Waste reuse as a tool for increasing sustainability in industrial production

Saetta S.*, Caldarelli V.*, Tapola S.**

** Dipartimento di Ingegneria, University of Perugia, Via G. Duranti, 93 06125 – Perugia – Italy (stefano.saetta@unipg.it, valentina.caldarelli@unipg.it)*

*** Meehanite Technology Ltd, – Finland (sara.tapola@ax.fi)*

Abstract: The environmental sustainability of production processes is an aspect that increasingly pushes the technological innovations that take place in the manufacturing sector. In fact, the need to have a lower environmental impact and to comply with national and international regulations on emissions drives the introduction of new practices that reduce polluting emissions from the entire process. However, it is essential that the entire process is also economically sustainable: indeed, the environmental impact reduction involves often costly economic investments. The paper aims to analyze a particular production process, one of the most polluting, and analyzes the possible innovations that make it greener and theirs environmental and economic impact. The research activity, carried out within the Green Foundry LIFE Project (LIFE17 ENV/FI/000173), aims to verify the possibility of reusing waste sand and the use of self-setting inorganic binders, through an economic analysis that compares the as-is state and a more environmentally sustainable configuration. The objective of the paper is therefore to highlight the importance and the need to make economically viable the improvement interventions that are carried out in a production process for greater environmental sustainability.

Keywords: Sustainable production, reuse, waste foundry sand, inorganic binders

1. Introduction

One of the most popular definition of Circular Economy, CE, is: "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Geissdoerfer et al., 2017). The circular economy has received increased attention in academic research (Andersen, 2007, Ghisellini et al., 2016, Lieder and Rashid, 2016, and Su et al., 2013).
The fact that reuse follows the CE paradigm reawakened the interest of firms.
Also, the revolution of Industry 4.0 facilitated the development of sustainability within industrial processes (Rocca et al., 2020).

In the Green Foundry LIFE Project (LIFE17 ENV/FI/000173) the aim is to increase the sustainability of Iron cast foundry industry by introducing inorganic binders. This introduction can contribute in reducing the emissions and waste in the process. Production process with inorganic binder is much more sensitive, but, thanks to Industry 4.0 tools such as IoT and Data Analytics is now possible (Saetta et al., 2021).

The foundry companies, characterized by a high environmental and energy impact, have for some time started policies that aim to make their business sustainable; efficient management of the environmental issue can bring benefits in economic terms, risk reduction, image and reputation of companies. The foundry sector is characterized by a high waste / net product ratio. In these foundries the production cycle is characterized by a high specific production of waste in particular consisting of exhausted and fine sand linked to the sand processing cycle and dust deriving from the dedusting of emissions into the air.

The attention of the foundries, in recent years has been very focused on the methods of managing the residues of the various work processes, both in order to reduce the quantities, encouraging both re-uses within the foundry processes themselves, and researching possible external uses alternative to the "traditional" disposal activity.

Thanks to the experimental results carried out in the Green Foundry LIFE project, it was possible to demonstrate an excellent reusability of the waste creating a significant improvement. The work aims to demonstrate that by inserting technological innovations and tools in the perspective of industry 4.0 in the production processes, an improvement in sustainability is possible, obtaining economic and environmental advantages. In particular, the innovations and the tools used make it possible to modify the waste management system, reducing the associated problems and bringing excellent advantages.

The remaining of the paper is organized as follows: Section 2 is dedicated to the description of a foundry production system, deepening aspects relating to the materials used for production. In Section 3 changes and tools to increase sustainability are described, while in Section 4 the experimental results for the waste reuse are explained. Section 5 contains the conclusions.

2. Foundry production system

An example of foundry plant layout is shown in Figure 1.

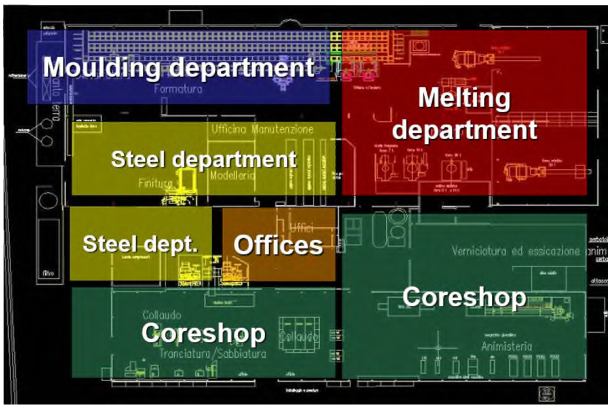

Figure 1: Plant layout

Three foundry areas (see Figure 2 for the schematization of production flows) are important:

(1) the coreshop department: the area for the cores production;
(2) the moulding department: the area for mould preparation and for all operations before casting;
(3) the melting department: the area for the melting and treatment of metal.

