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Enhancing Refractory Recycling: The Role of Automated Sensor-Based Sorting Systems

Elevating refractory recycling rates to unprecedented levels necessitates enhanced quality control. While manual sorting significantly contributes to improved material quality, it has reached its practical limitations and falls short in providing essential data for quality monitoring. The adoption of automated sensor-based sorting stands as a key driver in advancing recycling efficiency, enabling the processing of material fractions previously untapped. RHI Magnesita's activities, notably in the Horizon Europe ReSoURCE project, have established a robust foundation for the forthcoming implementation of automated sorting technology. This imminent advancement is anticipated to redefine standards in circular mineral quality. The article presents an overview of recent developments, addresses the ongoing challenges, and outlines the anticipated future of sorting technologies in the realm of refractory processing.

Introduction

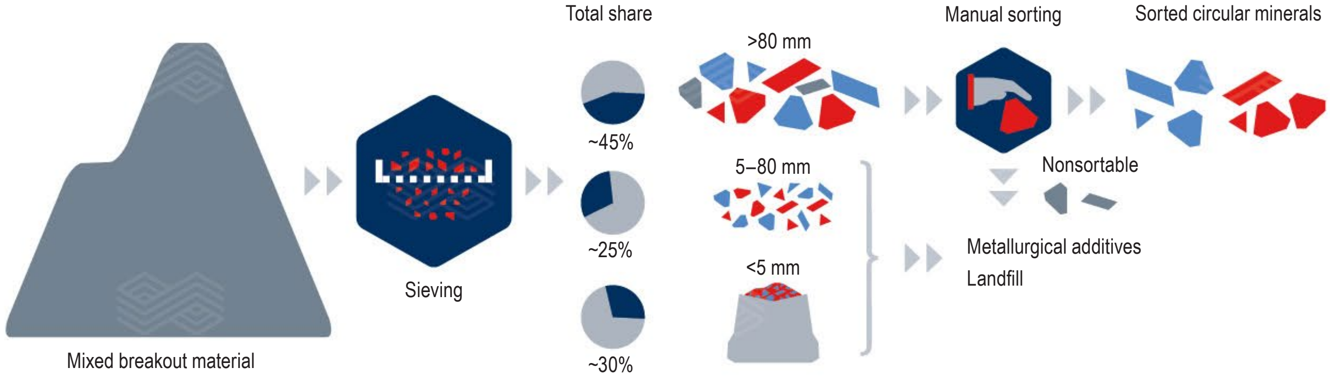
RHI Magnesita is at the forefront of enhancing refractory recycling rates and has made significant progress to reach the 2025 target of 15% [1]. However, the adoption of advanced technologies [2], such as automated sensor-based sorting technologies will ensure future continuous growth of the recycling business. This innovative approach exceeds the conventional manual sorting techniques by accurately analysing particles using advanced sensors, thereby enabling data-driven decisions regarding their potential reapplication. These advancements serve to invalidate the preconception that recycled materials are inferior, fostering greater trust and acceptance of circular materials in the future. By addressing challenges such as limited available feedstock, the traditional manual sorting of only larger particles without chemical insights, and a lack of comprehensive post-sorting data, automated sensor-based sorting stands as a pivotal solution. This article describes RHI Magnesita's pioneering developments in automated sensor-based sorting systems for recycling refractories, highlighting a significant advance toward resource sustainability.

Development of an Automated Sensor-Based Sorting System

Automated sensor-based sorting provides multiple benefits over traditional manual methods [3–6]. Manual sorting is constrained by the physical limitations of human operators, who can only handle large particles (i.e., >80 mm) to maintain an economical throughput (Figure 1). This restriction inherently caps the volume of material that can be processed within a given time. In contrast, automated systems equipped with advanced sensors and rapid ejection mechanisms can process smaller particles ranging from 5–80 mm, significantly expanding the accessible volume of source materials.

