A REVIEW OF POSSIBLE SAND RECLAMATION METHODS FOR ADDITIVE MANUFACTURING PROCESSES

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ABSTRACT

With the escalating price of new sand and the disposal cost of waste sand, sand reclamation has become increasingly important for foundry processes. This paper reviews the possibility of reclaiming and reusing waste furan-bonded sand generated during three-dimensional printing of sand cores. The paper describes the different reclamation processes applied to reclaim and reuse waste sand and discuss the suitability of the reclaimed sand in additive manufacturing, in particular voxeljet three-dimensional printing. The paper is a precursor to possible research in the field of three-dimensional printing sand recycling aiming at reducing the cost of local processes.

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1. INTRODUCTION

Three-dimensional printing (3DP) is an additive manufacturing technique for fabricating a wide range of structures and complex geometries from 3D model data [1]. It uses a software that slices the 3D model into layers. Each layer is then traced onto the build plate by the printer. Once the shape is completed, the build plate is lowered and the next layer is added on top of the previous one. 3DP technologies have evolved from rapid prototyping to rapid tooling, rapid manufacturing and rapid casting. The most important thing is that 3DP can realize the change from traditionally separated parts and labour-intensive processes to the saving of material, time, cost and weight. The layer-by-layer additive manufacturing methods are set to revolutionise the casting industry [2].

Ingberman and Assavaniwej pointed out that the casting process is very complicated. It involves making the pattern manually or by machine, making the core and mould separately. This requires skilled craftsmen to create each part of the pattern perfectly while considering the path of the molten metal, shrinkage allowance and the solidification process, which is often time-consuming. These disadvantages provide room for the application of 3DP technologies in casting production. 3DP is therefore slowly finding its way into the process, such as printing wax patterns, ceramic shells, sand cores and sand moulds [3].

Recent 3DP technologies for rapid sand casting include ZCast, ExOne and voxeljet; these are just some of the most visible examples on the market that are used to produce sand moulds and cores using a binder jetting technology. These technologies can be used in the foundry, automotive and design industry [4]. ZCast technology involves the printing of mould cavity and inserts directly on the 3DP using ZCast powder, a plaster-ceramic composite appropriate for metal casting. This technology eliminates the pattern-making step in the traditional casting processes [5]. ExOne 3DP uses a 3D CAD file to produce a custom-finished product from metal, sand or ceramic materials. With a high print speed and endless part geometry, ExOne technology is an optimum alternative for printing cost-effective, customized parts using industrial-grade materials [6].

Voxeljet technology uses a powder binder jetting process. A binder is selectively applied to a powder bed with the aid of nozzles, thus bonding the individual layers together. This type of technology produces sand moulds and cores for metal casting quickly and cost-effectively. The binding agents that can be used include furan and phenolic resins as well as inorganic binders [7]. However, during the printing of the furan-bonded sand cores using the voxeljet VX 1000 printer, waste sand is produced.

Sand reclamation of used moulding and core sand is defined as a treatment of waste refractory material. This allows the recovery of at least one component where the properties of the reclaimed waste product are similar to the properties of the new component, and can be reused for mould and core production. The advantage of sand reclamation is that it offers economic utilisation, self-sufficiency, no freight and delay, and no necessity for the bulk inventory [8]. If sand is to be reclaimed successfully the reclamation process must not only restore the condition of the sand by breaking down agglomerates and removing particles of metal flash but the process must also enable the sand to be reused with the same type of binding agent as before [9]. Equation 1 is used to determine the level of residual resin in the sand. For efficient reclaimed sand, P should not exceed 3.0% [10].

$$P = \frac{TB}{1 - TR}$$

Equation 1: %Resin in the sand.

Where B is the binder addition (%), T is the fraction of binder remaining after reclamation and R is the fraction of sand re-used. There are three types of sand reclamation methods applied to reclaim used sand systems in the foundry, namely mechanical reclamation, thermal reclamation and sand dilution.

1.1 Mechanical reclamation

Mechanical reclamation or mechanical attrition is a process that involves the breakdown of the lumps of sand to grain size. This is followed by mechanical scrubbing and the removal of the partially burnt binder [10]. The process relies on the fact that the heat of the casting burns the resin binder close to the metal. The more the sand has been heated, the more effective the reclamation of the sand. Prolonged scrubbing is also known to be effective [11]. The major benefit of using mechanical reclamation is that it is a low-cost method of reclaiming waste sand efficiently and up to 90% of the sand can be reused, provided that Sulphonic acid was used as a catalyst. Figure 1 shows the mechanical attrition process.

