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Evaluation of 3D-printed Pattern Material for Heat-hardened Inorganic Moulds

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Abstract

Inorganic binders for sand moulding are currently of high interest due to the need to lessen our environmental impact and emissions. In this study, a heat hardened solid inorganic sodium silicate binder was tested with a 3D printed resin material to see how the use of such a material affected a silica mould's quality, e.g. surface roughness. Results were compared to moulds made with metallic patterns. The unmodified binder had sticking issues when used with a metallic pattern, resulting in a rough as-moulded surface. Such issues were not seen with the printed resin patterns, also hinting at good performance with binders that contain performance increasing additives. The resin pattern material has a Heat Deflection Temperature (HDT) of 230°C, enabling the use of inorganic binders that require temperatures between 160–200°C to harden and dry. Additive manufacturing of such materials also allows designs for other hardening techniques than furnace heating, such as microwave heating. The moulds hardened with microwaves did not exhibit sticking issues. Additive manufacturing of tooling is a potential source of geometrical variation in final castings and are also studied in this work. In general, switching from traditional sand moulding patterns used with organic binder systems to inorganic systems, the patterns and core boxes need to be replaced by new ones made of a metallic or other heat resistant material. The studied material is a promising option for such a switch, especially when a complex shape enabled by additive manufacturing is also required.

Keywords:

solid silicate, inorganic binder, additive manufacturing, patternmaking, heat hardening

1. INTRODUCTION

Inorganic binders for sand moulding are currently of high interest due to the need to lessen our environmental impact and emissions. The foundry industry as a whole is moving towards more sustainable manufacturing processes, as mould materials, i.e. sand, binder and additives are researched to reach such goals. Considering different inorganic binder systems, sodium silicate based binders are those with the most potential for achieving green foundry production in the short term [1].

Solid hydrous silicates are dry counterparts of liquid sodium silicates. In their use as foundry binders, water is added to dissolve a dry powder and then the resulting mixture is used similarly to the traditional liquid silicate binders. One of the advantages of using solid silicates is their ease of storage and transport due to the reduced weight and volume of the material [2]. If foundries only need to add water to a premixed combination of sand and solid silicates or to sodium silicate coated sand, certain foundry operations could be simplified. However, before introducing solid silicates as mainline foundry binders, or their widespread use in 3D printing, more data and trials are needed to overcome the already known challenges, or to identify any new issues associated with their use. In a previous study, high surface roughness of castings was seen with solid silicate moulds [3], which was attributed at least partly to the difficulty of metal pattern release from the mould, as the mould stuck strongly to the pattern after heat hardening.

One way to rectify sticking issues is to study the pattern materials employed. In general, switching from traditional sand moulding patterns used with organic binder systems to inorganic systems, the patterns and core boxes need to be replaced by new ones made of metallic or other heat resistant materials, if the hardening is to be done physically with heat rather than chemically. Making all patterns for sandcasting purposes out of metal is neither cost-effective nor sustainable. Traditional synthetic pattern materials like polyurethane have heat distortion temperatures (HDT) generally less than 100°C, which is not enough for the silicate hardening process temperatures of around 160°C. One style of heating not so commonly used in mouldmaking is the use of microwaves, which is a potential way to heat up the binder to the required temperatures. It has been shown that the cost of hardening sodium silicate bonded cores could be much reduced with microwave heating [4], and the required strength could be obtained even with much smaller dosing amount of binder, as found out in [5]. Naturally, metallic patterns are not optimal for microwave heating due to the reflection of the waves, necessitating a pattern material of high enough HDT and microwave permeability.