Furthermore, automated sorting provides detailed specifications of each particle. By utilising technologies such as laser-induced breakdown spectroscopy (LIBS) for elemental chemistry analysis and hyperspectral imaging (HSI) for mineral phase composition, the sorting process ensures a consistently high-quality output with valuable data that can be leveraged in future product developments. This reduces the incidence of downcycling, where materials are

Figure 1.
Overview of manual recycling processing steps.



reused in lower value applications than originally intended, as well as the environmental implications and costs of landfilling.

The preliminary design of the mobile automated sensor-based sorting equipment, capable of sorting up to 10 tonnes/hour of spent refractories, is shown in Figure 2. The feedstock will be loaded into a hopper by a wheel-loader. Subsequently, the particles will be automatically singularised, characterised by sensors, and sorted, depending on their characteristics, either by pick and place robots or an air ejection system at the end of the conveyor.

The equipment design enables mobility and replication across different locations. As the cost of generating circular materials is substantially affected by transport distances, mobile sorting units will be used to achieve economic viability by minimising logistical expenses.

ReSoURCE: A European Horizon Project

Automated sorting entails complex processes, necessitating a holistic approach that incorporates feedback loops due to upstream and downstream interdependencies. As achieving optimal outcomes requires collaborative efforts among various experts, the ReSoURCE (Refractory Sorting Using Revolutionizing Classification Equipment) Horizon Europe project was initiated [7]. The framework of this European programme provides an ideal setting to establish well-defined development agreements, significantly accelerate progress, and provides substantial benefits to all partners involved. Within this collaborative environment, understanding across different technology sectors is enhanced, leading to the development of cutting-edge, tailor-made solutions. Additionally, the involvement of academic institutions ensures that best practices are applied throughout all processes. Featuring a total budget of ~€8.5 million, of which ~€7.0 million are funded by grants, enables the challenge to be tackled in an effective manner. Table I outlines the partners and their respective roles in the ReSoURCE project, illustrating the diverse contributions and expertise in this integrated initiative.

Sensor Combination

The integration of three distinct sensors in the equipment aims to redefine the standards for robust sorting (Figure 3). This multi-sensor approach not only increases the effectiveness of the sorting process but also enriches the data quality, paving the way for more sophisticated recycling operations.

Figure 2.
Mobile automated sensor-based sorting equipment based on transportable 40-foot containers.

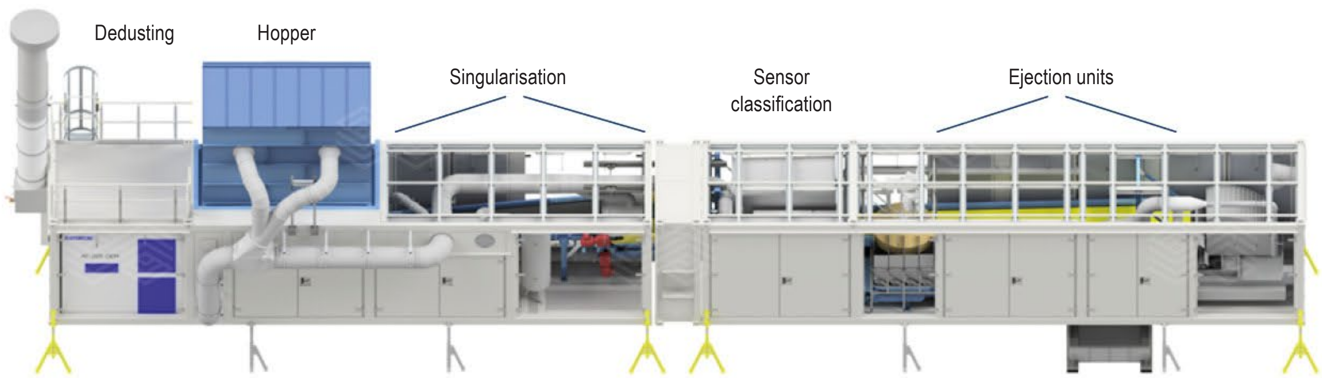


Figure 3.
Overview of the sensor combination to be used in the ReSoURCE equipment. Abbreviations include laser-induced breakdown spectroscopy (LIBS), artificial intelligence (AI), hyperspectral imaging (HSI), and region of interest (ROI).