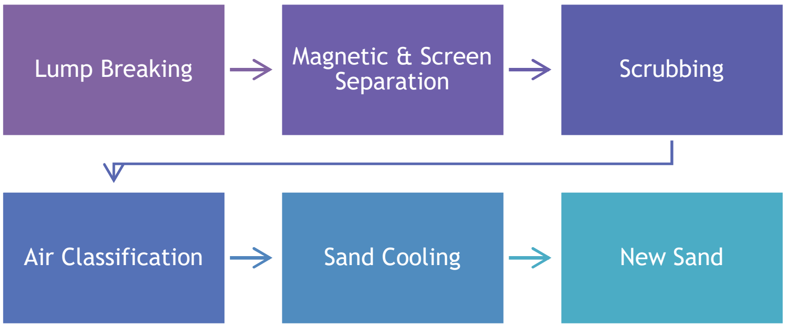


Figure 1: Mechanical attrition process.

Mechanical attrition does not remove all the residual binder from the sand; in fact, the continued re-use of reclaimed sand will result in increasing residual binder levels [10]. A decrease in ignition losses of the reclaimed material has been observed with an increase of reclamation time, indicating that the resin is removed more precisely with prolonged scrubbing [11].

Sand grain modification is another important aspect of mechanical reclamation [12]. During mechanical reclamation, rubbing occurs between sand grains and also against surfaces of the various equipment of the reclamation system. As a result, sharp corners of the original sand get rounded causing reduced surface-to-volume ratio, which ultimately reduces binder demand. Therefore the use of reclaimed sand to make sand moulds and cores is proving to not only be a green solution but an economical one as well, since less resin addition will be required. Consequently, there will also be a reduced chance of getting gas-related defects in castings [12].

1.2 Thermal reclamation

The thermal reclamation system is preceded by a mechanical system, which uses a unique fluidised, gas-fired bed design to combust and removes the remaining residual sand coatings. Figure 2 shows the thermal attrition process.

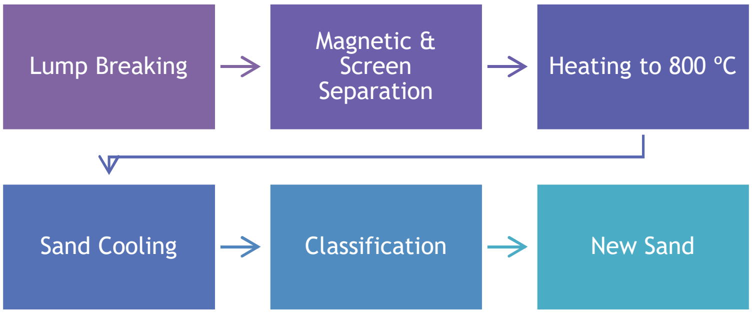


Figure 2: Thermal attrition process.

The thermal reclamation process has proven to be a better alternative to reclaim waste sand as most of the sand is reused; almost no dumping is necessary resulting in a safer and cleaner environment. It also conserves natural resources by eliminating the purchasing of new sand; making it a highly energy-efficient process.

Thermally reclaimed sand has been demonstrated to be better than fresh sand because the sand undergoes lower thermal expansion resulting in better mould stability. The sand grains are more rounded resulting in less binder demand. Irrespective of the binder system in the previous cycle, thermally reclaimed sand can be used with any chemical binder system [8].

1.3 Sand dilution

Sand dilution is a process that involves the mixing of contaminated sand with a portion of virgin sand while still maintaining the sand's properties. This is because the quality of three-dimensional printed moulds depends on properties such as strength, permeability, thermal stability, collapsibility and density, to name a few. During recycling, contaminated sand, which has a layer of resin from previous coatings, is mixed with new sand. The contaminants may change the shape and increase the size of the grains, consequently affecting the properties of the mould. Large grains would result in low compaction and consequently high permeability. It is known that enough permeability allows gases to escape from the mould, reducing pressure ahead of the molten metal and subsequently improving filling ability. However, high permeability might hint at the likelihood of metal penetration defect and poor surface finish. In addition to the above-mentioned disadvantages, mould strength and density are also reduced due to poor compaction [3].

2. METHODOLOGY

In this study, waste furan-bonded sand generated from 3DP using the voxeljet VX 1000 printer will be reclaimed using the previously mentioned methods of sand reclamation. The properties of the grains of sand produced from using reclaimed sand will be assessed and compared to those produced using new sand.

2.1 Raw material

The raw material will include waste furan-bonded sand, virgin sand, furfuryl alcohol resin and sulphonic acid. The waste furan-bonded sand will be collected during the removal of the sand after printing is complete.

