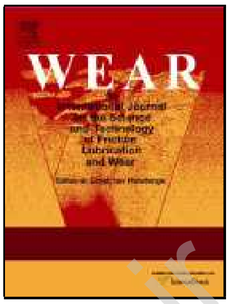

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Prediction of wear rates in comminution equipment

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Abstract

Raw material comminution equipment may be exposed to excessive wear, which makes it difficult to operate minerals processing plants continuously because lengthy and unplanned shut-downs interrupt the overall process. In general, most comminution equipment is fine-tuned to operate at low vibrations and to achieve guaranteed performance. From an economical point of view, it is always preferred to replace all worn parts during the planned maintenance shutdowns. When operating comminution equipment, the wear rate receives little attention and is considered a secondary matter. However, experience shows that a wear map can give eye-opening information on the wear behavior. A wear map provides insight into the interaction between the abrasive and the wear part material being studied. In this paper, three wear maps with highly different properties are compared. Testing was performed on an abrasion-resistant high chromium white cast iron (21988/JN/HBW555XCr21), a heat-treated wear resistant steel (Hardox 400) and a plain carbon construction steel (S235). Quartz, which accounts for the largest wear loss in the cement industry, was chosen as abrasive. Other process parameters such as velocity (1-7 m/s) and pressure (70-1400 kPa) were chosen to closely imitate real industrial processes. The authors are aware that a number of wear mechanisms such as erosion, fatigue and abrasion may occur simultaneously in comminution equipment. Nonetheless, this paper aims at discussing abrasion only due to its large contribution in the material removal process. The vertical roller mill has received special attention and this paper also discusses a simplified view on wear.

Key words: Wear, comminution equipment, quartz, wear maps, wear apparatus, abrasion

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1. Introduction

In the cement industry some 4180 million tons per year of raw materials are reduced in size to a final fraction of approximately 12%+90 μm (based on 2006 figures)[1]. Based on a conservative estimate of the average wear rate in both low stress (abrasive particles not crushed near the wear parts) and high stress (abrasive particles crushed at the wear part surface during grinding) abrasion of 10 g/t, 41800 tons of wear resistant material is lost every year due to size reduction of cement raw materials [6].

This calls for further studies on whether the amount of expensive abrasion resistant materials can be reduced.

Besides conducting expensive and time consuming full-scale wear tests on industrial equipment, various laboratory wear test apparatus imitating industrial wear situations have been used for many years to give a rough estimate of wear performance. For convenience sake, the wear performance of laboratory wear apparatus is typically measured as loss of wear part material. To mention a few, the ISO 8251 abrasive wheel wear test apparatus, the ASTM G99 pin-on-disc apparatus and the ASTM G65 rubber wheel apparatus are widely used to rank different wear part materials [2]. For instance, the standard ASTM G65 is designed to use Ottawa sand as the only abrasive, thus limiting its application to industrial situations. Due to the circular rubber wheel and the flat test specimen, the ASTM G65 struggles with a continuously increasing wear surface area during the test itself: At the beginning of a test cycle, the contact area is defined by few abrasive particles but this changes rapidly because the removal of material forms a concave bed. A soft wear part material will form a large concave area and a hard material the opposite. Consequently, the specimen undergoes continuously changing pressures (Fig. 1). The arrows in Fig. 1 explain the progress of each wear cycle; beginning at high pressures due to a very small contact area and then decreasing the pressure as the area expands. The ASTM G99 is represented by the horizontal areas: ASTM G99 is not strictly defined and thus pressures, speeds, abrasives and other parameters can be chosen by the operator. The figure shows a situation where the pin moves from the center to the periphery like a spiral. Hence the pressure is constant because the area of the pin is constant but the arrows show that the speed is increased continually during each wear cycle.

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As a result, most wear test apparatus are sufficient for ranking similar wear part materials with similar microstructures. However, there is a need to expand the range and number of parameters involved in industrial wear situations.

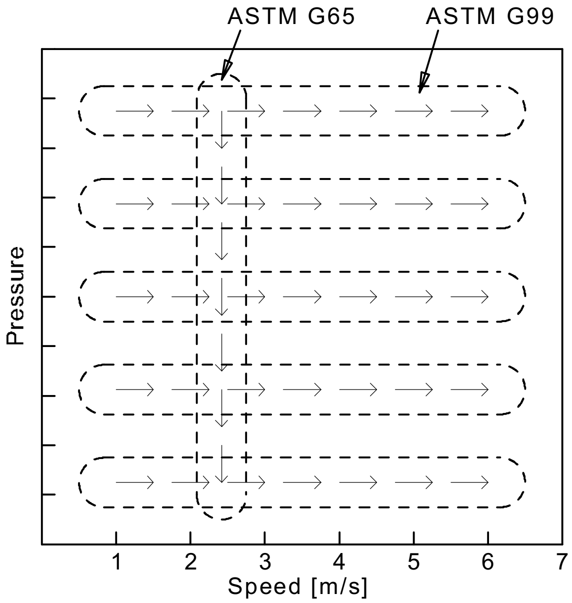


Figure 1: General graphical representation of where the ASTM G65 and ASTM G99 is located in a wear map. ASTM G65 is represented by the vertical area and centered at 2.4 m/s as outlined in the standard. Otherwise both standards do not require any additional fixed operating conditions, thus it is not possible to show the exact pressures and speeds of the specimens.

In the minerals industry, it is common to process heterogenous mixtures at the same time, which causes complicated and sometimes accelerated wear situations. Unless ordinary construction steel is used, soft minerals will not contribute to wear at all due to their low hardness. Due to its average hardness of 1200 HV, quartz is one of the main constituents that cause severe wear.

The focus of this paper will be on abrasion-resistant wear part material (21988/JN/HBW555XCr21) used in high stress abrasion comminution equipment such as vertical roller mills (VRM). 21988/JN/HBW555XCr21 is similar to Ni-Hard 4 [10]. This material is compared with a construction steel (S235) and a commonly known wear plate material (Hardox 400).

1.1. Wear maps

In this context, a wear map is a 2D or 3D graphical representation of a series of individual wear tests made on the same type of wear apparatus (Fig. 13, 14, 15). The graphical representation shown either as isographs or height profiles gives a clear view of the wear performance at various settings. So far, most work in the field of wear maps has been completed in metal-metal dry sliding situations without any abrasives [3].