These main areas are schematized in Figure 2: the typical flow through the departments is shown. Also, the core warehouse, the place where the cores are stored pending the request from the moulding department, is represented.

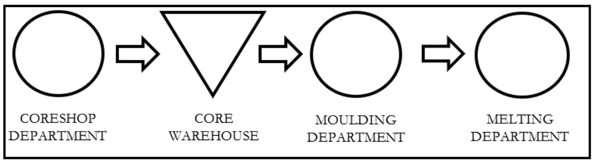

Figure 2: Production flow

The cores produced in the coreshop are elements used to create internal cavities where the melted metal does not have to penetrate, for functional reasons of the piece or to reduce its overall weight. The produced cores must minimize the formation of burrs, satisfy certain requirements, which vary according to the casting technique. After the solidification of the metal, the jet is extracted and the core is removed by dirt (Czerwinski et al., 2015).
In the moulding department, schematized in the Figure 3, the lower part of the mould is filled with sand and the operator inserts the cores manually. Then the mould is closed and sent to the melting department.

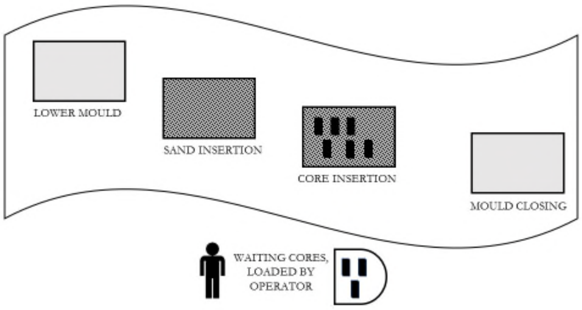

Figure 3: Moulding department

The last part of the forming process is the shake-out phase. The goal is to separate the mould from the sand and from the castings. The brackets automatically retract into the production line, while the sand and castings are transported on vibrating devices that allow the separation. The sand is conveyed to the regeneration plant, for the recycling and use of sand as new sand, and the castings towards the sandblasting machine for a more refined cleaning.
Subsequently, the moulding sand is passed through a polygonal sieve, inside which it is rotated and conditioned to hit metal nets so as to be filtered in order to eliminate the one that is no longer suitable for regeneration. Only after sieving the sand is sent to fluidized bed coolers in which the nebulized cold water allows a lowering of the temperature by about 20 ° C. At this point the sand is led towards the storage silos. According to the needs of the moulding line, the sand can be introduced into the mills, where it is mixed with water and a premix of clay and coal (premix), to give the sand again the qualities previously lost due to contact with the liquid cast iron.
From the mills, the sand is sent back to the moulding line.

2.1 Foundry sand

The sands and natural sands are obtained directly from the quarries and can be used as they are or following a working process aimed at achieving specific chemical and physical characteristics.
In the past, the most used sand was natural, essentially made up of clay on which water had settled. Currently, however, the production standard in foundries provides for the use of synthetic or green sand with a growing search for recovery and regeneration. The use of natural sand is limited and dedicated only to specific cases.
Sand is a material composed of grains of mineral matter with a diameter between 2 and 0.05 mm. The most used in foundries are mostly composed of silica (Si_2O_3).
Sands with particular characteristics given by some minerals are also used less frequently, including zircon ($ZrSiO_4$), olivine ($(MgFe)\ 2SiO_4$) and chromite ($FeCr_2O_4$).
Silica sands are the most used, as they have advantageous thermal properties, excellent chemical purity, high compatibility with all types of foundry binder systems and

are also the cheapest sands with which it is possible to make cores and forms.

In addition to the listed properties, there are also some problems in the use of silica sand due to the high thermal expansion that can lead to defects in the castings, to the low refractoriness that can lead to sintering in the castings and to the reactivity with ferrous alloys that contain manganese which reacts with silica to produce low melting silicates.

