

SENSOR-BASED IDENTIFICATION OF SPENT REFRACTORY BRICKS

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Abstract: Refractory bricks are essential for high-temperature applications in various industries. The fabrication of most of our daily life products consumes a certain amount of refractories. Although essential, they are often not perceived so by the public. Depending on their specific application and the position in the furnace, different types of refractories are necessary. The different types consist of a small number of naturally occurring high quality raw materials, such as dolomite, magnesite, bauxite and chromite. These raw materials have to meet strict quality specifications and account for 40 to 50 % of the refractory costs.

Currently, most of the spent refractory bricks are used for low-value applications, such as construction material, or landfilled. Therefore, reusing refractory bricks to substitute new raw materials in the production of refractory bricks holds large potential for adding value. Due to the variety of different brick types, the used refractories usually do not meet the strict specifications of those for new raw materials. Thus, it is necessary to sort the spent bricks into categories according to their type.

A useful tool is the sensor-based sorting (SBS) technology. SBS has been used in mineral processing for more than 30 years and is gaining more and more significance. To be able to use SBS to separate the different brick types it is necessary to find a suitable sensor, which can distinguish between the different brick types. This paper describes several tests with various sensor types to evaluate the possibility of SBS for spent refractory brick separation. The tested sensors include conventional sensors, such as near infrared spectroscopy and the promising LIBS (laser-induced breakdown spectroscopy) technology. All results were obtained within the European FP7-project REFRASORT, which aims to develop an automated sorting equipment for refractory bricks.

Keywords: Sensor-based sorting, refractories, recycling.

INTRODUCTION

Refractory bricks are solid ceramic products, which can withstand temperatures of more than 1500° C. At these temperatures; the refractories have to keep their shape and their mechanical strength over a defined period of time. Bricks of refractories have to withstand contact with highly corrosive liquids or gases. They are essential for various high temperature applications, such as the production of steel, copper, cement and glass.

For the production of refractories several naturally occurring raw materials are used. Table 1 displays the most important raw materials for refractories and their geographical origin. These raw materials have to meet strict quality specifications and are therefore only mined in few countries in the world. Depending on their position in the furnace, different raw materials are utilized.

Table 1, Important raw materials for refractories (Guéguen et al., 2014)

Raw material	Formula	Melting point	Main source
Silica	SiO ₂	1720° C	Global
Fireclay	SiO ₂ + Al ₂ O ₃	1100° C	Global
Alumina silicate	SiO ₂ + Al ₂ O ₃	1350° C	China
Alumina	Al ₂ O ₃	2050° C	Synthetic
Zirconia	ZrO ₂	2715° C	South Africa
Zircon	ZrSiO ₄	1775° C	Australia
Chromite	FeCr ₂ O ₄	2265° C	South Africa
Spinel	MgAl ₂ O ₄	2135° C	Synthetic
Magnesia	MgO	2820° C	China
Sinter dolomite	CaO + MgO	2370° C	Europe/Global
Graphite	C	3600° C	China

Due to the concentrated origin of the raw materials needed to manufacture refractories, producers are dependent on a few suppliers of these raw materials. The costs for raw materials account for 40-50 % of the costs for refractories. This makes the supply of high quality raw materials at affordable prices crucial for the production of refractories. (Guéguen et al., 2014)

One possibility for lowering the dependency on these limited numbers of suppliers is recycling. Currently, most spent refractory bricks are utilized in low-value applications, such as construction material, or are landfilled. Therefore, substituting spent refractory bricks for raw materials in the production of new refractory bricks creates a huge potential to cut costs.

MAIN TASKS FOR RECYCLING

At the end of their life time spent refractory bricks are taken out of the furnace and collected. Thereby, different types of bricks end up in one fraction. The main challenge in the recycling of refractories is the separation of the different brick types as well as the separation of impurities, such as slag or metal. Currently, only a small percentage of spent refractories are recycled. The separation of the brick types is usually done by handpicking, which is expensive and error-prone.

Sensor-based sorting is a useful tool from the field of mineral processing, which can be applied to separate the different refractory types. It is also referred to as automated picking and suitable for separating single particles individually. To do so, it is necessary to identify a sensor-technology that is able to distinguish between the different refractory types and to have a mechanical device that is able to separate the refractory bricks physically. The EU-funded REFRA SORT project aims to develop a prototype of an automated sensor-based sorting device for refractory bricks.