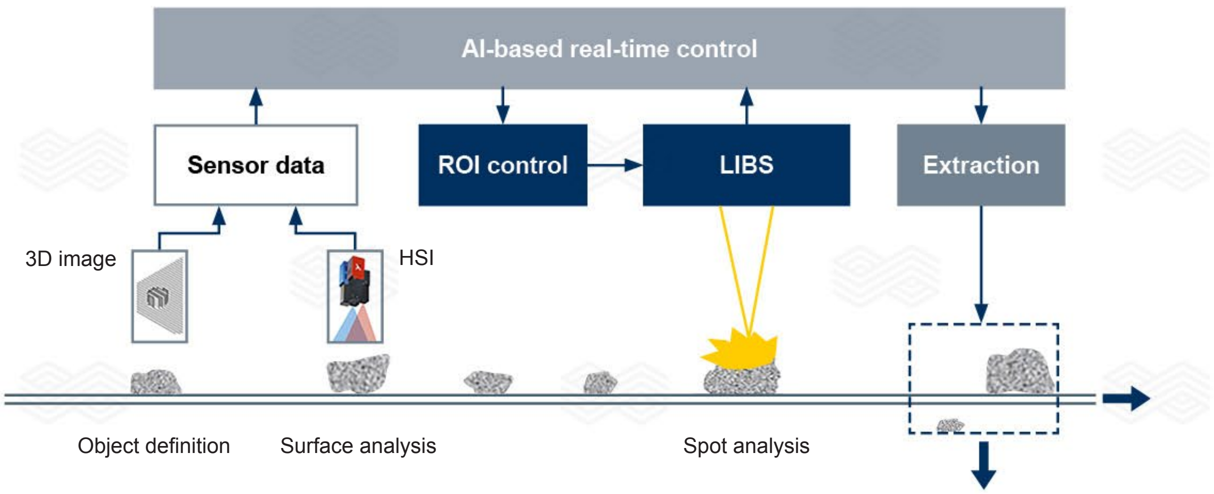


Table I.

ReSoURCE consortium members and their key roles in the project. Abbreviations include laser-induced breakdown spectroscopy (LIBS), artificial intelligence (AI), hyperspectral imaging (HSI), life cycle analysis (LCA), and techno-economic analysis (TEA).

	Partner	Key role	Nationality
RHI MAGNESITA	RHI Magnesita (Coordinator)	Refractory recycling and production	AUT
LSA Laser Analytical Systems & Automation	LSA GmbH	Development of LIBS unit and automation	GER
Fraunhofer ILT	Fraunhofer-Institute for Laser Technology	AI-based sensor data combination and analysis	GER
SINTEF	SINTEF	Powder technology for fine fractions	NOR
MONTAN UNIVERSITÄT LEOBEN	Chair of Mineral Processing	Optimised preprocessing	AUT
	Chair of Waste Processing Technology and Waste Management	Waste characterisation and process optimisation	AUT
INNOLAS LASER INC	InnoLas Laser GmbH	Customised laser development	GER
neo NORSK ELEKTRO OPTIKK AS	Norsk Elektro Optikk	HSI provider and developer	NOR
cpi	CPI Ltd.	LCA, TEA, and nonrefractory applications	UK
Crowdhelix COLLABORATION INTELLIGENCE	Crowdhelix	Stakeholder management and cross-linking	IRL

Initially, a 3D camera plays a crucial role by pinpointing the exact location of each sample on the conveyor belt while also mapping the complete topology of the particle. This is vital for scanning fractured particles with irregular surfaces. The 3D camera helps identify the geometrically ideal regions on these uneven surfaces for conducting LIBS measurements. Optimally, the laser should hit the sample perpendicular to the test surface to ensure high accuracy and low noise levels. In addition, analysis of surface features on the fracture surfaces by the 3D camera contributes to the sorting process. For example, it can facilitate preliminary classification—either confirming the particle's suitability for recycling or excluding it. In some cases, it might even refine existing sorting classes, enhancing the overall efficiency and precision of the sorting system.