The basic requirements that foundry sands must meet are:

- mineralogical-chemical composition
- granulometry
- shape of the granules

As regards the mineralogical-chemical composition, the ideal would be to have sand made up exclusively of quartz, but no foundry sand reaches this degree of purity.

Sands with quartz content ranging from 85% to 90% are usually used. However, there is no precise correlation between the refractoriness and the mineralogical-chemical composition of the sand: as a rule, sands richer in quartz are more refractory. The term refractory used in the field of foundry sands has a specific meaning: it does not refer to the softening temperature of the mass, identified through the cone method pyrometric, but refers to the temperature of incipient sintering, that is the temperature at which the granules begin to adhere to each other and to the metal. In fact, once cooled, the material is transformed into a mass that adheres to the pure metal in the form of a crust.

As for the granulometry it is necessary that the granules are of similar diameter, to maintain a good porosity of the sand.

The shape of the granules significantly affects the mechanical resistance which, due to the stresses caused by subsequent manipulations, is an important parameter. In most cases, rounded granules with few asperities are to be preferred.

The use of very expensive organic binders impose restrictive limitations on the sands. For this reason, the sands undergo a series of checks before being used for the production of cores:

- granulometry analysis: screening of a certain quantity of sand through various sieves, evaluating the fractions left on the various sieves;
- analysis of the percentage of fine (<0.125mm) and dust (<20mm);
- fineness index (IF): measures the average size of the sand grains;
- grain shape analysis: evaluation through a microscope;
- permeability defined as the volume of air (cm^3) which in one minute, under the pressure of 1 cm of water column, passes through 1 cm^2 of a test tube with a thickness of 1 cm;
- loss on calcination (P.A.C): the sample is heated in a muffle and the difference in weight is determined;
- acid request (ADV): allows you to define the acidity of the sand.

Furthermore, it is possible to regenerate the sand through a thermal and mechanical process, to eliminate the binder from the surface of the grains.

With reference to organic binders, a pyrolysis and therefore thermal treatment is necessary and sufficient. For inorganic binders, on the other hand, a mechanical treatment is also appropriate, which allows the sand to be completely untied.

2.2 Regeneration of foundry sand

Interest in the recovery of foundry waste, including sand, has grown in recent years and will grow again, since exhausted sand is still the most important item of solid waste produced in the foundry today.

The main reason for this interest is mainly of an ecological nature: all national and European laws aim to limit in an ever more stringent way the landfilling of industrial production waste.

The stimulus, imposed by the various legislative policies, has as its main objective the minimization of the environmental impact of foundries, limiting the production of final landfill waste. To this end, it is necessary to try to optimize and increase the efficiency of all production processes, including those of the regeneration of foundry sands.

In parallel with the ecological benefits, highlighted above, it should be emphasized the high quality obtained of the regenerated sand, comparable to a new one, which together with the increasing automation has led to a decrease in operating costs and an increase in the use of such installations.

The purpose of the sand treatment plants is to recover the sand that comes from shakeout in order to regenerate it so that it can be used again in a subsequent production cycle. For foundries that produce cast iron castings, the waste sands contain sands bound with bentonite and sands bound with organic resins, the sand coming from the cores, in fact, is mixed with the green sand resulting from the mould.

While for monotype sands the regeneration process is simpler, due to the presence of a single uniform compound, for mixed sands it is much more complex as the mixture has a composition that can vary over a wide range.

The process for the regeneration of the sand involves several operations in sequence.

In order to reuse the sand for core forming and the sand for the production of new moulds, both primary and secondary regeneration is required.

Primary regeneration makes it possible to obtain the sand grain in its free form. This result can be obtained through the following operations:

1. breaking of shapes and cores, usually obtainable by a vibrating grid;
2. separation of metal burrs through magnetic separators;
3. total separation of the sand grains, with a series of vibrating sieves;

4. elimination of dust and fine from the sand, through a fluidized bed operation;
5. cooling or heating by means of an exchanger;
6. storage in suitable sites.

The secondary regeneration follows the primary regeneration and has the purpose of eliminating the residual binder on the sand granules to obtain a sand comparable to the virgin one. The techniques for secondary regeneration are:

1. mechanical treatments that exploit the friction or collision between the grains and between the grains and parts of the machines;
2. fluidized bed heat treatments, in which the calcination of the sand eliminates the residues of organic binder, clay and mineral black;
3. wet treatments, necessary for the elimination of clay, mineral black, powders and finishes.