These types of wear map expand traditional wear performance and illustrate the severity of wear as a function of speed and pressure. Using that information makes it possible to design equipment that is exposed to less wear.

Especially in the minerals industry, it is worthwhile constructing wear maps to choose the right wear part material for the right application. A wear map may reveal that a perfect abrasion resistant material suffers decreased wear resistance if the operating conditions are changed. This explains why most standard wear apparatus provide a very limited view of a particular wear situation.

The main drawback of traditional wear apparatus is the application of low and uncontrollable pressures. The primary source for reliable wear maps is a set-up where the pressure is constant at all times, but unfortunately most wear test machines struggle with that criterion.

To construct the wear map it is extremely important to be able to continuously reproduce each wear cycle. A wear apparatus has been developed for that purpose. The apparatus allows changing both velocity, pressure and abrasive, thus constructing highly informative wear maps.

1.2. Vertical roller mills

In the less abrasive cement industry (wear rates typically below 20 g/ton), vertical roller mills (VRMs) are slowly outperforming energy intensive ball mills because they offer various advantages such as a 40% reduction in power consumption (Fig. 2). VRMs have also gained popularity in the power generating industry for grinding coal used in burners.

A typical raw material VRM will receive an input feed size of approximately Ø100 mm and generate a final product size of approximately Ø90 μm. This large size reduction made possible by the internal closed circuit function of the VRM. However, due to the closed circuit, a multitude of internal circulations take place, mainly the grinding table and in the separator (Fig. 2). As a result of the circulations, the percentage of hard abrasive particles will quickly increase on the grinding table and reach a steady state. This accumulation is due to the mineralogical properties (e.g. grindability) of the rocks.

The abrasion resistant wear part material used in VRMs is exposed to pressures far above the pressures applied in well known wear testing equipment. Pressure sensitive strain gauges built into the grinding table of a VRM show peak pressures well above 200 MPa [4]. Consequently, theses type of mills operate in the high stress abrasion mode. The pressures are so intense that standardized wear test apparatus have difficulty fully imitating such conditions.

2. The micro wear tester

Basically, the micro wear tester (MWT) is a modified metallographic polishing machine which is a commonly

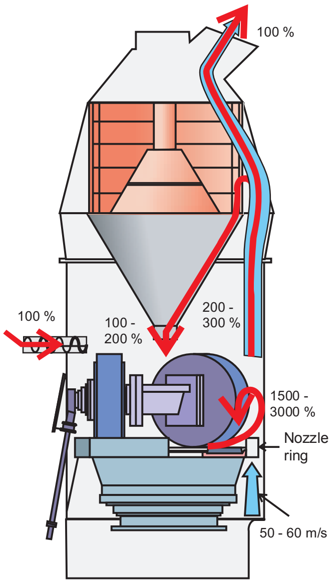


Figure 2: The VRM is made up of a rotating circular table with 2-4 rollers on top. Material is fed into the area between the table and the rollers, and due to frictional forces the rollers rotate around their fixed axis. Furthermore, a complicated circulation of material (red arrows) is dominating the performance of a VRM. Note how 100% of material enters the mill and 100% leaves the mill; the other percentages indicate the relative circulation factors. Hot air (blue arrows) at approx. $200°C$ and high speeds is drying the minerals and lifting the particle up to the separator. On top of the VRM, a dynamic separator (orange) will split the material stream in a final product and a separator returns product which will be size reduce once more. Additionally, various other complicated internal circulations are present.

known apparatus in metallographic laboratories (Fig. 3 and 5).

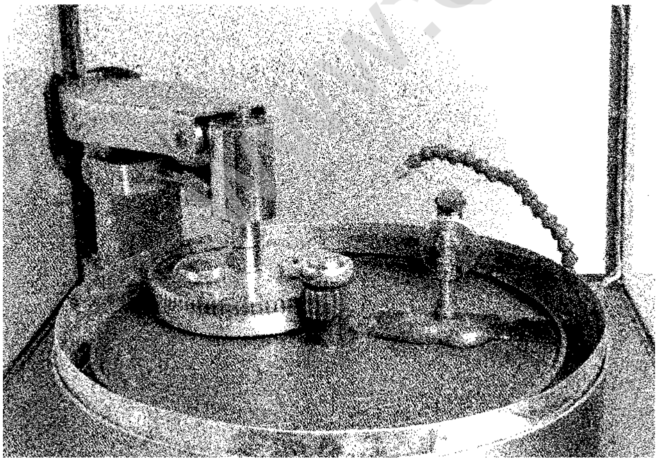


Figure 3: The main components comprising the MWT. A functional illustration is shown in Fig. 5.

Unlike many wear test apparatus that have difficulty keeping a constant area of interaction (section 1), the MWT design ensures that the force is proportional to the pressure at any time during the test cycle. The MWT can test all types of wear part materials such as metals, ceramics, polymers etc. The MWT generates a defined isotropic (grinding randomly in all directions) wear pattern (Fig. 4 and 6). By comparison, the ASTM G65 and G99 only imitate anisotropic wear. The center pinion is driven independent of the large circular disc and is connected to the sample holder by a geared tooth mechanism. The sample holder is connected to an hydraulic lever by a special ball joint: The ball joint ensures that each sample in the sample holder makes full contact with the disc. The isotropic pattern is the normal set-up when testing wear part materials using the MWT (Fig. 4).

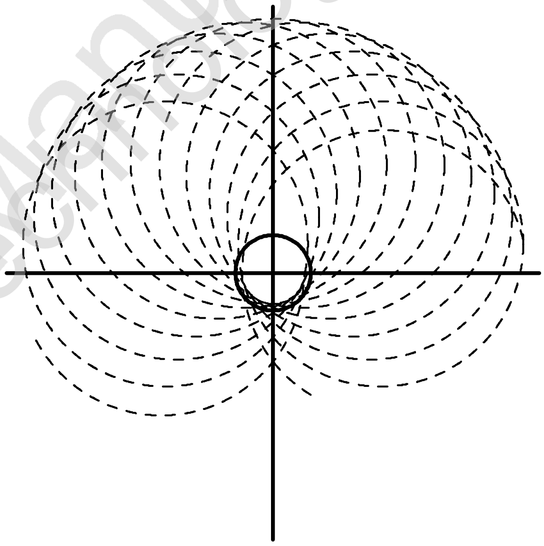


Figure 4: The pattern of a sample specimen when operated in isotropic mode.