Considerable research has been devoted to studying the chemical hardening processes and performance of inorganic binders, but research on the tooling materials themselves are rather rare or the documentation on the materials are very limited. In the case of microwave heating, one of the biggest challenges to the broader adoption by the industry has been the choice of tooling materials [6]. Microwave transparent materials like quartz glass or polytetrafluoroethylene (PTFE) are not particularly suitable due to properties such as wear resistance [6]. PTFE is one of the main-line studied materials when microwave hardening studies have been done [4]. One way of circumventing the whole use of tooling is to utilize additive manufacturing technologies such as sand 3D-printing [2, 7]. However, the complete replacement of traditional moulding methods with additive manufacturing does not seem industrially viable at least in the near term, necessitating research and progress on patternmaking for inorganic moulding materials. In this study, a heat hardened solid inorganic sodium silicate binder was tested with a 3D-printed resin material to see how such a use affected a silica mould's quality, e.g. surface roughness. Results were compared to moulds made with a metal pattern, in the style of a previous study [3].

2. EXPERIMENTAL METHOD

Two types of patterns were tested in this study; a metallic pattern made of aluminium and a plastic pattern additively manufactured from a commercially available heat resistant resin. The designed geometries are shown in Figure 1, while the final 3D-prints are shown in Figure 2. The resin used for pattern printing has a heat deflection temperature (HDT) of 230°C, which is higher than the usual hardening temperatures for inorganic binders. The size of the pattern geometry, the cavity, is 120 mm × 90 mm × 30 mm.

Base properties of the sand used in this study are given in Table 1 while the tested combinations of binders and pattern materials are shown in Table 2.

For each batch of sand and binder mixture, 2500 g of sand was used. Addition rate of solid silicate was 0.83% by mass of sand and water addition of 1.17% by mass of sand. Example: sand 2500 g, solid silicate 20.75 g, water 29.25 g. When the sodium silicate mould was heat hardened in a furnace, they were heated at 160°C for 1 hour. Microwave heating of moulds were done at 650 W and 5 min. The liquid silicate used for comparison is a commercial modified sodium silicate binder hardened with ester, with addition rates 2.5% of binder to weight of sand and 12% of hardener to the weight of binder. The liquid silicate has an organic element in the mixture and is useable with all common pattern materials, and as such do not generally have pattern release issues leading to it being chosen as a reference for the other combinations in this study.

The used patterns and moulds were 3D scanned at several stages using a system based on structured light, with manufacturer claimed accuracy up to 0.05 mm. Results of the 3D scanning were compared to the ideal dimensions of the designed 3D CAD-models using mesh-to-mesh analysis, showing areas of potential deformation and other defects.

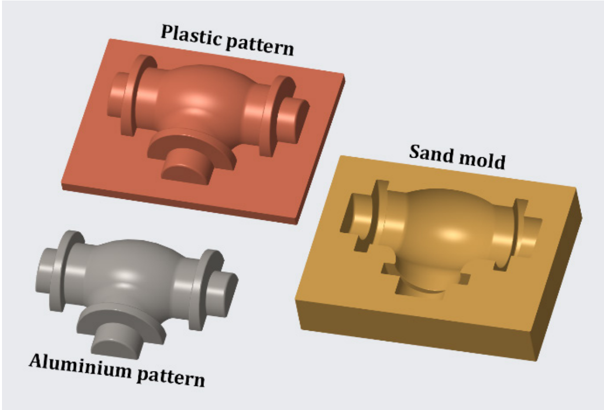

Fig. 1. Used pattern types and geometries

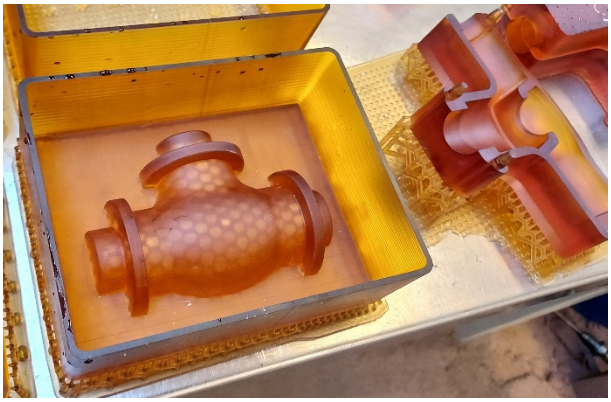

Fig. 2. Pattern and flask after 3D-printing

Table 1
Base properties of silica sand used in the study

Composition	Density	AFS GFN	Mean Particle Size
SiO_2 > 98%	1.52 g/cm^3	46.40	0.33 mm

