Abrasive wear of ceramic wear protection at ambient and high temperatures

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Abstract. Ceramic wear protection is often applied in abrasive conditions due to their excellent wear resistance. This is especially necessary in heavy industries conveying large amounts of raw materials, e.g. in steel industry. Some plants also require material transport at high temperatures and velocities, making the need of temperature stable and abrasion resistant wear protection necessary. Various types and wear behaviour of ceramic protection are known. Hence, the goal of this study is to identify the best suitable ceramic materials for abrasive conditions in harsh environments at temperatures up to 950°C and severe thermal gradients. Chamottes, known for their excellent thermal shock resistance are compared to high abrasion resistant ceramic wear tiles and a cost efficient cement-bounded hard compound. Testing was done under high-stress three-body abrasion regime with a modified ASTM G65 apparatus enabling for investigations up to ~950°C. Thereto heated abrasive is introduced into the wear track and also preheated ceramic samples were used and compared to ambient temperature experiments. Results indicate a significant temperature influence on chamottes and the hard compound. While the chamottes benefit from temperature increase, the cement-bounded hard compound showed its limitation at abrasive temperatures of 950°C. The high abrasion resistant wear tiles represented the materials with the best wear resistance and less temperature influence in the investigated range.

1. Introduction

1.1. Application: cokery

Coke is produced from coal in the cokery. The hard coal is heated to ~1260°C in low oxygen atmosphere in evacuated chambers for ~24 hours. After the coking process the coke is pressed out from the chamber onto the coke quenching car. To prevent it from burning down, it is quenched with water. Afterwards the coke slides onto the coke wharf at temperatures of ~120-150°C. Sometimes there are hot spots of unquenched coke inside the pile, which reach ~650-750°C. These burning spots are not treated and usually extinguish before the coke gets transported further on a rubber conveyor belt. During windy weather conditions this initial burning spots can spread to local fire on the coke wharf, destroying the coke and causing high thermal stress on the coke wharf. In such cases manual water quenching is conducted. After cooling down the coke is removed by a plough onto a conveyor belt for further transportation. The surface temperature on the coke wharf is quickly dropping to environmental temperature after exposure to ambient conditions. Hence, thermal shock of the wharf flooring takes
place and strains the flooring out of ceramic plates. The tiles get cracks and may start chipping or breaking into pieces. Besides thermal stress, high wear loss is caused by the abrasive coke. The mechanical load imparted by the coke depends on the slope of the wharf (~30-45°), with a bulk density of ~0.5 t/m² a surface load of ~0.24 t/m² is applied on the coke wharf. Hence, the static mechanical load is relatively small compared to the thermal and abrasive load. It is therefore neglected in the following investigation. A third component which stresses the applied materials in the coke wharf is chemical attack of corrosive elements in the surrounding environment. After quenching the coke, quenching cars still contain a significant amount of quenching water which is spread onto the coke wharf. This water contains corrosive components from the coke, e.g. Ca, Cl, SO₄, NO₃. [1,2] Nevertheless, this investigation does not deal with chemical effects.

1.2. Ceramics for wear protection
Abrasion is a serious issue in heavy industries like mining or steel production. Transportation of goods is a main reason for serious wear loss on plant components. In addition to the material costs for worn parts, production losses due to component failure must be kept in mind. In the face of worldwide competitive markets this is intolerable. To avoid excessive maintenance expenses wear protection is inevitable. Here, a beneficial material choice is very important in relation to the tribosystem’s properties of the application. The tribosystem describes the interplay of surfaces including lubrication, abrasive particles and wear particles as well as operating parameters such as load, velocity, temperature, etc. Conveying systems are so called open tribosystems, as no encapsulation is possible due the nature of the application. This normally renders the reduction of friction and wear by lubrication impossible. Hence, other forms of wear protection must be utilised in the form of wear resistant surfaces. [3-4]

To meet the application’s requirements, e.g. the wearing processes and the thermal shock, it is fundamental to investigate prospective materials and compare materials under close-to-real application conditions in the laboratory. Lab-scale tests must ensure the simulation of equal wear processes as taken from failure analysis and application measurements.