Secondly, two HSI cameras play a critical role by capturing the spectral signature of each particle in the range of 400–2500 nm. This technology extends far beyond traditional image analysis, enabling precise visualisation of optical features with a spatial resolution of 384 pixels for the first camera and 1800 for the second. By interpreting reflectance curves obtained from the HSI, it is possible to gather information about the bonding system and identify specific mineral phases. Such information is invaluable for enhancing quality monitoring in refractory recycling, as it provides crucial insights into the material's composition [8].

Moreover, HSI data is instrumental in assessing the mid-scale homogeneity of samples—typically spanning a few centimetres. This capability is particularly significant because it helps mitigate a major limitation of LIBS, which can only analyse small spots on the material (i.e., tested volumes usually in the range of a few hundred μm^3). In determining the material heterogeneity, HSI aids directing the LIBS to the most relevant regions for targeted analysis. It also plays a crucial role in detecting nonrefractory materials, such as attached process media like slag or clinker, that might be present on the sample.

In summary, the broader imaging scope of HSI offers various advantages, including the ability to classify materials directly into specific sorting categories based on underlying models. By integrating these insights, HSI contributes to a more nuanced and effective sorting process, providing visual surface information as a basis for the subsequent selection of coordinates for the LIBS measurement.

Finally, LIBS measurements will be executed at optimal positions, as determined by the data from the 3D camera and HSI sensors (see Figure 3). LIBS plays a pivotal role by analysing the elemental chemistry of each particle [4,9]. This capability is fundamental for classifying materials based on their chemical composition, which is a primary specification that circular minerals must meet for recycling purposes.

Due to its high sensitivity to nearly all elements in the periodic table, LIBS can be utilised to further refine the sorting process. It enables the establishment of new sorting classes with more precise elemental limits. Following each sorting campaign, LIBS not only categorises materials but can also provide quantitative data regarding the levels of specific elements within each particle (Figure 4). This information is crucial for targeted applications in products and can also provide the basis for blending strategies at later stages. Additionally, LIBS is particularly useful for identifying contamination gradients or harmful substances in used bricks. By targeting the precrushing and liberation of infiltrated zones, automated sorting can isolate material volumes requiring special treatment, thereby reducing them, leading to more economical processing costs.

All data collected from the three sensors will be continuously analysed to identify ways to streamline the sensor setup. Furthermore, using the information gained from this initial setup, the goal is to develop more cost-efficient equipment in the future, optimising both technological and economic aspects of the refractory recycling processes.

Advanced Sensor Setups Tailored to Refractory Applications

Currently, sensor and analysis technologies available on the market do not fully meet the specific needs of refractory recycling. For instance, existing LIBS systems are predominantly optimised for sorting metal scrap. This presents a significant challenge for refractory materials, which typically feature a highly heterogeneous microstructure. Unlike metals, where representative volumes are only a few hundred micrometres cubed, coarse ceramic refractories have larger representative volumes, sometimes exceeding 5 mm in terms of the individual raw material components. This size difference means that a random sample may not accurately represent the total chemistry of the refractory product, as indicated in Figure 5.

Furthermore, refractories often possess contamination layers or nonrepresentative layers that can exceed 1 mm due to process media, dust, and oxidation effects. Therefore, efficiently sorting these particles requires a laser capable of quickly ablating any coating material before the measurement pulse analyses the sample. Furthermore, the precision in detecting certain elements is crucial as even minimal levels of contamination can severely impact refractory performance.

To address these challenges, the ReSoURCE project is developing a novel laser source in collaboration with InnoLas (Germany). This advanced technology achieves higher energy levels suitable for testing larger volumes and incorporates tailored pulse modulation to enable both cleaning and analysis pulses within short repetition times. The two new lasers being developed increase the maximum energy level from 150 mJ to up to 430 mJ as well as

Figure 5.