Table 2
Tested combinations of binder, hardening method and pattern type used in the study

Sample name	Binder	Hardening method	Pattern type	Mold release
SFM1	Solid Silicate	Furnace heat 160°C, 1 h	Metal	No
SFM2	Solid Silicate	Furnace heat 160°C, 1 h	Metal	Yes
SMP1	Solid Silicate	Microwave	Printed Plastic	No
SMP2	Solid Silicate	Microwave	Printed Plastic	Yes
SFP1	Solid Silicate	Furnace heat 160°C, 1 h	Printed Plastic	No
SFP2	Solid Silicate	Furnace heat 160°C, 1 h	Printed Plastic	Yes
LM1	Liquid Silicate	Ester	Metal	No
LM2	Liquid Silicate	Ester	Printed Plastic	No

3. RESULTS

The plastic pattern was manufactured with a stereolithography (SLA) type of machine, with a layer height of 100 µm. The prints were cured after printing under UV light at 60°C. Figure 3 shows 3D scanning results for the plastic pattern after 3D-printing and post curing. The part geometry is accurately matched to the ideal 3D-model geometry defined in CAD, although some minor deformation can be seen in the parting surface area. Generally, the printing quality of the material is good without visible layer lines and other surface integrity related aspects often seen with additive manufacturing technologies.

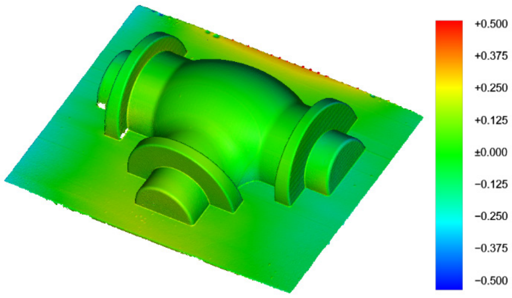

Fig. 3. 3D-scan results of pattern compared to the ideal CAD dimensions, e.g. mesh-to-mesh analysis. Scale in millimetres

Generally, the unmodified solid silicate binder had sticking issues when used with a metallic pattern, resulting in a rough as-moulded surface. Such issues were not seen with the printed resin patterns, hinting also at good performance with binders that contain performance increasing additives. Figure 4 shows one mould sample made with the plastic pattern. The ester hardened liquid silicate binder showcased very little to no issues with either the metal or the plastic pattern.

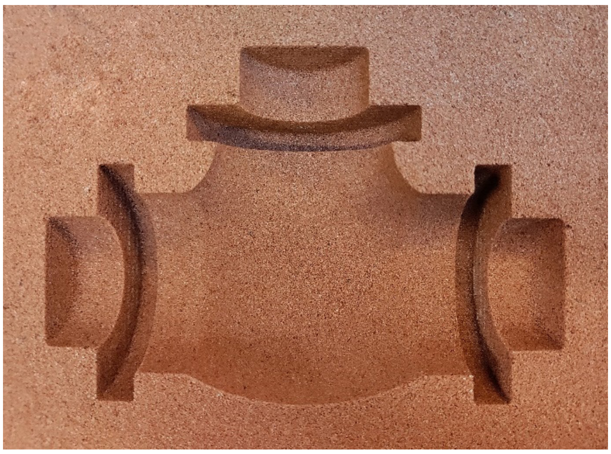

Fig. 4. Example of a mould cavity made with 3D-printed plastic pattern

Results of 3D mesh-to-mesh comparisons of mould cavities are shown in Figures 5–12. In these results, the deviation from the ideal reference model dimensions are indicated as either red, surface higher than the ideal, or blue, loss of sand from the intended cavity geometry.

Figure 5 showcases the results of a solid silicate binder used with a metal pattern. The solid silicate combination tended to stick to the pattern surface, seen as a very rough surface also in the 3D-scan results. The roughness of the sand mould surface was also clear in visual inspection.