Non-metallic components or hard materials, e.g. ceramics have special properties, like high hardness, low density and high crack resistance. These properties are based on the chemical bond of ceramics and non-metallic components which are mostly covalent. These special properties entail excellent wear- protection characteristics in the field of abrasion. Almost all ceramics which are used in coke wharfs have a heterogeneous microstructure with large phases and a significant amount of porosity. [5]

Also the application’s temperature, especially the temperature of the medium is of high relevance in the wear process. Ceramics usually have a very high melting point and are stable over a wide temperature range. This does not hold true for many SiO₂-types, which feature transition points already below 600°C. This effect on high temperature wear is not yet fully scientifically established up to now. Certain ceramics or non-metallic components have a very good thermal shock resistance and temperature resistance. [5] In most cases the main problem is not the maximum temperature but rather the temperature fluctuations, so called thermal shock. This is also a crucial factor for coke wharfs.

The aim of this work is to cast light on the high temperature abrasive wear of commercially available ceramic wear protection for the thermal shock regime. In view of the application coke wharf the currently used chamotte should be compared with high wear resistant materials in a high temperature abrasive wear test. Results should point out temperature limitations of certain material groups and present wear mechanisms in order to aid material selection for the application.

2. Experimental
2.1. Materials
Different ceramic material groups can be applied for high temperature applications. Typical commercially available materials were chosen and are given in Table 1. Usually chamottes are used for highest temperatures. Chamottes are heterogeneous mineral aggregates, which are hydraulically pressed before the sintering process. The compositions of chamotte 1-3 is based on the binary system SiO₂-Al₂O₃. Whether the chamotte is fire resistant or chemically resistant depends on the Al₂O₃- and SiO₂-content.
The thermal shock resistance can be customised by the particle size distribution, the particle shape as well as the size and shape of pores.

For heavy wear regimes, especially in abrasive environments, very dense and hard ceramics are used, which usually impairs thermal shock resistance. The wear tiles 1-2 are based on the ternary system Al₂O₃-ZrO₂-SiO₂. By the addition of zirconium oxide the material reaches a harder structure. Wear tile 1 is prepared by a melt-cast process and wear tile 2 is made by vibro-casting followed by a subsequent sinter-process. Wear tile 2 thereby is optimised for high thermal shock resistance, like the chamottes, with additional high wear resistance.

The hard compound is a low cost wear lining material based on cement and hard material which can be applied by the customer as a monolithic liner on-site. In Table 1 the examined materials are listed and some basic physical properties are given.

**Table 1.** Chemical composition and main parameters of the materials investigated.

| Name          | Chamotte 1 | Chamotte 2 | Chamotte 3 | Wear tile 1 | Wear tile 2 | Hard compound |
|---------------|------------|------------|------------|--------------|--------------|---------------|
| Chemical composition | 69 % SiO₂ | 69 % SiO₂ | 46 % Al₂O₃ | 51 % Al₂O₃ | 82 % Al₂O₃ | 70 % Bauxite SiO₂ bal. |
| Density [g/cm³] | 2.2        | 2.2        | 2.3        | 3.5          | 3.2          | 2.7            |
| Compressive strength [MPa] | 150        | 150        | >110       | 400          | 400          | 135            |
| Max. application temperature | 1000°C | 1000°C | 1000°C | 1250°C | 1200°C |
| Thermal shock resistance | 300°C/h | 300°C/h | 150°C/h | 300°C/h | 300°C/h |

**Figure 1.** Microstructures of the materials investigated: a) Chamotte 1, b) Chamotte 2, c) Chamotte 3, d) Wear tile 1, e) Wear tile 2, f) Hard compound.
The microstructures as seen by optical microscopy (OM) are given in Figure 1. Chamottes 1-2 are of inhomogeneous microstructure with intergranular porosity. The grains are covered with a glassy phase. The grain size of the large SiO$_2$ grains is of several millimetres, with some smaller Al$_2$O$_3$ grains (white in Figure 1a, b). Chamotte 3 (Figure 1c) shows an inhomogeneous microstructure with significant inter- and intra-granular porosity. The Al$_2$O$_3$-content is higher compared to the chamottes 1-2, the grain size is smaller.

Wear tile 1 is of homogenous microstructure with shrinkage cavity in the centre of the tiles. The microstructure grows finer and less porous to the border of the tile, as can be seen in Figure 1d on the left side. Wear tile 2 is of inhomogeneous microstructure with a low percentage of porosity. Al$_2$O$_3$ hardphases are of large size of several millimetres (Figure 1e).

The hard compound is of heterogeneous microstructure with a hydraulic bounding. Particle size is of several millimetres as can be seen in Figure 1f.