2.2 Sand reclamation

2.2.1 Mechanical reclamation

The excess contaminated waste sand will be transferred into a batch mixer for dry milling. Milling time will vary between 20, 30 and 40 minutes depending on the residual resin after milling. Equation 1 will be used to determine the level of residual resin in the sand after each milling cycle. Sand dilution

2.2.2 Thermal reclamation

The thermal reclaimer unit with the fluidized bed is a mixing system that is composed of a fluidizing agent which is a combination of air and oxygen at a ratio of 1:2. The fluidising agent will be fed into the system for 10 seconds. Thermal reclamation with periodic fluid bed mixing will take place at 800 ºC and the time of reclamation will vary between 10, 20 and 30 minutes. Equation 1 will be used to determine the level of residual resin in the sand after each cycle.

2.2.3 Sand dilution

The excess contaminated sand will be characterized by performing X-ray fluorescence and X-ray diffraction to check the chemical composition and the quality, followed by testing loss on ignition. Addition rates of 10, 20, 30 and 40 percent of used sand will then be mixed with new sand. Equation 1 will be used to determine the level of residual resin in the sand after each sand addition.

2.3 Sand characterization

The sand reclaimed will be tested as per procedures recommended by the American Foundry Society to determine the following properties:

- Grain size distribution
- Grain shape
- Chemical composition
- Flowability
- pH
- Loss on ignition
- Acid demand value
- Bulk density

2.4 Sand coating

The process of sand coating will begin once the reclaimed sand has been tested and characterized. Sand coating will consist of the addition of sulphonic acid to 50 kg of silica sand in a foundry batch sand mixer. The sulphonic acid addition will vary while the mixing time is maintained at a constant 5 minutes per batch of sand. The prepared coated batches will be stored in sealed plastic buckets before additive manufacturing in order to prevent acid evaporation and moisture pick up.

2.5 Three-dimensional printing

A Voxeljet VX1000 three-dimensional printer will be used for this study. The pre-coated sand will be fed into the system. The system will apply successive layers of pre-coated sand which are 300 microns thick, printing out the tensile and transverse sand cores. The geometries and dimensions of specimens will be according to the AFS standards.

2.6 Curing & testing

The printed standard specimens will be oven-cured at 105-110 °C for two hours to achieve complete bond strength. The transverse and tensile test specimens will be tested for mechanical properties and will be assessed in terms of tensile and transverse strength. The test specimens will also be tested for other physical properties such as hardness (Scale B), friability, surface finish and density. Appropriate foundry sand testing equipment and corresponding testing instructions from Ridsdale and Ridsdale Dieter [14] will be used to determine the strength, hardness, and friability. The surface finish will be determined using a TIME instrument model TR 110 [15].

3. RESULTS & DISCUSSION

A study was conducted by Nyembwe et al. [16] to try and understand the suitability of sulphonic acid-coated sand for 3DP applications. The study found that a high content of sulphonic acid results in an increase in mechanical strength of the sand cores, but a drop in the flowability of the coated sand was observed which could cause difficulties such as clogging during the printing of sand which uses a layer-by-layer manufacturing technique. However, it was reported that the flowability of the coated sand tends to improve with prolonged storage time as the sulphonic acids in the sand drop due to acid evaporation [16]. Figure 3 shows the effects of storage time on sulphonic acid-coated sand.

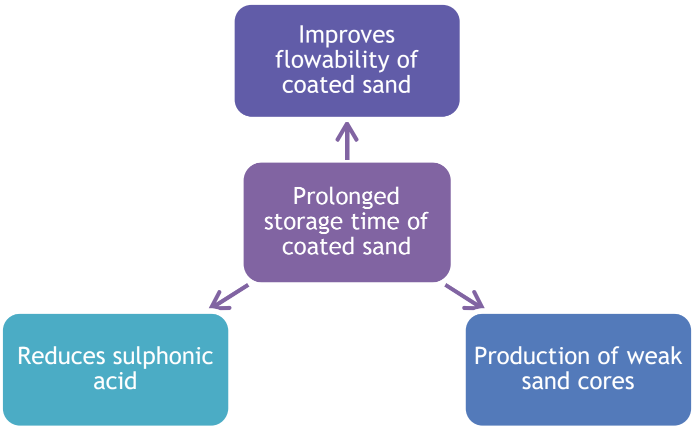


Figure 3: The effects of storage time on sulphonic coated sand.