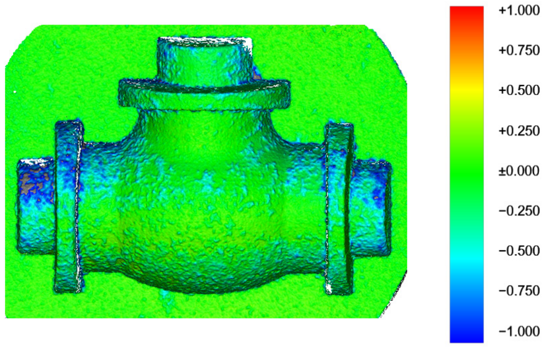

Fig. 5. Mold cavity, sample SFM1, compared to the ideal CAD dimensions. Scale in millimetres

Figure 6 shows the solid silicate binder being used with the metal pattern, with additional use of pattern release compound. The pattern release did not help with the sticking issue, rather than making the general situation worse. This combination had a particularly rough as-released mould surface, like the sample shown in Figure 5.

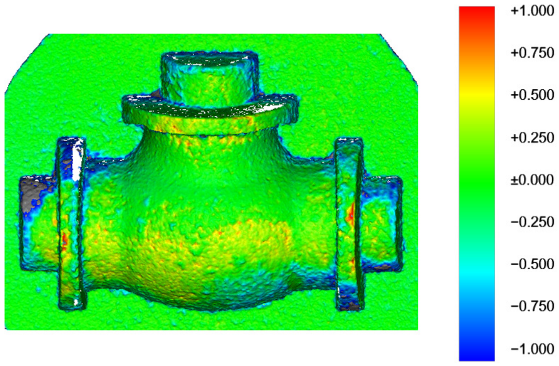

Fig. 6. Mold cavity, sample SFM2, compared to the ideal CAD dimensions. Scale in millimetres

Figure 7 shows the combination of solid silicate binder used with 3D-printed plastic pattern and microwave heating. Very little deformation and sticking was seen in this combination, with a small defect in the sharp corners of the cavity.

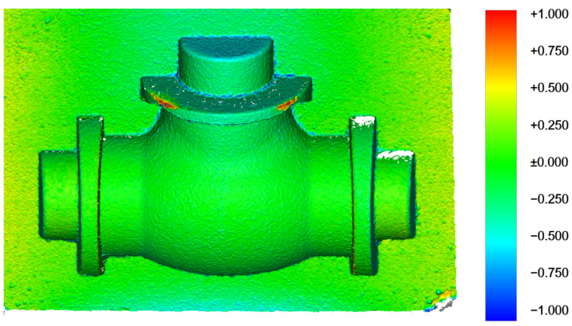

Fig. 7. Mold cavity, sample SMP1, compared to the ideal CAD dimensions. Scale in millimetres

Figure 8 shows the same combination as SMP1, with the addition of mould release. The addition did not change the situation dramatically, having generally very little deviation in the part cavity areas and no major loss of sand from the surface like in the samples made with a metal pattern (SFM1 and SFM2).

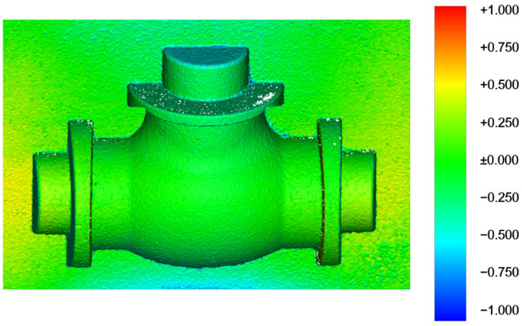

Fig. 8. Mold cavity, sample SMP2, compared to ideal CAD dimensions. Scale in millimetres

Figure 9 shows sample SFP1, furnace heated solid silicate binder used with the 3D-printed plastic pattern. The result is very similar to the microwave heated sample (SMP1) shown in Figure 7. Mould cavity deformation or loss of sand from the surface is very minor.