2.2. Abrasive wear testing - High temperature continuous abrasion test.

The high temperature continuous abrasion test (HT-CAT) is based on a rotating wheel where a sample is pressed against (Figure 2a,b). An abrasive flow is introduced between the contacting bodies. To simulate a typical high temperature application, where hot abrasive is transported, the abrasive can be heated. Furthermore, to simulate also enhanced operation temperatures ceramic samples can be preheated and placed into the test rig with a certain start temperature. Reference tests were done with all components cold: i.e. sample, abrasive and wheel at room temperature (RT). This was compared to tests with heated abrasive (950°C) and cold sample and wheel, as well as preheated samples (750°C, 1 h), heated abrasive (950°C) and cold wheel.

A Hardox® 400 steel wheel is used as counter body ($ø$232$\times$12 mm, 360±12 HV10 [6]), the load was set to 10 N and the speed was 1 m/s. Two test distances were used, in order to cope with the different abrasion resistance of the materials investigated: 114 m for the chamottes and the hard compound and 664 m for the wear tiles. The longer tests were necessary for accurate determination of the wear loss. As abrasive fused silicon carbide (SiC) was used in broken condition (angular), which is much more temperature stable as commonly used quartz abrasive for similar tests (e.g. ASTM G65 [7]), but also the angularity and higher hardness entails higher abrasivity of the abrasive [cf. 8]. The abrasive is displayed in Figure 2c. For the two high temperature tests it was heated in a tube furnace to 950°C and introduced into the wear zone by a pipe system at a flow rate of 180 g/min. To guarantee high temperature
conditions the first 10 s of the abrasive flow are not used, after that the sample is brought into contact and begins to heat-up and abrade the sample.

Three samples were tested for each condition. Wear quantification was done via determination of the mass loss. The wear volume was than calculated via material’s density and set in correlation to the wear distance. This resulted in the wear rate [mm³/m]. Furthermore the temperature evolution during testing is recorded by thermal imaging. Thereto a FLIR® SC7600 MB infrared camera with InSb-detector was utilised. The sample’s surface is captured right after the end of the test and turn-off of the abrasive. Thereby the temperature distribution and maximum temperature of the wear track can be measured. An example is given in Figure 2d. After testing exemplarily wear tracks were also measured by OM and 3D topography measurements (Alicona® InfintFocus G5).

3. Results and discussion
3.1. Abrasive wear results
The results of the abrasive wear tests at the different temperature conditions are displayed in Figure 3a. The RT condition shows three wear levels: highest wear rates were measured at the chamottes with ~3.8-4.1 mm³/m, with no significant difference between the types 1-3; the second level of about half wear rate with 1.8 mm³/m features the cement bounded hard compound; lowest wear rates were found for the wear tile types. They both have ~0.6 mm³/m wear rate.

The enhanced temperature tests were done first with heated abrasive (950°C) and second with both heated, abrasive (950°C) and sample (750°C). Temperature influence is diverse for the materials investigated: chamottes and wear tiles show a decrease in wear rate with increasing temperature input. The hard compound on the other hand shows considerably increased wear rates.

![Figure 3. Results of HT-CAT testing: a) wear rates; b) temperature in the wear zone after testing.](image)
The wear tiles show the lowest wear rates in the temperature regime investigated. Like chamotte 1 already at heated abrasive testing the wear rate significantly decreases, and then stays constant also at preheated sample testing. Wear rates reduce from ~0.6 mm³/m for wear tile 1, RT testing, to ~0.45 mm³/m at HT testing. For wear tile 2 the reduction is from ~0.65 mm³/m to 0.55 mm³/m.

The cement bounded hard compound shows diverging behaviour. While featuring a relative good wear resistance at RT with ~1.8 mm³/m, this more than doubles at hot abrasive testing to ~3.8 mm³/m and reaches the same level as the chamottes. For further temperature increase with preheated sample, the wear rate peaks at to ~8.8 mm³/m, meaning a 4.8-fold wear increase compared to RT testing.

3.2. Temperature evolution
For exact reproduction of temperature conditions of the application, testing was not done at isothermal condition (e.g. in a closed oven), but with heated abrasive. This entails inhomogeneous temperature distribution, both locally and temporally: heating of the sample starts at the contact area with the abrasive (see Figure 2d), and the sample heats-up with time for the test configuration of cold sample and hot abrasive. Figure 3b shows the maximum temperature of the contact area (wear zone) directly after testing and turn-off of the heated abrasive flow. Temperature increase after 2 min testing time was lowest for the chamotte 1, resulting at ~175°C followed by the hard compound with ~280°C. The other values are close together in a range from 320-370°C. With the highest value for the wear tile 1. Here must be kept in mind, that the wear tiles were tested 4-times longer than the other materials and hence had more time to heat-up.