Contrary to the standard polishing machine, the MWT is designed to use different abrasives in the form of loose particles. Additionally, the machine is designed to operate at optional speeds and pressures chosen by the operator (Table 1). The result from each experiment, the abrasion index, has an accuracy of +/- 8% based on a series of equal experiments at constant operating conditions:

$$A_i(p,v) = \frac{M_N 10^4}{ANv(2.38+\rho_s)}[\mu m/m] \qquad (1)$$

where the A_i is the abrasion index as a function of p (pressure) and v (speed). M_N is the total weight loss after N periods. A is the area of the samples, ρ_s is the density of the wear part material and 2.38 defines a factor necessary to describe the area relationship between the wear part and the epoxy resin (Section 4 for further discussion).

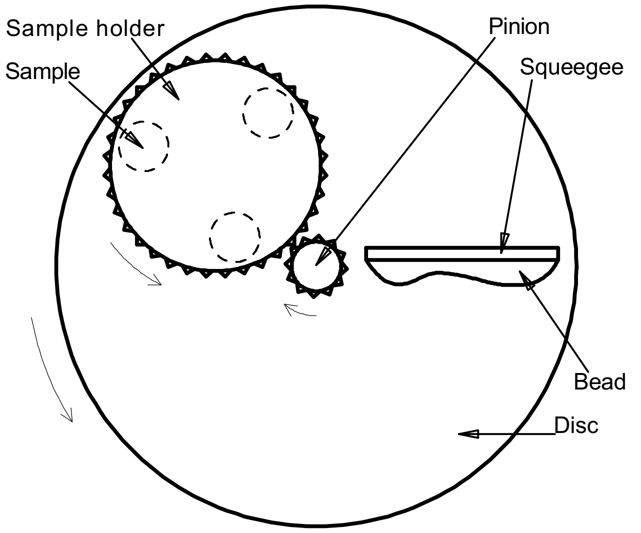


Figure 5: The main functional components of the MWT. A fixed squeegee keeps a bead of slurry abrasive on the circular disc. The pinion drives the sample holder by means of the fixed gear set-up to ensure an isotropic pattern.

epoxy resin).

On a standard basis, each sample will experience abrasives for 20 seconds at a predetermined pressure and speed. Experience shows that 20 seconds is a satisfactory setting as it avoids uncertainties from small distances (short test cycles) and reduces the amount of reused material at long distances (long test cycles). After each cycle, the samples are weighed to measure the weight loss, and the weight loss is converted to a height loss. Thus, the MWT abrasion index has the dimensionless expression [μm/m]. Eq. 1 shows that if N=20 sec the unit will become [μm/20m]. This unit will be used throughout the study. Even though the abrasive index measures the wear rate, it is a defined measure of wear rate and hence it does not explain the exact wear rate found in industrial equipment.

Property	Range	Accuracy
Abrasion index [μm/20 m]	0-100	0.08*
Sample size [mm^2]	100	+/- 0.01
Duration [s]	20	+/- 1
Abrasive loss [gr]	0-10	+/- 0.0001
Speed [m/s]	1-7	+/- 0.1
Pressure [kPa]	70-1400	+/- 1
Abrasive cut size [μm]	90	0.05*

Table 1: Specifications for the MWT. * = 1 standard deviation. Industrial VRMs operate at approx. 6 m/s and hence a valid range is automatically chosen.

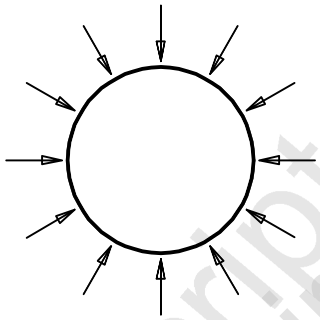


Figure 6: Isotropic wear situation on a circular specimen.

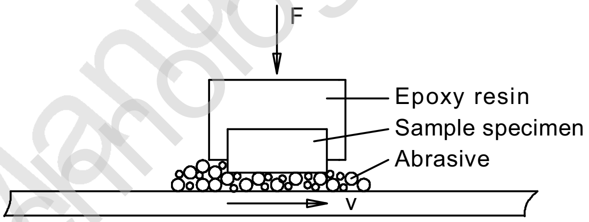


Figure 7: Main function of the MWT: Particles are drawn underneath the sample at a predetermined speed and force.

Depending on frictional forces, operating the MWT at 1000-1400 kPa and 7 m/s requires an electric motor of approximately 1.8 kW. Still, in an industrial VRM the average peak pressures are roughly 200 times larger and hence the MWT would theoretically require a 200 kW electric motor to operate at these pressures. In section 3 it is shown that the MWT can imitate and reach the point of plastic deformation seen in micrographs.

The main advantage and applications of the MWT can be summed up as follows: Industrial equipment may suffer from severe wear rates and may be very expensive to replace. Predicting an alternative wear part material based on past experience can be highly risky and have disastrous consequences. To avoid doubt, the best option is an inexpensive and practical wear map.

2.1. MWT operation

A particulate industrial sample (dry or wet) is analyzed to determine the constituents that are present. Each constituent is ranked on the hardness scale and their individual particle size distributions are determined. Based on the hardness ratios between minerals and wear part materials, the minerals with the greatest impact on wear are chosen for a mixture. In most cases a 100% quartz mixture is chosen, but mixtures of different hard abrasives (garnet, flint, corundum, carborundum) are also common. A range of promising wear part materials are tested against the specific abrasive to determine any reduction or increase in wear rate. The abrasive particulate material used in the MWT has a specification of 35%+90 μm with all particles being less than 200 μm (Fig. 11). This PSD is obtained by size reducing a coarse sample in a disc mill. The sharpness of the abrasives is not taken into consideration, because it is a result of the mineralogy, cleavage planes, impurities etc alone, and cannot be controlled in industrial applications anyhow.