Through primary regeneration it is possible to use the sand only for the production of mould, but the production of cores is not possible. On the contrary, after secondary regeneration it is possible to eliminate the introduction of new sand within the core and mould production cycle. In reality, in the process it is necessary to gradually introduce quantities of new sand to compensate for the losses due to the elimination of the fine, small fractions of sand, with the dust.

2.3 Binders

The binders are used to give greater mechanical resistance to the sand cores. The binders can be:

- natural binders (sodium bentonite and natural drying oils);
- artificial inorganic binders (sodium silicate);
- artificial organic binders (phenolic, polyurethane, furan, acrylic resins);
- synthetic binders.

The main properties required of a binder system are the speed of polymerization, the mechanical resistance to cold, the sterrability, the limited production of gas in moulding and casting, the limited effect on the environment and the ease of reuse for the sand after regeneration.

2.4 Issues and emissions

The land sector is one of the most environmentally impacting industrial sectors.
The main challenge regarding the design is to follow the increasingly stringent environmental and safety standards (UNI EN 13725: 2004; Directive 2010/75 / EU of the European Parliament).
For this reason, the entire sector is constantly developing to achieve ever-increasing optimizations in the various aspects that can make the foundry increasingly ecological and safe.
For this purpose, the main fields in which research is concentrated are the minimization of emissions, the efficient use of raw materials and energy, the optimal use of process chemistry, waste reduction and the search for solutions to achieve an always increasing recycling and reuse.

3. Changes and tools to increase sustainability

The attention to greener production processes, involves changes in the production systems. Also the foundry sector is investigated due to its high environmental impact. In particular, within a European project, the Green Foundry LIFE project (LIFE17 ENV/FI/000173) novel technologies are introduced for sand-moulding systems to cut emissions, improve indoor air quality and support the circular economy through re-use of foundry sand that is normally landfilled. The use of inorganic binders in ferrous foundries applied in sand moulding systems improves the environmental and economic impact and also increases competitiveness of the industry. But their use influences the production process to be implemented.
Many foundries use the cold box method to form the cores: the process allows the production of cores in a few seconds and ready for immediate use without using heat. But the traditional process (cold box) undergoes changes if new inorganic binders are introduced: the core blowing machines currently used for the cores must be modified or it is necessary to purchase new machines suitable for the new process.
Cores obtained with inorganic binders are hygroscopic, i.e. they are prone to water absorption causing their rapid deterioration. To solve the problem of the hygroscopicity of the cores, several measures concerning their storage are possible.
Another problem linked to the introduction of the inorganic binder is that it does not burn in contact with the casting metal remaining entirely attached to the sand used to create the mould. So, the inorganic binder must be recirculated together with the sand, using a land recirculation plant.
Some necessary changes and technological innovation in the foundry production processes are investigated in Saetta and Caldarelli (2021).
Saetta et al. (2020) investigate the use of inorganic binders in an Italian foundry: they demonstrate that by acting on operation management it is also possible to improve the company from an environmental point of view. Through a simulation model applied in production planning in order to reduce storage times, it is possible to achieve not only a leaner production system but also an environmentally sustainable production.

3.1 Use of inorganic binders

The use of inorganic binders in the foundries production processes is investigated in some European foundries.

Cores produced with inorganic binders are tested and their behaviours are evaluated. Also the characteristics of castings made with inorganic cores are evaluated.

Both for the environmental point of view and both for the mechanical properties, the results are very encouraging. The cores produced with the new binders

are comparable in properties to those currently used and formed with organic binders. These inorganic cores have some advantages, such as the absence of imperfections in the casting due to the minimum formation of gas evaporated during casting, and some disadvantages which, however, do not preclude their use on an industrial scale.
From the industrial plant point of view, however, it is necessary to understand any critical issues regarding the use of this technology. Compared to the current systems, the necessary changes should be evaluated both from a technological and from an economic point of view. In particular, the regeneration of waste sands is a crucial aspect, because specific treatment plants are not yet in production. Surely this aspect could be the greatest obstacle to the introduction of the new technology. However, on the basis of the results obtained, relative to the quality of the cores produced, and on the basis of the possible environmental benefits this process deserves increasing attention as well as use of resources. This effort is necessary to pursue the ambitious goal of reducing polluting emissions for one of most pollutant sectors.

