

3D structures by spark plasma sintering with compliant binder jetted salt moulds

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Short abstract

Additive manufacturing poses challenges for metal composites, hard materials, and some other materials. Here, a 3D printing process is reported for shaping materials into intricate geometries without the need for their printability but instead using 3D printed structures as leachable moulds for near-net-shaping by sintering under geometric constraints. To prove the principal feasibility of such an approach, salt moulds are printed using a binder jetting process with NaCl powder and water-based binders. The moulds are infiltrated with aluminium alloy powder and co-sintered by spark plasma sintering, a fast-sintering technology. The salt moulds are then washed out with water creating finally complex-shaped architectures. The co-sintering process has already been demonstrated in earlier work, employing a different mould manufacturing process.

The reported work focuses on the manufacturing of the moulds as green parts. Several powder compositions combined with several binder formulations have been investigated to find the best combination providing enough stability of the salt mould. To further improve the binder jetting of salt, an active drying system has been integrated into the binder jetting system to dry the bonded layers, thereby increasing stability during the binder jetting process and preventing unwanted diffusion of the binder into the powder bed. In addition, a new recoating blade has been developed that allows finer salt powders and bimodal powders to be processed with improved powder layer quality. The feasibility of the full process chain and the cost-effective and sustainable nature of this new 3D printing process was demonstrated.

Keywords: additive manufacturing, binder jetting, salt printing, near-net-shaping

1. Introduction and background

Near-net shaping of hard materials could support the tool making industry to become more sustainable. This is addressed with a new research project at inspire AG together with sallea (a start-up from ETH Zurich) and the Advanced Manufacturing Lab AMLZ of ETH Zurich. Unlike conventional approaches such as subtractive manufacturing or binder jetting, the project targets two key outcomes: reduced manufacturing effort and minimal material waste. A further motivation is that certain materials, such as pure copper valued for its high electrical conductivity, are difficult to fabricate directly using existing methods (Jiang et al., 2021). Recent work by demonstrated that copper components can be produced using NaCl sacrificial moulds, opening a promising route for near-net shaping of such materials (Bambach et al., 2026). As this will be an entirely new 3D manufacturing process, there are many challenges to overcome. To prove the concept, the first steps comprise material systems that work with moderate temperatures and do not require strong chemicals. Therefore, salt (NaCl) is used to develop a salt mould production method using binder jetting (BJ). The salt mould will then be put in the graphite sintering cylinder and filled with powder of the desired build material, for which the aluminium alloy AlSi10Mg is used. The entire cylinder will then be co-sintered by Spark Plasma Sintering (SPS), a fast-sintering

technology that has advantages due to reduced cycle times and thus low coarsening of the component's microstructure. When compacted, the salt can easily be dissolved in water afterwards. The result is a near-net-shape part. The feasibility of using salt (NaCl) as a space holder material for basic aluminium structures (cones, concentric structures) was recently demonstrated at inspire.

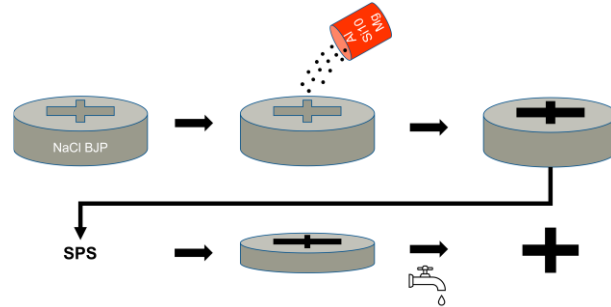


Figure 1: Process chain to be validated.

This work focuses on the manufacturing of salt moulds as green part by binder jetting. The feasibility of the SPS co-sintering has already been proven in earlier work at AMLZ and is not included here.

2. Materials and methods

2.1 Salt powder manufacturing

Sodium chloride (NaCl) is used as a powder, employing two different particle size distributions. The NaCl used was purchased from Sigma Aldrich with a particle size average of 0.5 mm. NaCl powder was wet milled in a Retsch PM100A planetary ball mill, using IPA as a liquid. To create powder with different grain sizes, the milling speed was set to 200 rpm for a bigger particle size and to 400 rpm for a smaller size. The powders P1 to P5 in Table 1 have been manufactured accordingly. Also, a salt powder containing 10 wt% starch was tested, as well as a salt from Schweizer Salinen with anti-caking agent.

Table 1: Used salt powders and their composition

Powder label	Powder composition
P1	100 % wt. 200 rpm
P2	100 % wt. 400 rpm
P3	50 % wt. 200 rpm, 50 % wt. 400 rpm
P4	75 % wt. 200 rpm, 25 % wt. 400 rpm
P5	25 % wt. 200 rpm, 75 % wt. 400 rpm
P6	90 % wt. 200 rpm, 10 wt% starch
P7	NaCl from Schweizer Salinen with anti-caking agent

2.2 Binder evaluation

The binder is an essential component of the Binder Jetting Process and must match both the jettability with the inkjet printhead and the binding characteristics with the salt powder used. Additionally, it must be compatible with the SPS process, where no organic matter should enter, even if this means that the binder is not optimal for the Binder Jetting process. Alternatively, the binder can be removed via a de-binding step, where low organic amounts are preferable.