Various references [7] show that particles in the indicated range will result in the most severe wear rates, and fortunately this range is also the optimum for the operation of the MWT: If the particles become excessive in size (above 200 μm), they will form a bead in front of the sample holder. The size between approximately 90 and 150 μm is the optimum balance between the amount of sharp edges penetrating into the metallic surface coupled with their physical size being able to remove the largest possible chip. The main purpose of the -90μm fraction is to support the +90μm particles during the test cycle.

The abrasive particles are mixed with 1,4-butandiol to make a thick slurry. 1,4-butandiol is an odorless chemical compound with a melting point of 20 °C. The chemical serves as a corrosion inhibitor to avoid contributions from tribo-corrosion [5]. The low vapor pressure at ambient temperatures will ensure that the slurry avoids drying out as a result of the heat generated during a wear cycle. The slurry will form a bead in front of a squeegee and the particles are kept on the rotating disc by means of the same (Fig. 3 and 5). The squeegee continuously spreads out the abrasive particles, ensuring that the entire disc is fully covered during the test. Due to its nature, the bead ensures that new, fresh particles are fed to the sample holder while used particles are absorbed in the bead or thrown off the disc by centrifugal forces. This regenerating process cannot go on forever so the entire bead in front of the squeegee needs to be changed to a fresh slurry mixture after each cycle.

In a standard raw material VRM (for cement raw mixes) all particles have to pass the 90 μm cut size and the MWT therefore has an ideal design for testing under these conditions. A multitude of studies [8] show that smaller fractions will remain in the mill for an extended time due to less mineral flaws and ineffective fragmentation conditions. This explains why the MWT provides a strong indication of the wear rates occurring inside the VRM.

It is worthwhile noting that the MWT is a genuine laboratory test machine which is able to determine the significance of using different wear part materials with different abrasives. The MWT cannot take into account if, in the industrial application, the abrasive becomes wet, is mixed with other materials, if the abrasives are larger than 200 μm or if the abrasives experience fragmentation etc.

3. Hertz pressure

The abrasive particles typically show sharp edges and a conservative estimate of the radius of curvature results in values of approximately 5 μm. This is based on the assumption that completely sharp edges are non-existing and that a particle is slightly rounded off during the mixing and separation processes. Furthermore the sharpness of the particles remains unchanged even after processing in the MWT (Fig. 8).

It is necessary to distinguish between the pressure applied by the MWT resulting in an average surface pressure (apparent area of contact) and the pressure exerted by each single apex in contact (real area of contact). When operating the MWT, a very narrow particle distribution is chosen. Thus, even small operating pressures will exert very intense apex pressures (Eq. 6).

As mentioned, localized average pressures exceeding 200 MPa in industrial VRMs will result in both plastic deformation and micro cutting in the wear part material. To highlight the abrasive mechanism in an abrasion resistant wear part material, a polished sample of 21988/JN/HBW555XCr21 was abraded with Al_2O_3 (2000 HV) grit paper instead of quartz (1200 HV) grit paper. Al_2O_3 will thereby expose the transition from the soft to the hard phases (Fig. 9).

To verify the application of the MWT, it is interesting to determine whether this high stress abrasion is initiated at the pressures present. Fatigue mechanisms are not considered due to the short time of each cycle. The Hertz pressures form the basis for this approach and a very conservative estimate is desired to determine the pressure setting at which the particles start to form lasting indentations. Possible indentations will ensure that a metal chip can be removed in the MWT. Hertz derived that the maximum shear force occurs approximately 0.5a below the surface, where a indicates the radius of the circular indentation area (Fig. 10). From Tresca the yield criterion is fulfilled, if [9]:

$$2\tau_{max} = Y \tag{2}$$

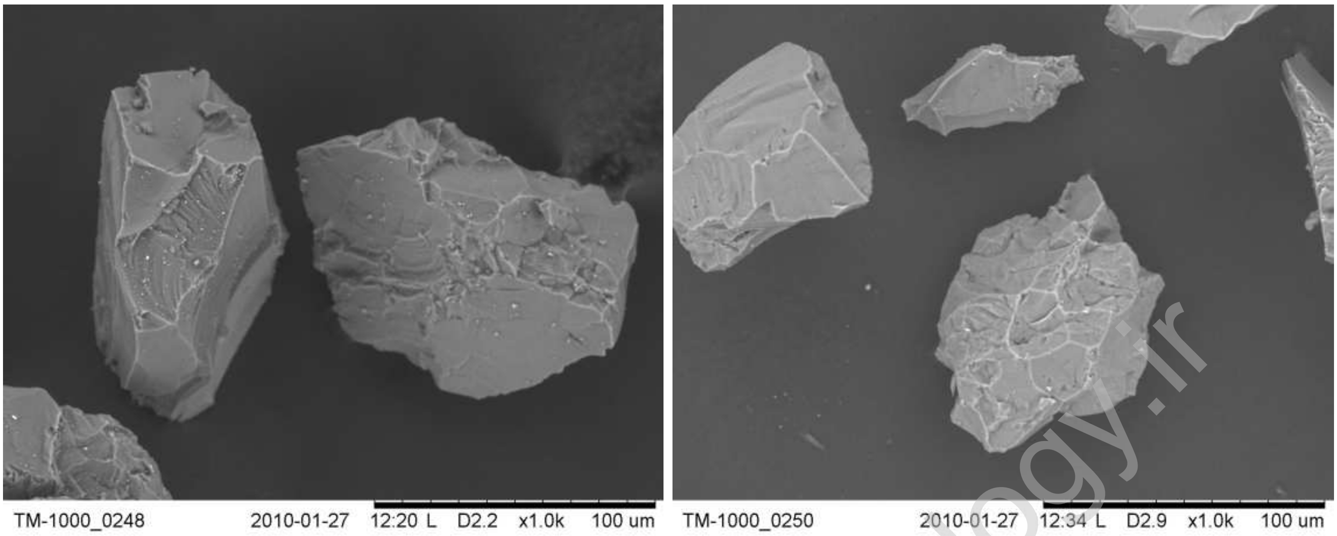
which states that yielding occurs if the yield strength (Y) equals twice the shear strength (τ_{max}). According to German Standard DIN 1695 [11], high chromium white cast irons will have no elongation before rupture. Hence yield strength and tensile strength are equal (Table 2).

$$\tau_{max} = 0,31\sigma_{c,max} \tag{3}$$

$$0.62\sigma_{c,max} = Y \tag{4}$$

$$\sigma_{c,max} = 1.61Y \tag{5}$$

When $\nu = 0.3$, the Hertz derivation shows, that the maximum shear strength (τ_{max}) equals approximately one third of the maximum Hertz contact pressure ($\sigma_{c,max}$). When the maximum Hertz contact pressure reaches 1.61 times the tensile strength of the white cast iron, yielding



(a) Quartz particles before processing in the MWT.