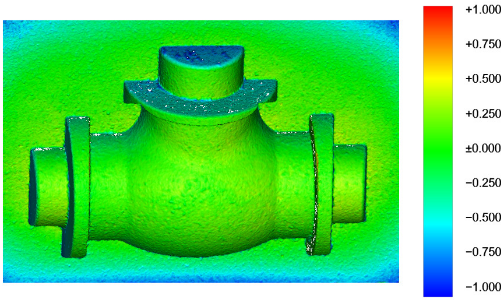

Fig. 9. Mold cavity, sample SFP1, compared to ideal CAD dimensions. Scale in millimetres

Figure 10 shows sample SFP2, furnace heated solid silicate binder with plastic pattern with the addition of mould release. The other mould samples made with the plastic pattern generally had very good surfaces in the cavity, but this combination seemed to be very damaging to the final surfaces.

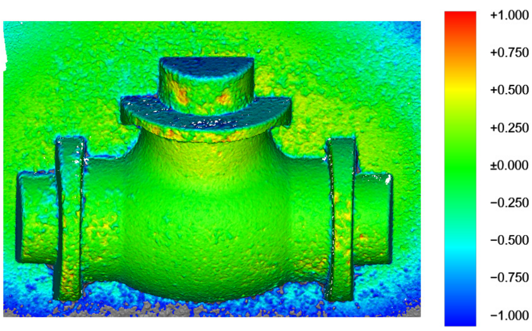

Fig. 10. Mold cavity, sample SFP2, compared to ideal CAD dimensions. Scale in millimetres

Figure 11 shows sample LEM1, ester hardened liquid silicate with metal pattern. Small areas of sand stuck to the pattern can be seen, although the general finish is very good. This combination of works with the metal pattern with no issues.

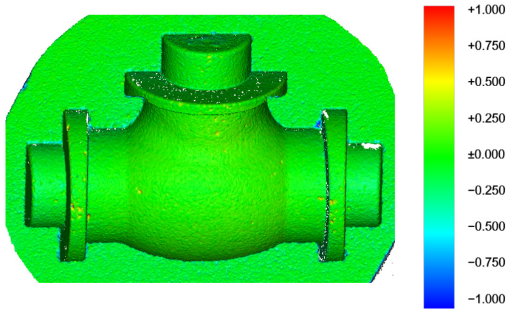

Fig. 11. Mold cavity, sample LEM1, compared to ideal CAD dimensions. Scale in millimetres

Figure 12 shows sample LEM2, ester hardener liquid silicate with plastic pattern. Just a few particles of sand have been stuck to the pattern, while the general quality of the cavity surface is very good. The 3D-printed plastic pattern was scanned again after being used in the various tests, results of which are shown in Figure 13. Neither was there significant deformation to the data when compared to the ideal CAD dimensions nor between the as-printed and used data is seen. Thus, the material is stable at least in the number of moulding operations performed in this study, although additional testing is required to find out longer term performance.

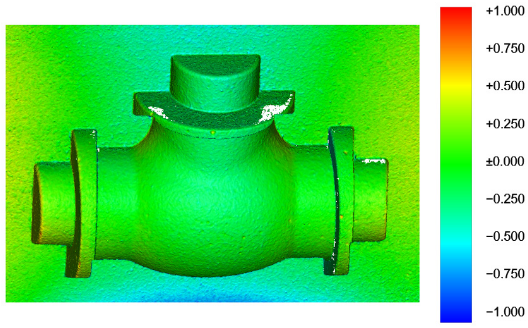

Fig. 12. Mold cavity, sample LEM2, compared to ideal CAD dimensions. Scale in millimetres