Further work was conducted by Nyembwe et al. [4] to investigate the physical properties of the sand cores using the voxeljet VX 1000 3DP. Their observations found that the general strength and density of sand cores produced from 3DP are lower than hand-rammed cores simply because there is little to no compaction of the sand. The study also recommended the heat curing of the sand cores after 3DP to compensate for the poor compaction of the sand as well as to maximize the strength. This process will ultimately improve the friability of the grains of sand produced. Hardness, surface finish and density were not found to be affected by the heat curing [4]. Figure 4 shows the effects of sand grain fineness on sand cores.

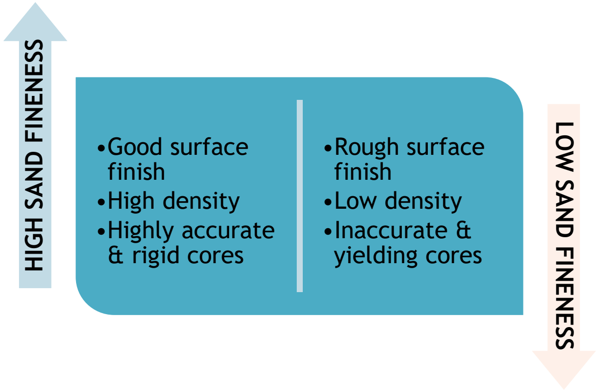


Figure 4: The effects of sand grain fineness.

Surface finish and density are majorly affected by the physical state of the sand. In a study conducted by Nyembwe et al. [17], it was found that the AFS and AGS will affect the surface finish of the sand: the finer the sand grains, the smoother the surface finish of the sand core and vice versa. The sand analysis was conducted on recycled sand and new sand. The results indicated that recycled sand is slightly finer than new sand, see figure 5. As such, recycled sand is expected to produce grains that have a smoother surface finish. An SEM analysis was also conducted on recycled sand and new sand and the results show that recycled sand is sub-angular to rounded whereas new sand is more angular, see figures 5(a) and 5(b). In addition, round and spherical grains pack better than angular and elongated grains, and will generally produce much denser and more rigid sand cores and moulds [17].

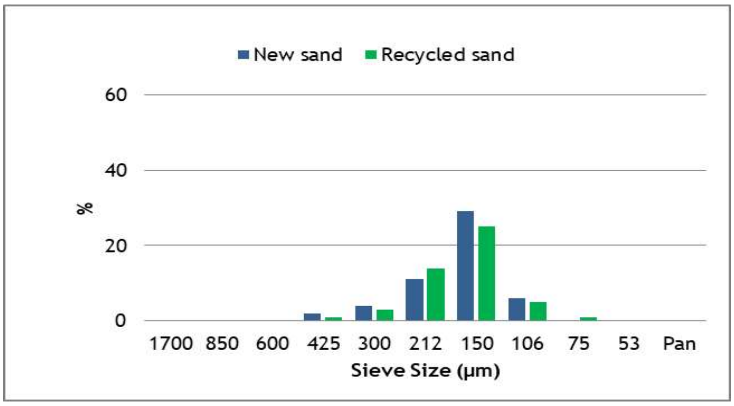


Figure 5: Grain size distribution of new sand vs. recycled sand.

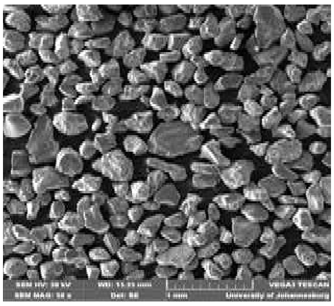
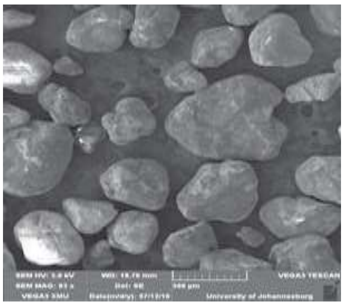
(a)  (b) 

Figure 6: Average grain shape of *(a)* new sand, *(b)* recycled sand.

4. CONCLUSION

The demand for more complex and highly precise castings is increasing in conjunction with strict health and environmental regulations. This becomes difficult for foundries that are still using the old traditional method of casting to remain competitive. And, with the rising foundry waste disposal costs as well as the possible restriction on the mining of sand, green solutions, such as reclamation and re-use of self-hardening sand, have become a matter of increasing importance. This research is aimed at reviewing possible sand reclamation methods for additive manufacturing of sand cores. The mechanical and thermal reclamation process is capable of specifically removing the binding agent thus allowing large quantities of sand to be reused. With the addition of recycling by dilution, all three processes result in reducing the costs of purchasing new sand, storage and transport to the landfills. Tonnages of discarded sand are reduced, which in turn saves lives and the environment.

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