(b) Quartz particles after processing in the MWT.

Figure 8: SEM micrographs of quartz particles used in the MWT. Note how the sharpness remains unchanged after processing.

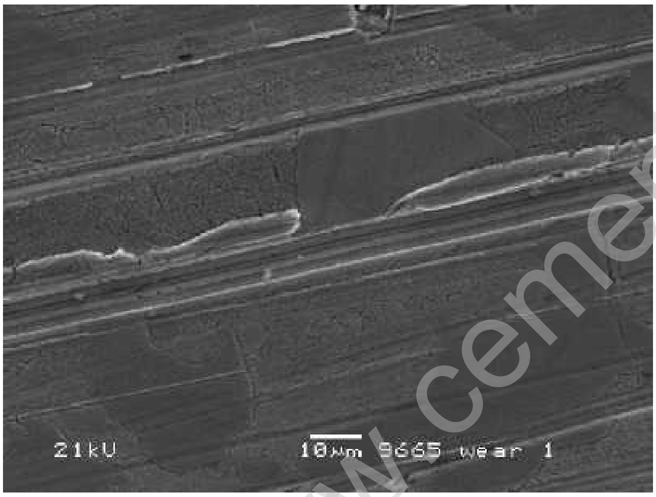


Figure 9: SEM micrograph of an abraded 21988/JN/HBW555XCr21 surface. The abrasive particles (Al_2O_3) are approx. Ø120 μm. Note plastic deformation and cutting of the soft matrix (700 HV).

is expected at 0.48a below the surface and thus increased chance of subsurface fatigue.

On the wear part surface, three principal stresses are considered and applying Mohr's circle gives [9]:

$$\sigma_{c,max} = 5Y \tag{6}$$

Thus, when the hertzian contact pressure exceeds 5 times the yield strength (or tensile strength for white cast irons) plastic deformations will occur at the surface.

$$\frac{1}{E_E} = \frac{1-\nu_s^2}{E_s} + \frac{1-\nu_p^2}{E_p} \tag{7}$$

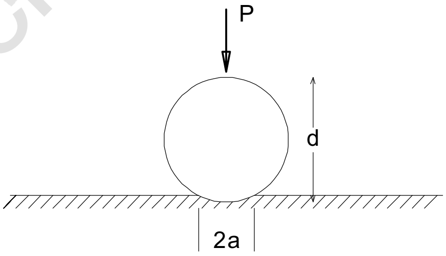


Figure 10: A simplified quartz particle is pressing against the flat metal surface. The maximum shear force occurs approx. 0.48a below the surface.

$$\sigma_{c,max} = \sqrt[3]{\frac{6E_E^2 P}{\pi^3 r^2}} \tag{8}$$

The above equations are the classical Hertz expressions for the situation shown in Fig. 10. E_E is the modified elastic modulus, ν is the poisson ratio for the particle and surface respectively, E_x is the elastic modulus for the particle and surface respectively, P is the applied total force and r is the radius of the apex in contact. Solving for P gives the minimum force for yielding and thus obtaining plastic surface deformation:

$$P = \frac{\pi^3 r^2 5Y}{6E_E^2} \tag{9}$$

Using the properties in Table 2 results in a critical force of P=2.38 10^{-3} N for each single particle (using a radius of curvature of 5 μm). An average particle size of approximately 63 μm is determined by analyzing the quartz particle size distribution (Fig. 11) used in the MWT test, whereby it is calculated how much space each particle takes up. As a rough estimate it is assumed that the particles are arranged side by side, each particle covering an area of 63x63μm.

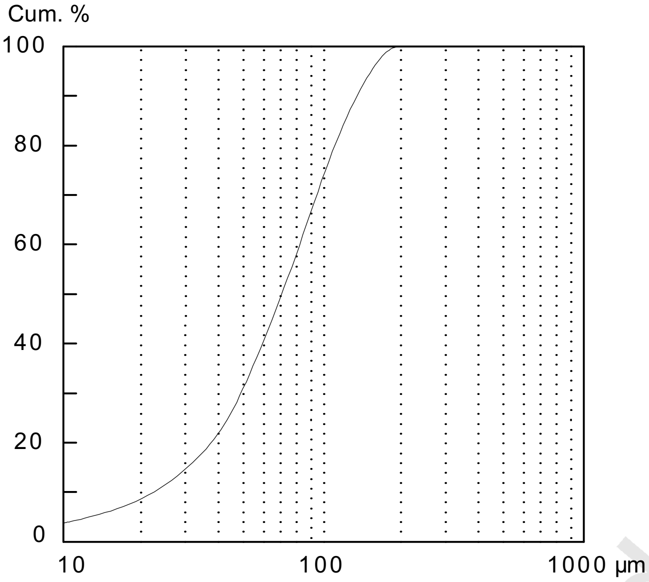


Figure 11: Particle size distribution of quartz used in the MWT.

$$p = \frac{P}{A} \tag{10}$$

Plugging in the critical force (P) and the area taken up by one single particle (A) results in an average apparatus pressure of approximately 760 kPa. Due to the particle radius of curvature this pressure will result in an approximate surface apex pressure of 5Y or 3750 MPa. Consequently, it can be concluded that the MWT easily reaches pressures which will deform the surface similar to hardness indentations (Table 1).

Property	White cast iron	Quartz
Elastic modulus [GPa]	172	70
Poisson ratio [-]	0.3	0.25
Tensile strength [MPa]	750	48

Table 2: Mechanical properties. The white cast iron elastic modulus is an average [11]. Due to difficulties measuring tensile strengths of cast materials, the average tensile strength has been chosen [12], [11].