To evaluate the ability of different sensor-technologies for distinguishing between refractories, three main types of refractories were defined. The selected refractories are meant to represent the most common refractories utilized in the steel industry, as this industry is the major consumer of refractories.

Type A is based on magnesite and has a high MgO-content. Type B is based on dolomite and contains MgO and CaO, whereas Type C is based on bauxite and has high SiO₂ and Al₂O₃ content. Type A and C are each subdivided into three types and type B is subdivided into two

types. A suitable sensor should at least be able to distinguish between the three main types but preferably it should identify as many as 8 subtypes.

BASICS ON SENSOR-BASED SORTING

Sensor-based sorting is an umbrella term for applications where particles are detected singularly by a sensor and afterwards separated by an amplified mechanical process. (Wotruba and Harbeck, 2010)

Commonly, sensor-based sorters use chutes or belts to convey the particles and compressed air to separate them. For any sensor-based sorter, the sorting process can be divided into these sub-processes:

- Material conditioning (1)
- Material presentation (2)
- Detection (3)
- Data processing (4)
- Separation (5)

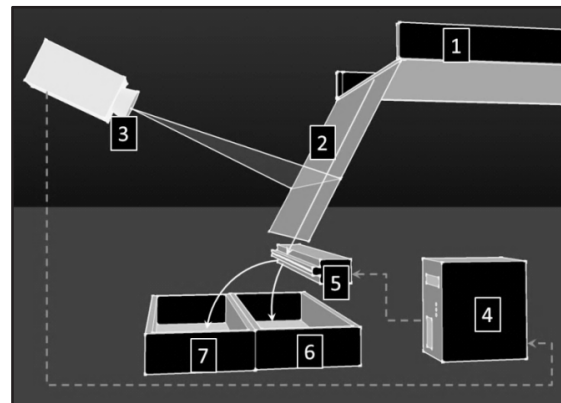


Figure 1, Schematic illustration of a chute-type sensor-based sorter (Neubert et al., 2013)

Figure 1 displays the functional principle of a sensor-based sorter. The feed stream is separated into an accepted (6) and a rejected fraction (7). Commonly, less than 50 % of the material is rejected to reduce the energy consumption for separation. (Wotruba and Harbeck, 2010)

The process step of detection is the most crucial one, for evaluating the applicability of sensor-based sorting for a certain ore. Sensor-based sorting can be applied only if a sensor is able to distinguish between particles which should be rejected and particles that should be accepted.

TESTED SENSORS

To evaluate the ability of a sensor to distinguish the different brick types; cylinders of fresh refractories of all 8 types were tested with different sensors. Figure 2 shows the cylinders of all 8 types of refractories. For the sensor tests, three samples of each refractory type were used to increase the reliability of the results.

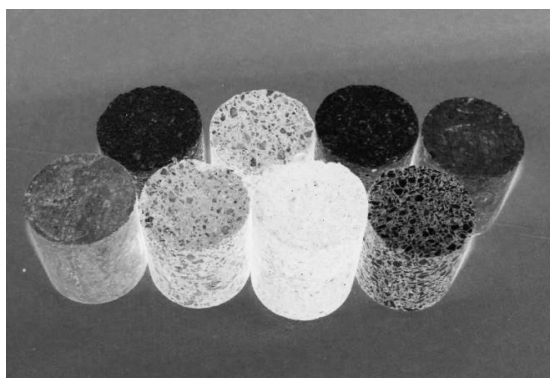


Figure 2, Cylinders of fresh refractories

In this paper the tests using near infrared spectroscopy, optical sensors and laser-induced breakdown spectroscopy (LIBS) are described.

