein to the liver, where it is predominantly stored in hepatocytes (Stal *et al.*, 1990), and it is estimated that about 0.1-0.5% of individuals of Northern European origin have inherited this disorder of metabolism (Edwards *et al.*, 1998). With increasing iron overload, organelle dysfunction and alterations in cellular function may occur, resulting in sideronecrosis of iron-laden hepatocytes and increased collagen synthesis (Deugnier *et al.*, 1992). Iron overload is also a clinical feature of refractory anemias such as thalassemia major, and sideroblastic anemias (Pippard, 1944). Here, excess iron is delivered by repeated transfusions, or taken up from the gut as a result of increased iron absorption.

In sub-Saharan dietary iron overload, ingestion of iron-containing home-brewed beer in combination with a probable genetic defect leads to parenchymal iron deposition (Gordeuk et *al.*, 1992). In Ghana traditional alcoholic beverages such as "Akpeteshie" and "Pito" are brewed in steel drums from which iron may get into the traditional "beer" either by dissolution or corrosion. Similarly, the probable ingestion of iron-containing ground/milled corn dishes (e.g. Kenkey, Banku, Akpele, and many others) constitutes a potential source of iron overload. The risks associated with such iron ingestion are expected to be higher in persons who also consume alcoholic beverages such as beer, "Akpeteshie", "pito", etc, since iron is known to act synergistically in combination with liver cells damaging agents, such as alcohol (Stal and Hultcrantz, 1993). The seriousness associated with any possible dietary iron overload via such corn-related dishes is underscored by the fact that about 90% of all Ghanaians living in Ghana consume such dishes, which are the most consumed on a daily basis.

It is important to mention that at this point the result of this work is not sufficient to conclude that debris from locally manufactured corn-mill plates contributes to iron overload. On the other hand, the possibility of it being a contributing factor, just as home-brewed beer (Gordeuk *et al.*, 1992), cannot be discounted altogether. Therefore further investigation is required to ascertain the extent of metal debris contamination of the ground/milled corn from the point of milling to the point prior to consumption. In addition, it is required to ascertain whether the metal debris consumed, if any, comes out of the body as solid waste, in which case it poses no serious health risk, or it gets deposited in the liver and other parts of the body and cause iron overload with its health consequence. For the case of the latter it is important to improve the wear resistance of the locally-manufactured plates and also standardize products to minimize contaminations, or consider the use of a ceramic material as grinding media.

CONCLUSIONS

Some locally-manufactured corn-mill grinding plate samples were analysed to investigate the causes for their rapid service failure. Specifically, chemical and microstructural analyses, as well as hardness and wear tests were performed. Results showed that the plates have varied hardness and wear resistance, although they are supposed to be of same quality. The differences in wear and hardness values could be related to the differences in microstructures. Sample C is of chill cast white iron with fine pearlite in a matrix of fine cementite. Sample A and B have coarse pearlite and cementite in their microstructures with sample B having some graphite flakes. Thus, the three samples are of different heats, and since they are perceived to be of the same quality, the marked difference in properties is indicative of non-reproducibility, resulting from lack of quality control/quality assurance procedures.

There appears to be a strong correlation between the average wear rate, R, and the Brinnel Hardness value of cast iron, the rate of wear being inversely proportional to the hardness of the material.

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