4. Experimental

In this work 21988/JN/HBW555XCr21, S235 and Hardox 400 have been analyzed and compared (Table 3).

21988/JN/HBW555XCr21 is within the group of high chromium white cast irons known to result in better wear protection compared to Ni-Hard 4. Hardox 400 is marketed as an abrasion resistant wear part material and is used extensively in many applications where equipment is in contact with abrasive granular material. S235 also known as St-37 is the most commonly known construction steel.

Three metallic cubes of the same material with a cross sectional surface area of 1 cm^2 are cold molded in a standard metallographic epoxy resin. The epoxy resin will always wear faster than the sample itself and this feature ensures that the abrasive particles are fed continuously underneath the metallic samples without forming any beads (Fig. 7). The cured samples are mounted onto the sample holder and a series of initial cycles under constant operating conditions are carried out to form and imitate a worn surface. The correct roughness has been achieved once the weight loss under the same operating conditions has become constant. Speeds from 1 to 7 m/s and pressures from 100-1000 kPa are chosen.

For typical cement raw mixes, quartz or chert/flint is the hardest mineral and the selection of quartz as the abrasive will cover approximately 95% of all cement raw mixes. A coarse fraction of quartz was ground in a disc mill and sieved to 35%+90 μm -200μm with an accuracy of +/- 5% on the 90 μm cut size (Table 1).

From analyzing more than 50 raw mixes it can be concluded that the abrasive particles are sharp edged in nearly all cases. Precipitated abrasives within limestones will always be sharp, but in a few cases eroded (round shaped) quartz might be added manually to raw mixes. However, such particles are typically above 1 mm in particle size. As a result of the comminution process, these particles are quickly reduced in size by fragmentation and shattering, whereby sharp particles are formed.

After each cycle (20 m) at a predefined pressure and velocity, the samples are removed, cleaned in a ultrasonic bath (ethanol, 1 min) and dried in an electric oven (80 °C for 7 min). The weight loss of all three samples is measured and averaged using a digital balance with an accuracy of 0.1 g. The weight loss is recalculated to a height loss thereby making it possible to evaluate materials at different densities. Consequently, the abrasion index is equivalent to the height loss in μm for every 20 meters of abrasion.

A full wear map typically requires 40 single wear tests, but experience can greatly reduce the effort by interpreting the results in advance.

The MWT operates at 20 °C which is a few hundred degrees below the normal industrial application (typically 200 °C in an industrial VRM) [4]. However, various studies show that wear behavior will not change noticeably within that temperature range, hence from a temperature point of view, the results are reliable [13].

	C	Mn	Si	Cr	Mo	Ni	Cu	P	S	B
21988/JN/HBW555XCr21	2.7	<1	<1	15	1	1.4	<1.5	-	-	-
Hardox 400	0.32	1.6	0.7	1.4	0.6	1.5	-	0.025	0.01	0.04
S235	0.2	<1.4	-	-	-	-	-	<0.045	<0.045	-

Table 3: Chemical compositions of 21988/JN/HBW555XCr21 (white cast iron), Hardox 400 (wear resistant plate) and S235 (a conventional construction steel).

5. Discussion

A wear map gives a sophisticated insight to the wear dynamics and interactions between abrasive particles and wear part materials. The single most important information from wear maps lies in the fact that the classical wear approach, in which a simple hardness ratio is considered, may yield results that differ from the results found in reality: Wear is strongly dependent on a multitude of factors which cannot be simplified by using the bulk macro hardness of the interacting materials alone.

A wear map consists of several topographical height curves and for simplicity a 2D representation has been selected. Each curve represents an abrasive wear index with values plotted on the map.

Considering the wear map shown in Fig. 13: The abscissa represents the velocity and the ordinate represents the pressure. A wear situation will always consist of two vectors; a force vector and a velocity vector, both resulting in one single resultant vector (Fig. 16). Analyzing the wear map close to the ordinate will reveal how the abrasive/metal couple behaves in a lapping mode as the pressure is very low. Analyzing the wear map close to the abscissa will reveal how the abrasive/metal couple behaves at high loads similar to 2-body abrasion (Fig. 16). Beginning at the abscissa, everything in between is a slow transition from 2-body abrasion (cutting) to 3-body abrasion (rolling) to lapping (Fig. 17).

5.1. Erosion vs lapping

It is necessary to make a distinction between the lapping and erosion mechanism and their relation to the MWT:

- Erosion can be characterized as a mass (particle) having a velocity component parallel and perpendicular to a surface. A large velocity component parallel to the surface corresponds to shallow angle erosion as outlined in Fig. 16. The classical erosion approach is concerned with a bouncing off of abrasive particles when they strike the surface. This behavior (i.e. anisotropic wear) cannot be imitated on the MWT.

- Like erosion, lapping is similar in its behavior as the mechanism is based on small pressures (small perpendicular vector) and high speeds (large parallel vector). However, in the lapping process the abrasive particles are kept close to the surface all the time and thus the MWT is better at imitating this mechanism. Compared to erosion, lapping necessarily operates at somewhat higher pressures, which is inevitable due to the weight of the sample holder itself.

It is worthwhile noting that erosion and lapping have similarities and their mechanisms cover each other, in some cases depending on the operating conditions.

5.2. Pressure independence

Fortunately, most wear maps show an interesting wear phenomenon: Above approximately 1000-1500 kPa most abrasive/wear part combinations indicate that wear becomes independent of pressure and speed. In other words, the wear will not continue to increase above 1000-1500 kPa. At the onset of plastic deformation, the abrasive will remove a chip and deform the wear part material relative to the applied pressure. At elevated pressures (above 1000 kPa) the abrasives can no longer be fixed in the wear bed. Thet show a tendency of "jumping" out of the grooves and move towards a rolling mode (Fig. 9).

5.3. 21988/JN/HBW555XCr21

The 21988/JN/HBW555XCr21 wear map shows an intuitive behaviour (Fig. 13): The wear rate is pressure dependent and essentially velocity independent. At large pressures, the wear rate seems to level out as expected. At low pressures, the wear rate increases at high velocities. Hard abrasive such as quartz particles will introduce both micro cutting and plastic deformation (Fig. 9 and 12).