Near Infrared Spectroscopy (NIR)

In near infrared (NIR) spectroscopy the sample is irradiated with light covering the whole range of near infrared wavelength (1000 – 2500 nm). Afterwards, the reflected light is measured and evaluated. As a result of the interaction between radiation and the molecules in the surface of the sample, some molecules show vibrational transitions. These vibrational transitions cause the absorption of specific wavelengths, which are characteristic for the molecular structure. Therefore, NIR spectroscopy allows the identification and quantification of certain molecules/minerals. Especially OH-groups, H₂O and CO₃ cause characteristic absorption features. (Robben et al., 2012)

In industrial applications of sensor-based sorting, NIR-sensors are used as line scan cameras and are usually mounted above the conveyor belt. Figure 3 shows the most common setup, which consists of a detector and rotating polygon mirror. This mirror reflects the point signals into the spectrometer allowing the point scanner to scan the whole width of the belt. On a moving belt, the movement of the conveyor belt and the scanning point overlap and form an angular scanning pattern. (Robben et al., 2012)

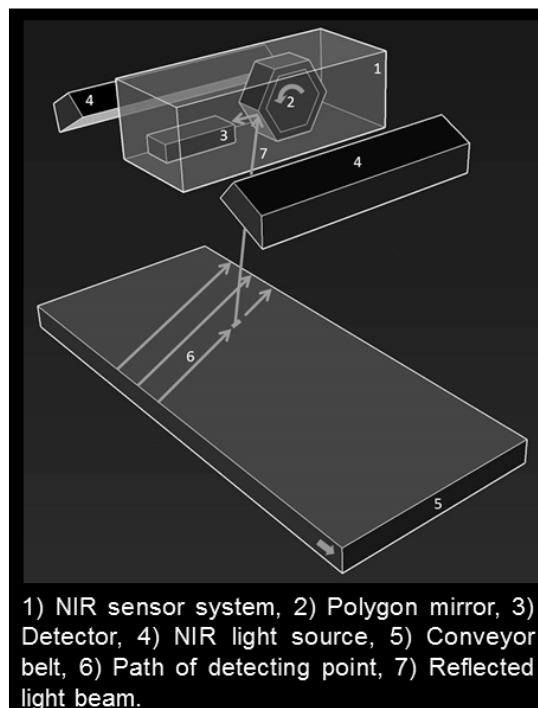


Figure 3, NIR line scan sensor (Robben et al., 2012)

For the feasibility tests, five point measurements were performed on each sample. The measurement spots with a diameter of about 3 mm were selected randomly. The variation between the five measurements of the same sample provides information about the homogeneity of the sample.

Optical RGB Sensors

In optical RGB sorting the samples are illuminated with light and analyzed with CCD-cameras. The cameras use differences in the reflection of light within the red, green and blue region of the electromagnetic spectra. Industrial sorters usually apply line scan cameras, which create an image of a particle while passing the sensor.

The generated images are processed and compared to preset calibration settings. Each pixel is classified into a color class to reduce the amount of identified colors. The resulting false color picture can be used to identify several material classes. Optical sensors detect surface properties and are therefore sensitive to surface contaminations, such as dust or dirt.

For the feasibility tests an area scan camera was used in combination with a stationary particle. The resulting image should be similar to the image of a line scan camera and a moving particle. The resulting images were analyzed

using the image processing software of an industrial sensor-based sorter.

Laser-Induced Breakdown Spectroscopy (LIBS)

The LIBS-technology uses a high-power focused laser pulse to produce a plasma on the samples surface. Figure 4 illustrates a set-up for LIBS measurements developed for sensor-based sorting. (Werheit et al., 2011)

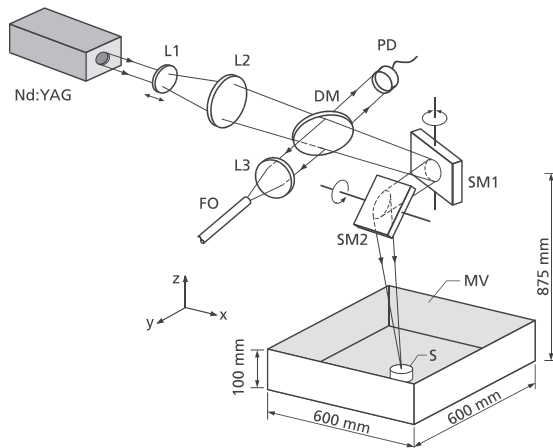


Figure 4, Schematic drawing of the optical components of 3D scanning LIBS. L1 diverging lens, L2 two lens focusing system, DM dichroitic mirror, SM1,2 scanner mirrors, S sample, MV measuring volume, L3 focusing lens, FO optical fiber, PD photodiode. (Werheit et al., 2011)

In LIBS a lens is used to focus laser pulses on the samples surface. The plasma light is collected by using a fiber optic cable. The collected light is transmitted to a spectrometer. Each laser pulse produces a single LIBS spectrum for multi-element detection. Nevertheless, LIBS measurements are often averaged spatially and over several laser pulses to increase accuracy and representativeness.