Table 2: Compositions of the used binders

<i>Binder label</i>	<i>Binder composition</i>
B1	Distilled H ₂ O
B2	70 % wt. H ₂ O, 30 % wt. Trehalose
B3	60 % wt. H ₂ O, 40 % wt. Trehalose
B4	50 % wt. H ₂ O, 50 % wt. Trehalose
B5	40 % wt. H ₂ O, 60 % wt. Trehalose
B6	45 % wt. H ₂ O, 55 % wt. Glycerol
B7	40 % wt. H ₂ O, 60 % wt. Glycerol

To save time, a manual binder pre-evaluation has been done. Each powder of Table 1 has been filled in a row of cylinders (Ø 16 mm, height 3 mm) and each binder of Table 2 has been applied to a column by spraying. All 49 cylinders containing now different powder-binder combinations have been examined for their stability after drying.

2.3 Recoating

The recoating system used is a blade system that is attached to the y-axis of the BJ-Printer. For the evaluation of best recoating results, both the angle (α) of the blade and the distance (h) between the blade and the building surface can be varied to get a good powder layer quality (see Fig. 2).

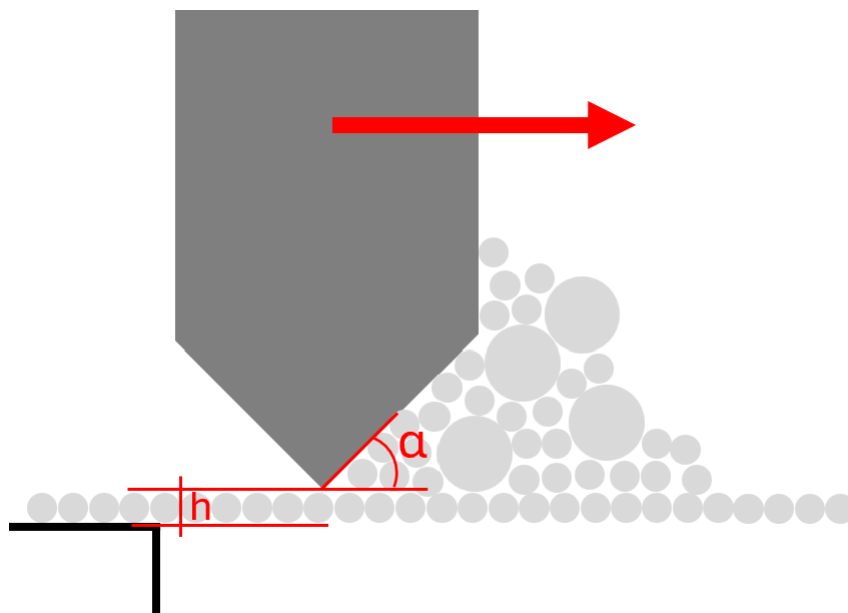


Figure 2: A schematic of the cross-section of the blade recoating system, with powder particles.

Different blade angles α were tested with the same salt composition and with the salt dried before the test runs, as salt easily takes up humidity from the surrounding air and supports agglomeration of the salt powder. The distance h was investigated experimentally and showed some dependencies on the salt composition. The blade material was switched from PETG to steel.

2.4 Binder jetting

A homemade binder jetting platform is used. It has been specifically developed for the purpose of flexible binder jetting with any powder material, a wide range of powder particle sizes, and a set of different inkjet print heads, allowing enough freedom in binder formulation.

2.5 Active drying

Based on earlier work at Inspire, it was evident that active drying of the layer after jetting the binder on it is needed, because recoating of a new layer when the previous one is still wet negatively affected the previous one. An evaluation of drying methods showed that NIR drying offers the greatest utility value. The advantages of NIR LEDs over other heat sources are that the full heat output is available immediately and disappears immediately after switching off. Additionally, they are lightweight, compact, durable, and economical. A FireJet One NIR unit from Phoseon was attached to the printhead holder (fig. 3). This allowed at the same time for pre-drying the powder reservoir prior to recoating. To get rid of the moisture created by the NIR drying process, sufficient air convection was applied by a ventilating system.