LIBS measurement spots on a 50 mm diameter test cylinder of a basic refractory brick.

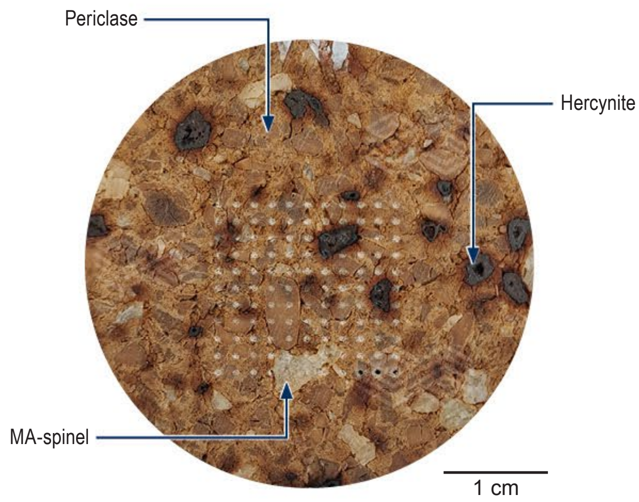
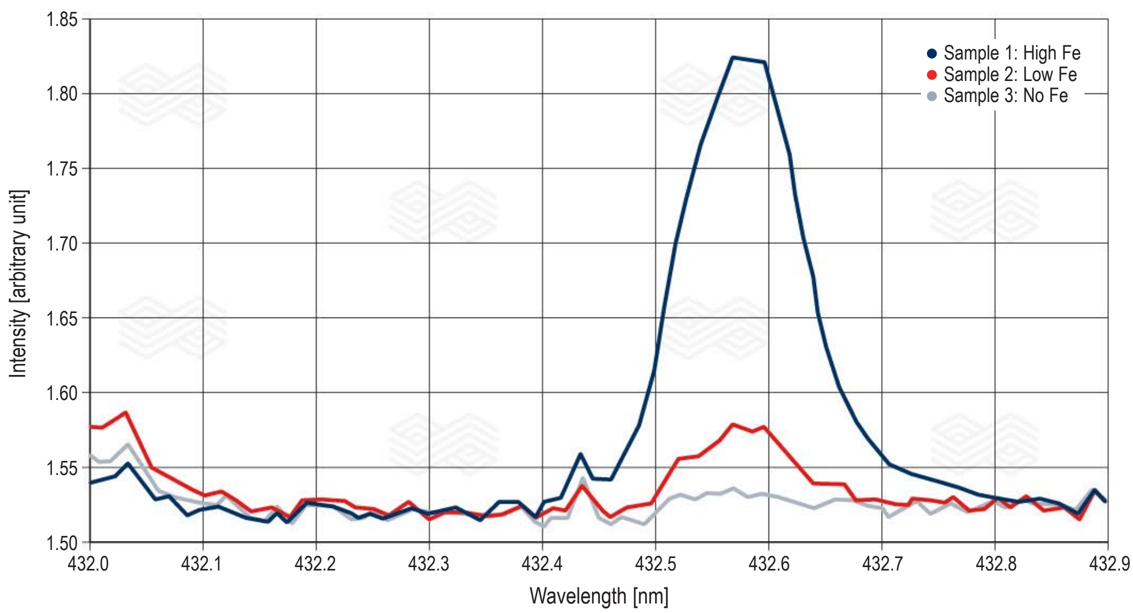


Figure 4.

LIBS spectra showing the Fe peaks for three refractory samples, indicating the different Fe levels detected.



increase the measurement rate up to 400 Hz, when used at lower energy levels. Additionally, a novel spectrometer design and novel optics developed by LSA GmbH (Germany) will enable higher resolution (in the range of 50–150 pm), particularly for critical elements.