During the feasibility tests, the refractory cylinders were measured several times with the LIBS-system. Each measurement was recorded separately and compared afterwards.

RESULTS

In this section, the results of the tests with NIR, optical sensor and LIBS are described. Three cylinders of each refractory type were presented to each of the sensors.

Near Infrared Spectroscopy

The measured NIR-spectra showed only few characteristic absorption features, which makes a distinction difficult. Only the samples of main type B showed a clear absorption feature at about 1412 nm (see Figure 5). Absorption features at 1412 nm are known to be caused by water. It seems, that the bricks of type B have a detectable higher water content than Type A and C.

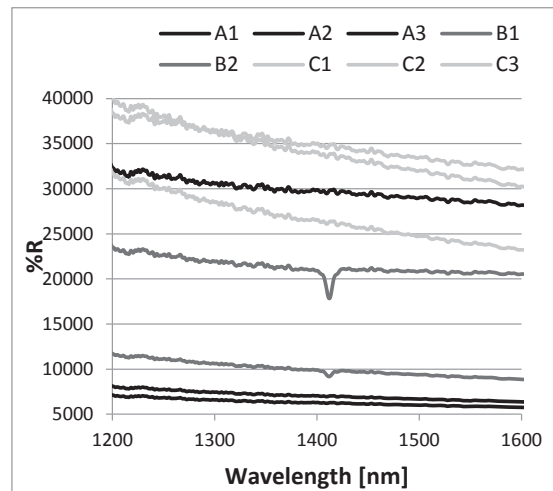


Figure 5, NIR spectra of all eight refractory types

To prove that NIR spectroscopy can be used in an industrial sorting application, more tests will be necessary. It will also be necessary to evaluate the influence of changing water contents on the measurement. It was not possible to distinguish refractories of type A or C with NIR spectroscopy. Therefore, NIR spectroscopy does not seem to be a suitable sensor.

Optical RGB Sorting

The images of all eight cylinders were processed with suitable image processing software (see Figure 6). It showed that refractories type C can be distinguished from type A and B. It might be possible to distinguish Type B refractories from the other two but more research will be necessary.

It is possible that the measured colors can change, if the material composition changes slightly. For example the addition of carbon or graphite will change the color of the brick and therefore, change the results of the measurements.

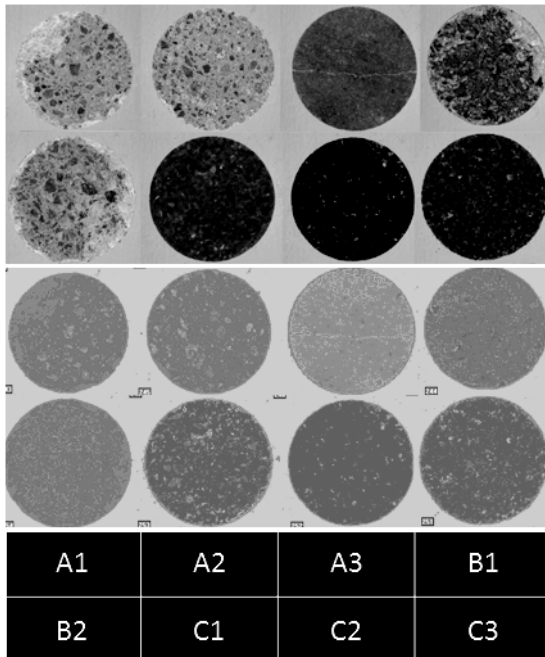


Figure 6, Unprocessed image (top), processed image (middle) and legend (bottom) of all eight cylinders

Another drawback of optical RGB sensors is their susceptibility to surface contaminations, such as dirt or dust. As the working conditions in a recycling plant for refractories include dust and the optical sensor wasn't able to distinguish all refractory types, it seems that optical sorting is not ideal for recycling of refractories.