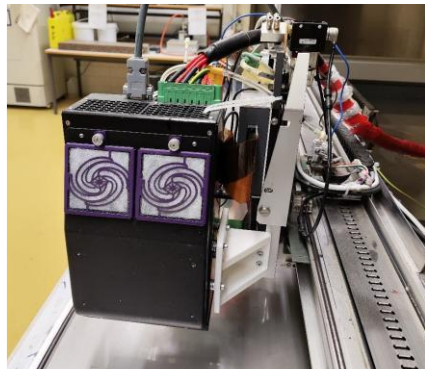


Figure 3: Phoseon FireJet One NIR mounted onto the printhead holder

3. Results and discussion

The pre-evaluation of all powder-binder combinations as described in chapter 2.2 showed that binder B2, consisting of distilled water and 30 wt% trehalose, showed the best stability with most of the powders. Initial recoating tests were carried out on the binder jetting printer using the salt powder from Schweizer Salinen and recoating blades out of PETG. The issue with these blades was that they became statically charged due to friction on the machine table. As a result, a lot of salt stuck to the blade and the powder bed had a correspondingly poor surface. As an improvement, an existing steel blade with a 10° beveled lower edge was tested. With the lower edge opening in the recoating direction, an almost flawless powder layer was produced. Comparable improvements could be achieved with the other salt powders. For all angled blades, the optimum distance h was found to be 1 mm. It is expected that this is also strongly influenced by the particle size of the salt powder. With this improved configuration of the binder jetting printer, simple structures such as cylinders, cubes, and rings have been printed.

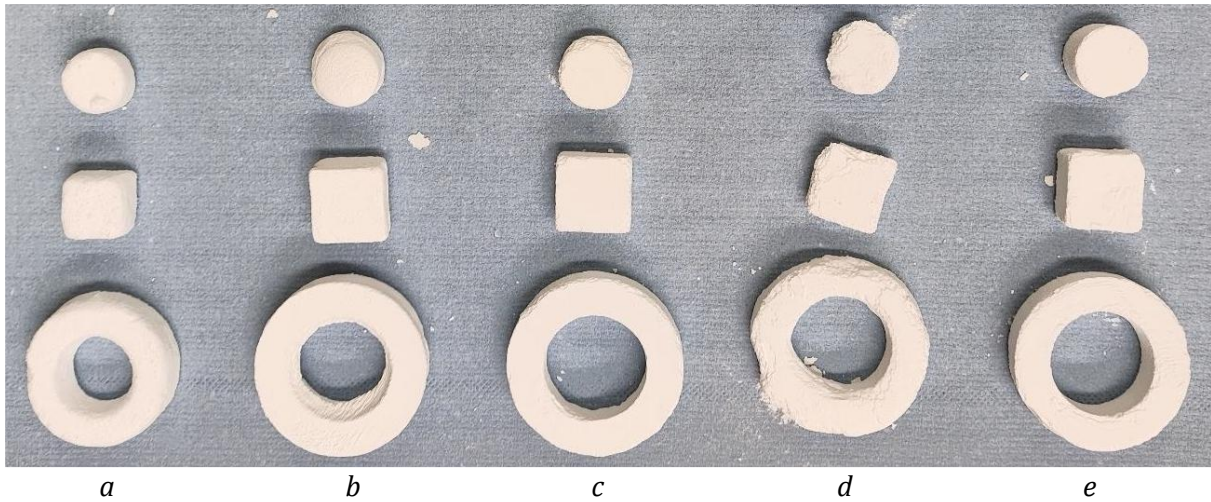


Figure 4: a) Salt P7 from Schweizer Salinen jetted with distilled water (B1) without active drying
b) Salt powder P6 jetted with distilled water (B1) without active drying
c) Salt powder P6 jetted with distilled water (B1) with active drying at a speed of 10 mm/s
d) Salt powder P6 jetted with 30 wt% trehalose binder (B2) with active drying at a speed of 10 mm/s
e) Salt powder P6 jetted with 30 wt% trehalose binder (B2) with active drying at a speed of 100 mm/s

The samples of Figure 4e showed the best stability and accuracy.

The structures produced with pure water and those with the trehalose binder B2 were subject to compression tests to quantify the stability. The mean values are shown in Table 3.

Table 3: Mean values of compression tests

Sample	Salt powder P6 Binder B2 Active drying at 100 mm/s	Salt powder P6 Pure water binder B1 Active drying at 10 mm/s
Young's modulus	2.55 MPa	1.4 MPa
Compressive strength	0.20 MPa	0.15 MPa

As a next step, a structure with overhangs at different angles was printed. The angles are 30°, 45°, 60° and 75°. However, due to the insufficient stability, no complete sample could be produced. The best result is shown in Figure 5, but a part of the structure has broken off due to generally still insufficient stability for such fine structure elements. In principle, even flat overhanging angles should be producible.



Figure 5: Structure with different overhanging edges. The angles are: 60° on the left, 30° on the right, 45° on the back, and 75° on the front.

4. Conclusions

It could be demonstrated that binder jetting of salt moulds by processing salt powders in combination with suitable binders is a feasible approach. A key part in the whole process is active drying, which adds to the quality of the powder layers, helps to increase the stability of the structures during the printing process and prevents unwanted diffusion of the binder into the powder bed. Even a smaller lamp with lower power should be sufficient to dry the powder bed sufficiently. Additionally, the absorption of the NIR radiation could be further improved by adding NIR absorbers tuned to the wavelength of the lamp.

However, the stability of the structures is still critical. Improvements in stability are certainly possible. For this, the optimum ratio of binder quantity, layer thickness, and drying power would have to be evaluated. We are also searching for other binder formulations compatible with the SPS process.

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