Given the chemical complexity of refractories, AI-based algorithms are being employed to enhance the accuracy and efficiency of data analysis. This cutting-edge approach not only improves sorting accuracy but also ensures that recycled materials meet stringent quality standards.

Calibration—The Key to Robust Sorting

The current sorting classes used in recycling operations often feature broad specifications. This is partly due to limitations in the precision of existing sorting technologies but can also result from a deliberate choice to accommodate the infrastructure capabilities at recycling plants. As a result, a wide variety of products, and consequently an even greater diversity of raw materials, are grouped into each sorting class. This diversity poses significant challenges in calibrating the sorting machinery effectively.

For the LIBS technology, an initial calibration step involves using a variety of raw materials to pinpoint individual peak positions in the spectrum. So far, just in the ReSoURCE project more than 20 primary raw materials and 100 circular mineral samples have been tested, analysed, and categorised. These identified peaks will be crucial for later stages, where they will help differentiate between various recycling classes. Furthermore, the precision of these measurements was remarkably high, with an average classification accuracy of far more than 90% being achieved for all investigated product types (Table II).

To classify materials based on spectral data gathered with the HSI, models such as pixel class majority are being trained and applied on the samples. To establish a solid ground truth within the project, absorption spectra of over 350 crushed circular mineral samples, raw materials, and possible impurities (e.g., slag and clinker) have been recorded. The first results show a promising average classification accuracy of the HSI data (Table III).

The effectiveness of these spectral features, proven by their high accuracy, has also been applied to the classification of circular minerals. An initial outline of this application demonstrates the potential for enhancing the precision and efficiency of sorting practices in refractory recycling, paving the way for more tailored and effective recycling processes.

Table II.

Classification accuracy of different product types by LIBS.

Product type	Classification accuracy [%]
Alumina-silica—low Al_2O_3	98
Alumina-silica—medium Al_2O_3	96
Alumina-silica—high Al_2O_3	96
Magnesia spinel	94
Fired magnesia	93
Alumina-magnesia-carbon	92
Magnesia-carbon with antioxidants	93
Magnesia-carbon without antioxidants	91

Table III.

Example of a confusion matrix based on the pixel class majority of different product types determined by HSI, showing only a minimum number of the samples were incorrectly classified (red shading) even with the nonoptimised model.

Actual refractory class	Sample number	Predicted refractory class		
		Magnesia spinel	Hercynite low Fe	Hercynite high Fe
Magnesia spinel	30	30 (100%)		
Hercynite low Fe	36	3 (8.3%)	33 (91.7%)	
Hercynite high Fe	70			70 (100%)

Conclusion

The advancements in automated sensor-based sorting technologies are set to revolutionise refractory recycling. These systems go beyond replicating manual sorting by significantly enhancing precision and efficiency. The ability to specifically target materials that require treatment ensures economic benefits, particularly when refractory producers provide direct input on sorting criteria. Moreover, extensive data collection and subsequent big data analysis are instrumental as they not only facilitate streamlining equipment features but also lay the foundation for future technological developments. In addition, this strategic approach ensures that only necessary material treatments are applied, optimising both resource usage and economic outcomes in the refractory industry.

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Cover picture: The image depicts the lower section of a RH degasser, a secondary metallurgical unit used in steel plants. In the RH degassing process, snorkels are submerged into liquid steel contained in the casting ladle. Argon gas is purged through the inlet snorkel, creating a suction effect that draws liquid steel into the lower vessel of the RH degasser, where a vacuum is applied. The steel treated in the lower vessel flows back to the ladle through the outlet snorkel, creating a continuous steel circulation between the ladle and the RH degasser. The strong negative pressure (vacuum) within the RH degasser facilitates various metallurgical processes that enhance steel quality, with the key process steps including degassing, decarburisation, deoxidation, and alloying under vacuum. Rail steel, flat steel for the automotive industry, and steel plates for shipbuilding are just a few examples of products that benefit from the RH degasser. Prefabricated snorkels, which RHI MAGNESITA manufactures ready for use and delivers to our globally operating customers, are essential components of the RH degasser.