For experiments with preheated samples, the temperature lowers over the test duration: Samples are introduced into the test with ~750°C, gradually cooling down in the open environment. Opposite to this cooling stays the concomitant heating-up by the hot abrasive. This entails ~500°C after the test for the chamottes 1-2. Chamotte 3 shows ~690°C and seems to have a higher heat capacity. The wear tiles show lower temperature of 430-460°C, which most probably is the result of the higher test duration and thereby longer time for cooling-down. The hard compound shows ~530°C and lies between the temperature values of the chamottes.

3.3. Wear mechanisms
To elucidate the change of wear rates with temperature increase more detailed investigations of the wear zones are required. Therefore for each material and test condition the 3D-topgraphy was measured. A 5×5 mm section from the centre of the wear zone is displayed in Figure 4. Here the first line corresponds to the cold sample-cold abrasive condition, the second to cold sample-hot abrasive and the third to hot sample-hot abrasive. Furthermore, the roughness parameters according to ISO 25178 were derived from topography data (Table 2). Generally roughness levels are high after high-stress abrasion testing of the ceramics. Only the hard and more homogenous material wear tile 1 shows significantly lower roughness values, which is also clearly visible in the topography images in Figure 4. The roughness of chamotte types decreases at higher temperature testing, leading to the assumption that breakage, which induces high roughness, takes place less often.

| Table 2. Roughness parameters of the centre of the wear zone after wear testing at various conditions. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cold sample-cold abrasive       | Sa [µm]         | 44.9            | 60.6            | 75.7            | 17.6            |
|                                 | Sz [µm]         | 517.3           | 664.0           | 697.0           | 160.1           |
| Cold sample-hot abrasive        | Sa [µm]         | 39.2            | 53.4            | 52.1            | 19.4            |
|                                 | Sz [µm]         | 535.1           | 617.0           | 435.8           | 344.9           |
| Hot sample-hot abrasive         | Sa [µm]         | 41.3            | 35.8            | 34.2            | 23.1            |
|                                 | Sz [µm]         | 337.4           | 408.5           | 339.3           | 345.6           |

*Note: Sa = Arithmetic mean roughness, Sz = Statistical mean roughness.*
Figure 4. 3D-topography in the centre of the wear zone (5×5 mm) after the various test conditions.

The roughness of wear tile 1 stays in a similar range over the temperatures investigated. Sz values are not very meaningful for that material, as there are many small pores present. Wear tile 2 and the hard compound have very course microstructure, hence the measured area only shows a small insight on the wear process. The hard Al$_2$O$_3$ particles remain more wear resistant and the matrix between them is removed, which is similar to metal matrix compounds wear [cf. 9,10], where the metallic matrix is removed more easily than the hard phases.
Taking these information into account a hypothesis about the wear rate drop at high temperatures for the chamottes and wear tiles can be set up. The glassy phase present in these materials is not very temperature stable, and especially in the range >500°C significant softening of this phase can be assumed. Temperatures in this range were approved for the preheated samples, but also with just heated abrasive, the temperature transfer on the microscale over the hot abrasive particles likely entail local high contact temperatures. This softening of the glassy phase reduces the brittleness of the compounds leading to an improved wear resistance. Nevertheless, one must keep in mind that the further softening at even higher temperature will significantly destabilise the microstructure and wear will definitely increase.

4. Conclusions
In order to study the abrasion resistance of ceramics and its temperature influence, six commercially available ceramics for high temperature (HT) application were investigated under a high-stress three-body abrasion regime.

The two wear tiles with high Al₂O₃ + ZrO₂ content showed least wear loss at all temperatures investigated. Here, especially the wear tile 2 shows beneficial behaviour, as it has a thermal shock resistance comparable to chamottes. The cement bounded hard compound featured the next best wear resistance at room temperature (RT), but showed wear increase when exposed to HT-environment (950°C abrasive temperature in this investigation) due to its chemical bounding. Close together on a third wear level lie the chamottes.

The three chamotte-types and wear tiles show decreasing wear rates at HT, which was put down to the softening of the glassy phase therein, increasing their ductility. This limits the dominant brittle wear mechanism present at room temperature testing.

For practical application the low wear rates of the wear tiles are promising, compared to chamottes. As long as the mechanism of abrasive wear is dominant, their use will significantly reduce maintenance expenses.

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