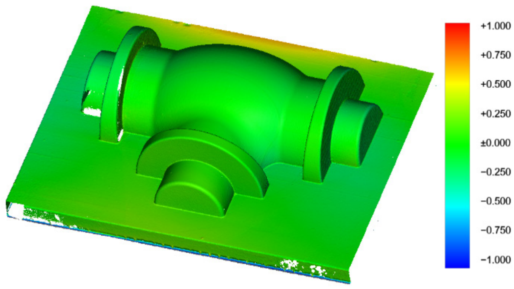

Fig. 13. 3D-scan results of pattern after use, compared to the ideal CAD dimensions, e.g. mesh-to-mesh analysis. Scale in millimetres

4. DISCUSSION

Unmodified solid silicates tend to stick to patterns as seen in this study, as well as in a previous study [3]. Moulds hardened with microwaves did not exhibit sticking issues in the current work. Other than the liquid silicate binder hardened with ester, all the cases with a metallic pattern exhibited issues, seen as loss of sand in the cavity and very rough as-moulded surfaces. The use of a release agent on the surface of the pattern did not make the pattern release visibly better. The plastic pattern used in the study had very good release properties, seen as very minor or any defects seen in the 3D-scan results of the mould surfaces. Use of the release agent did not affect the situation dramatically but did degrade the results in certain cases like furnace heating. From these results, it can be said that this type of plastic material does not require the use of modifiers in the binder or a release agent to work well. The pattern was scanned after printing and post curing, as well as after all the tests done in the course of this study. The pattern did not deform or degrade in this use-scale, which is a promising result for the potential usability of such materials. However, a longer use case-study needs to be made to find out the longer-term effects of heat hardening and heating cycles on the properties.

In general, switching from traditional sand moulding patterns used with organic binder systems to inorganic systems, the patterns and core boxes need to be replaced by new ones made of a metallic or other heat resistant material. The requirement of heat to harden is naturally a hindrance to these type of binders as the additional energy demand affects the required time and thus also costs. Heating large moulds made of insulating sand mixtures evenly poses operational challenges for the foundries, especially when kilns or furnaces are being used. Microwave hardening could be a much faster and efficient process compared to processes like furnace heating [4, 5], if the challenge of applicable microwave transparent pattern materials are overcome [6]. Use of heat resistant pattern materials with a HDT of higher than 160°C, like the plastic material used in this study, also allows processes like microwave hardening. Another potential advantage in additive manufacturing is also the efficient use of materials, enabling the use of different infill structures and hollow sections.

The studied material and its' bulk equivalents are a promising option for a switch to inorganic binders, especially when also the complex shaped enabled by additive manufacturing is required or is advantageous for cast components. However, additive manufacturing of tooling is a potential source of geometrical variation in final castings [8], studied also in this work. Enabling larger scale manufacturing as needed for industrial foundry patterns, the need for printing speeds and volumes are high. More research is needed to find the niche and best available processing methods for any additively manufactured components, as raw material costs often favour the use of traditional subtractive processes. The possibility to use high performance and functionally graded materials [9], allowing location-specific properties, should also be investigated for the use of foundry patterns and core boxes. Investigations on large-scale additive manufacturing in the production of self-heated moulds [10] for composite production have been done. Integrating heating wires and other functional components into tooling during printing process allowed locally heated tools. Such systems could be beneficial for specific foundry tooling as well, especially for inorganic binder systems like those studied in this work. Self-heating tools with a high enough HDT for inorganic binder systems would be an efficient way to transition towards greener foundry processes.

5. CONCLUSIONS

- Unmodified solid silicates tend to stick to patterns as seen in this study, requiring either modification in the binder or a more suitable pattern material.
- One potential pattern material group for the heat hardening process of inorganic silicate binders are plastics with heat deflection temperatures of higher than 160°C, which is required for the silicate binding process. The studied plastic material worked well with the tested material combinations.
- The tested plastic was made with additive manufacturing using the SLA technology, which was seen to produce useable surface qualities for sand moulding. The pattern's geometrical accuracy was not seen affected by the different heating processes, nor was there any large-scale deformation seen in the moulds produced with the pattern.
- The use of a plastic pattern enabled microwave heating to harden the sand-binder mixtures. The use of microwave technologies can enable the production of fast and efficient moulds and coremaking with inorganic binder systems.

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