5.4. S235

The S235 wear map shows an interesting topography with an abnormal behavior (Fig. 14): S235 is highly pressure and velocity dependent at low speeds. Thus, minor changes in industrial operating conditions could greatly reduce the wear rate. Furthermore, at 5.5 m/s there is an isolated "island" with increased wear. At the highest pressure (>1000 kPa) and speeds (>5 m/s), the wear rate drops off again, making S235 a challenging substitute for 21988/JN/HBW555XCr21. Unlike most wear parts, S235 does not show pressure independent wear behavior at low speeds.

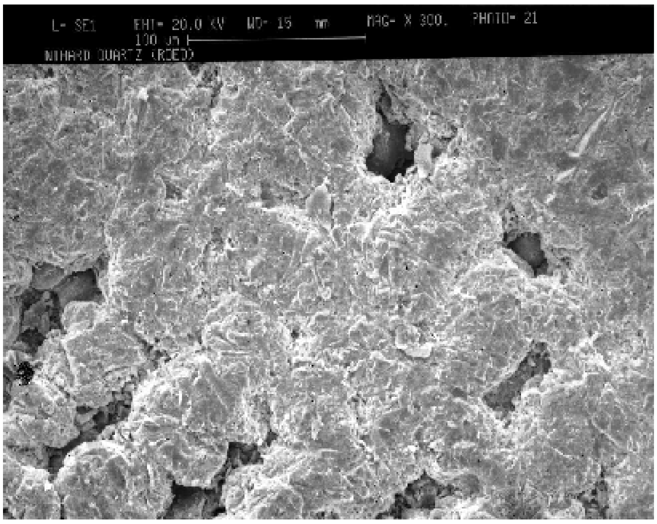


Figure 12: SEM micrograph of 21988/JN/HBW555XCr21 which has experienced quartz wear in the MWT. Approx. 90% of the area is covered by chromium carbides. It is clearly seen how the soft matrix is worn faster compared to the hard phases.

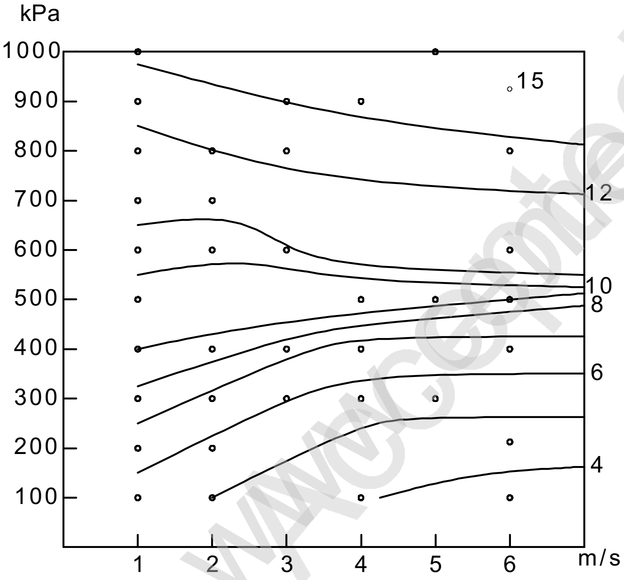


Figure 13: 21988/JN/HBW555XCr21 wear map. Abrasive: Quartz with a hardness of approx. 1200 HV. The abrasion index ranges from 4 to 15 μm/20m. The single abrasive index measurement (15 μm/20m) found in the wear map indicates that the system has reached a plateau in the adjoining areas. The dots indicate measurements. The bulk hardness of 21988/JN/HBW555XCr21 is approx. 700 HV.

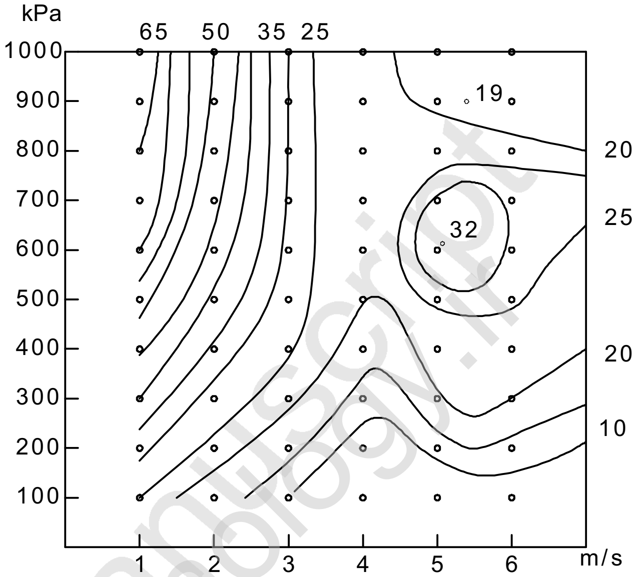


Figure 14: S235 wear map. Abrasive: Quartz with a hardness of approx. 1200 HV. The abrasion index ranges from 10 to 65 μm/20m. The single abrasive index measurement (19 and 32 μm/20m) found in the wear map indicates that the system has reached a plateau in the adjoining areas. Note the highly sensitive behavior. Due to the complicated isographs it was necessary to increase the number of measurements. The hardness of S235 is approx. 150 HV.

5.5. Hardox 400

The Hardox 400 wear map shows a wear behavior similar to 21988/JN/HBW555XCr21, except that the wear rate is approximately twice as pressure dependent as 21988/JN/HBW555XCr21. At high speeds and high pressures, the Hardox 400 wear rate will be twice as large as that of 21988/JN/HBW555XCr21. Even though Hardox 400 is marketed as an abrasion resistant wear part material, it is worthwhile noting its forces: At low speeds, the Hardox 400 performs twice as well as S235. But at high speeds the S235 outperforms Hardox 400.

6. Simplified wear approach

By analyzing the wear maps it is observed that a wear map will imitate both erosion/lapping and heavy abrasion due to its force acting vectors. Any particle-metal wear situation can be simplified by considering a force vector perpendicular to the surface and a velocity vector parallel to the surface. For instance, in a high speed erosion situation, the angled velocity will contribute to a force vector (small) perpendicular to the surface and a speed vector (large) parallel to the surface (Fig. 16).