4. Waste reuse

Different surplus foundry sand purification and reuse methods reduce the amount of waste sand and create new reuse applications for surplus foundry sand. One of the reuse applications is cleaning the waste sand by composting method.
Organic binders are almost exclusively synthetic resins which are cured by the addition of a separate hardener or catalyst. Inorganic binders are based on sodium silicates. Combinations of foundry sand with animal manure or other organic waste sludges are made and the different material mixtures are carefully studied and monitored to find out the most effective way of handling and cleaning the foundry waste sand. The process is steered in a direction that useful humus occurs with good fertilizing abilities. The end-product must meet the national regulations and limit values.

The "pure" foundry sand is in all cases silica sand (quartz sand). All the tested sand and dust specimens were analysed and compared with the limit values of non-hazardous inert waste.

The results of the inorganic and organic binder system waste sand and dust specimens are presented in table 1. Organic sand "Sample D" represents organic binder system "Alphaset" phenolic waste sand type and "Sample E" is the same sand type dust specimen. Inorganic binder system samples are from different suppliers.

In the table 1 only those compounds which exceeded the limit value set of the non-hazardous inert waste are presented. DOC, phenol, fluoride and molybdenum concentrations of the organic binder system waste sand and dust (phenolic type) exceeded the inert waste limit values. Highest DOC concentration was detected in phenolic dust specimen.
Some inorganic binder system waste sand samples exceeded the DOC and fluoride concentrations of inert waste limit values. Based on the information received the inorganic binders themselves are free of organic substances but some suppliers may use small amount of organic substances in the hardener. Therefore, higher DOC concentrations were detected among some inorganic binder system waste sands. Fluoride origin most likely from the feeder systems used in the foundry.

Some of the tested inorganic binder systems fulfilled both the limit values of non-hazardous inert waste as according to the Government Decree of landfills and the Government Decree on the Recovery of Certain Wastes in Earth Construction 843/2017 (some reuse categories). These inorganic binder system waste sands could be reused without any additional cleaning method e.g. in geo-engineering and road construction purposes. It could also be mixed with other compost materials in the beginning or end of the composting process instead of using virgin soil material that is needed as part of the compost material.

Based on project composting test results, the existing harmful substances of the organic binder system waste sands/dusts will be effectively degraded by composting method. This can be recommended as efficient cleaning method for foundry waste sands and the purified waste sand and compost material can be re-used as mixture soil material in gardening, green construction or noise embankment purposes.

Summarizing, the use of inorganic binders in foundry processes introduces a change in waste management. In the left part of Figure 4 we can see that the exhausted sand of the foundry and the animal manure are separately brought to the landfill. On the right side, with technological innovation, it is possible to compost these two types of waste together to obtain a composting material to be used in the fields, etc.

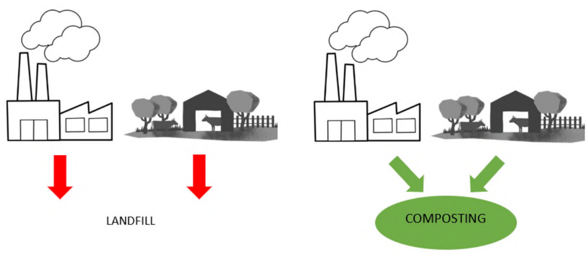

Figure 4: Changes in waste management

Table 1: Results of the inorganic and organic binder system waste sand and dust specimens tested

	INORGANIC SANDS					ORGANIC SANDS			LIMIT VALUE FOR NON-HAZARDOUS INERT WASTE
	A1	A2	A3	B1	B2	C	D	E	
Dissolved organic carbon (DOC) [mg/kg dm]	90	37	230	640	680	610	1600	4500	500
Phenol index [mg/kg dm]	<0,1	<0,1	0,11	<0,10	<0,10	<0,10	2,10	1,20	1
Fluoride [mg/kg dm]	<5	5,5	<5,0	<5,0	41	32	23	180	10
Molybdenum (Mo) (mg/kg LS = 10 l/kg) [mg/kg dm]	0,04	0,02	0,03	0,03	<0,01	<0,01	0,02	1,08	0,5

5. Conclusions

The paper shows interesting results on reusability of the foundry waste. Introducing technological innovations and tools in the perspective of Industry 4.0, economic and environmental advantages are obtained. In particular, the innovations and the tools make possible an important change in the waste management system, reducing the associated problems and bringing excellent advantages.

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