Laser-Induced Breakdown Spectroscopy (LIBS)

The LIBS-system was able to produce a plasma on the samples surface. Due to the small size of the measurement spot of the LIBS-system and the heterogeneous surface of the spent bricks, the decision was made to repeat the measurement several times to increase accuracy. Figure 7 shows a refractory sample while the plasma is produced on its surface.

From the measured LIBS-spectra several spectral features were selected, which correspond with the elements Ca, Si and Mg. Figure 8 shows the normalized signal intensity for these three spectral features for all eight refractory types. It shows that the spectral feature of Mg is high for all samples of type A and low for all samples of type B and C. The signal for Ca is above 0.4 only for the samples of refractory type B. Whereas the Signal for Si is only high for Type C. It appears that it is possible to distinguish the three main types with LIBS measurements

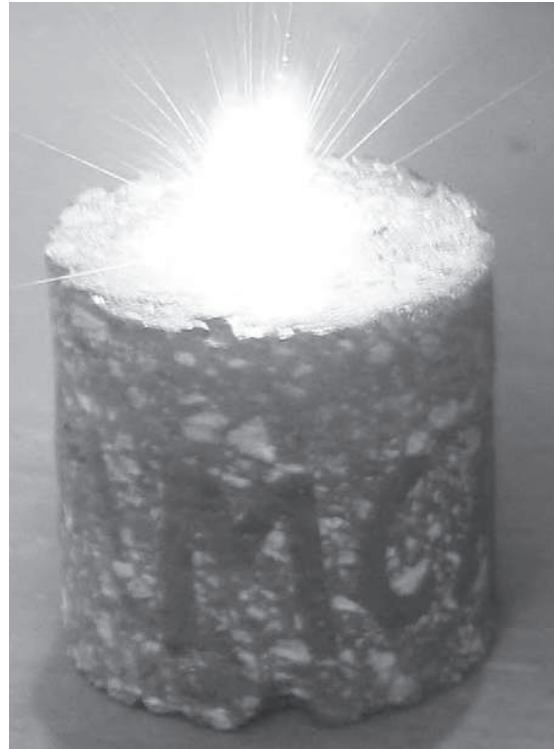


Figure 7, Refractory sample with a plasma generated by the LIBS system

It might even be possible to further distinguish the different subtypes but more research is necessary.

CONCLUSION

Refractory bricks are essential for the production of many daily life products. Quality and the price of refractories depend on the availability of specific raw materials. Recycling can help to reduce the dependency on such raw materials and lower the costs for refractories. Today, only small amounts of refractories are handpicked and recycled. Sensor-based sorting can provide a technological solution for producing high quality raw materials from spent refractory bricks.

The tests with different sensors have shown that distinguishing eight different types of refractories is a challenging task. It was not possible to distinguish the different refractory types with optical RGB sensor or NIR spectroscopy. A combination of both technologies could improve the results but is still unlikely to deliver satisfying results.

The LIBS technology was able to identify the three main refractory types reliably and holds the potential to further distinguish the eight subtypes. It seems therefore that it is possible to develop an automated sorting device for refractory bricks by utilizing the LIBS-technology.

Acknowledgements

The REFASORT project has received funding from the European Union's Seventh Program for research, technological development and demonstration under grant agreement No 603809.

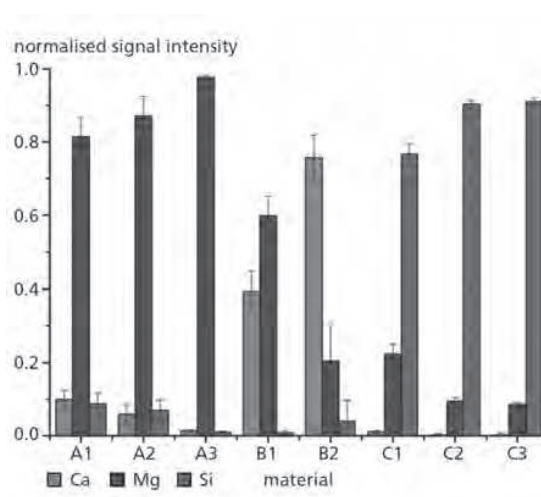


Figure 8, Normalized signal intensities observed by LIBS measurements (Guéguen et al., 2014)

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