In a classical wear situation a distinction is made between rolling particles and fixed particles. In one extreme situation, a particle will only indent the surface, for instance in a crushing process. In the other extreme situation, a particle will only roll on top of the wear part surface because the perpendicular forces are insufficient to cause any severe micro cuts (high speed erosion at shallow angles or lapping). However in most cases, a wear situation

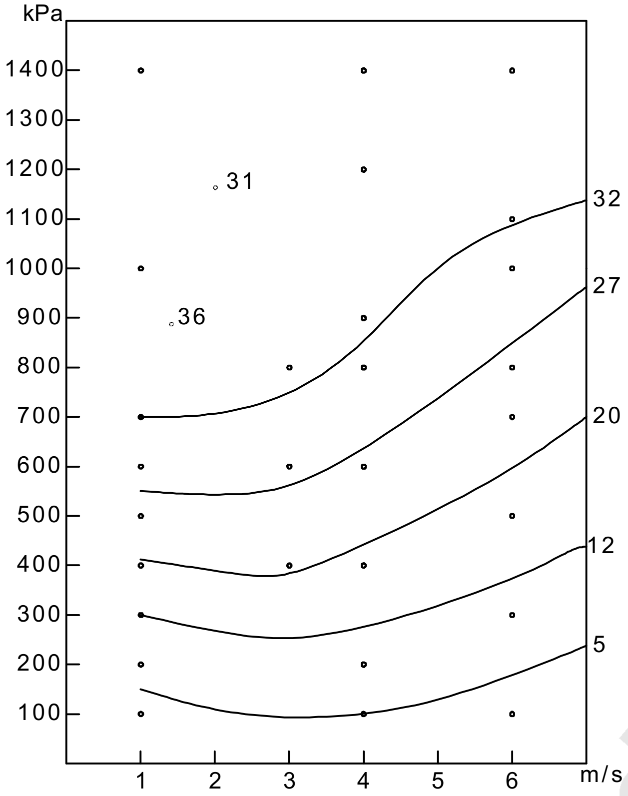


Figure 15: Hardox 400 wear map. Abrasive: Quartz (1200 HV). Wear part material: Hardox 400 (400 HV). The abrasion index ranges from 5 to 36 $\mu m/20$m. The single abrasive index measurement (31 and 36 $\mu m/20$m) observed in the wear map indicates that the system has reached a plateau in the adjoining areas. The dots indicate measurements.

is a mixture of wear mechanisms with different intensities. Unless one of the wear mechanisms is really dominant, it is difficult to assess the mechanism which will need further attention (Fig. 17).

7. Conclusion

Using the Micro Wear Tester (MWT), it is possible to compare and rank different wear part materials. The MWT used in this work has proved a reliable wear test machine producing repeatedly consistent results at various settings. It would not have been possible to construct such wear maps using the ASTM G65/G99 for the reason that they cannot keep vital operating parameters unchanged during a wear cycle.

Due to the approximately evenly distributed horizontal curves, it is no advantage to change the velocities for the high chromium abrasion resistant 21988/JN/HBW555XCr21. This key information is essential when designing new comminution equipment using

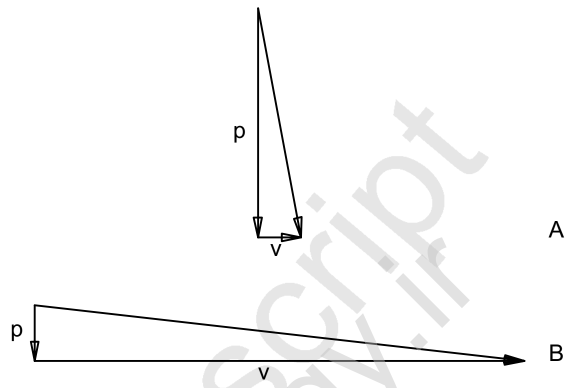


Figure 16: Vectors showing forces on a particle during abrasion/lapping. A: Extensive 2-body wear situation with a high load and slow movement. B: Lapping wear situation with small load and fast movement.

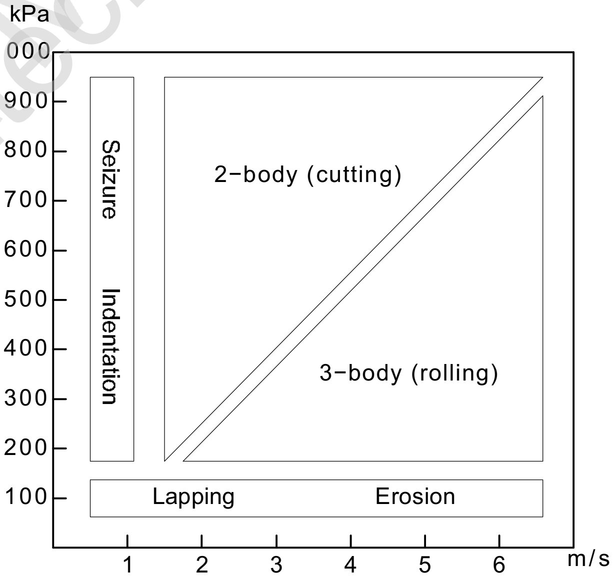


Figure 17: The wear map shows where different wear mechanisms might be found depending on speed and pressure. This map serves as a rule of thumb only.

21988/JN/HBW555XCr21 as a wear part material. Additionally, the wear rate reaches a maximum at 1000-1500 kPa showing that increasing or decreasing the pressures in an industrial VRM will not change the already existing wear rates. This key information is also vital when designing new high performance comminution equipment.

Even though 21988/JN/HBW555XCr21 is an advanced wear part material, it only has its major strength in the low speed region: Due to its horizontal topographical wear lines it only marginally outperforms S235 and Hardox 400. Depending on the concentration of quartz in the processed material, the Hardox 400 and S235 may be a low-cost and interesting substitute for expensive high chromium wear parts.

The wear maps, and especially that of S235, may show surprising and confusing behaviors. This explains how sensitively wear parts react when facing various operating conditions and abrasives. However, it is beyond the scope of this paper to precisely identify the metal removal mechanisms in each region of a wear map.

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