An Early Trial on Milling 3D Printed Concrete Geometries: Observations and Insights of the Process

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Abstract. As 3D Concrete Printing (3DCP) technology develops, requirements on the form and surface quality of the final products are increasing. Layer-wise deposition results in the so-called 'staircase effect' which can lead to limitations on the attained precision and accuracy of geometries. Applying other shaping processes with a higher manufacturing precision can be deployed to combat this and milling is one example that has been shown to yield benefits. This paper presents an early trial of a milling process applied after printing and before the final hardened state of the material. A case study of a panel component is presented and observations are reported, which include: the critical nature of the material state, the control of debris and milling path sequence and direction. Insights are formulated into a three-tier structure to help develop signpost issues for the development of the approach.

Keywords: Concrete printing · Milling · Subtractive postprocess · Geometric conformity · Surface finish

1 Introduction

3D Concrete Printing (3DCP) has been the focus of significant research and development activity in architecture, construction and infrastructure in recent years [1]. It enables significant freedom to create complex building forms without formwork in a digitally driven, automated way. Like the other Additive Manufacturing processes, the implicit layer-wise deposition limits the resolution and precision of the features that can be manufactured; sharp corners and surface finish are two examples [2]. There may also be deformation in build due to the material rheology [3]. Such matters become more significant as manufacture moves away from one-off components to those that are needed to integrate with other building systems.

R. Buswell et al. (Eds.): DC 2022, RILEM Bookseries 37, pp. 9–14, 2022.
https://doi.org/10.1007/978-3-031-06116-5_2

Inspired by hybrid manufacturing processes found in manufacturing [4], a few researchers have proposed subtractive post-processes with higher precision such as milling, onto printed surfaces to obtain desirable tolerances [5]. The milled surface finish of printable concrete has also been explored in [6], but the milling process dynamics remain unreported. This paper provides observations of implementing milling mortars prior to their hardened state based on an early trial of manufacturing a curved, ribbed panel component at Loughborough University. Insights are discussed to support future work to develop systematic milling strategies that compliment 3DCP.

2 Milling a Printed Panel Part

A test part of 950 mm long, 400 mm wide and 100 mm high was designed to be curved, ribbed and reinforced. Figure 1 shows the curved surface (Fig. 1a), the reverse surface with three ribs (Fig. 1b) and the cross-section (c), which also indicates where a sheet of alkali-resistant glass textile reinforcement, and 6 mm diameter fibre-reinforced polymer (FRP) bars, were placed.

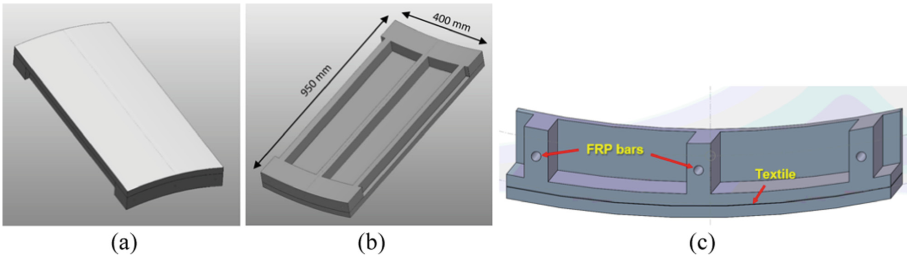


Fig. 1. The trial panel CAD models showing the upper surface (a), ribbed sections (b) and cross-section (c).

A hybrid concrete printing (HCP) workflow was developed and implemented for the manufacture, as shown in Fig. 2. The milling toolpath needs to be generated and physically verified by moving the robot along the toolpath, prior to manufacture. Because this part was not flat, the preparation of a support surface was required, for which the milling was applied to a dense foam base to prepare a curved support in a pre-production step. Reinforcement (textile and FRP bars here) was hand placed during printing, using the printed material as the support. Optical measurement was applied on the completed component for geometric verification (details can be found in [2, 5]).

The part was printed in curved layers onto the milled foam base in an ambient temperature of ~ 20 °C. One layer was printed, the process paused to allow the textile reinforcement to be placed, and then resumed, pausing again for the placement of the FRP bars, before the final layers were printed. The mix reported in [2, 6] was used: a water-binder-sand ratio of 0.255:1:1.499 with 1% superplasticizer and 0.506% retarder (relative to the mass of the binder: 70% cement, 20% fly ash and 10% silica fume). The process configuration was a 30 mm wide filament with a 20 mm stepover and 13 mm layer height.

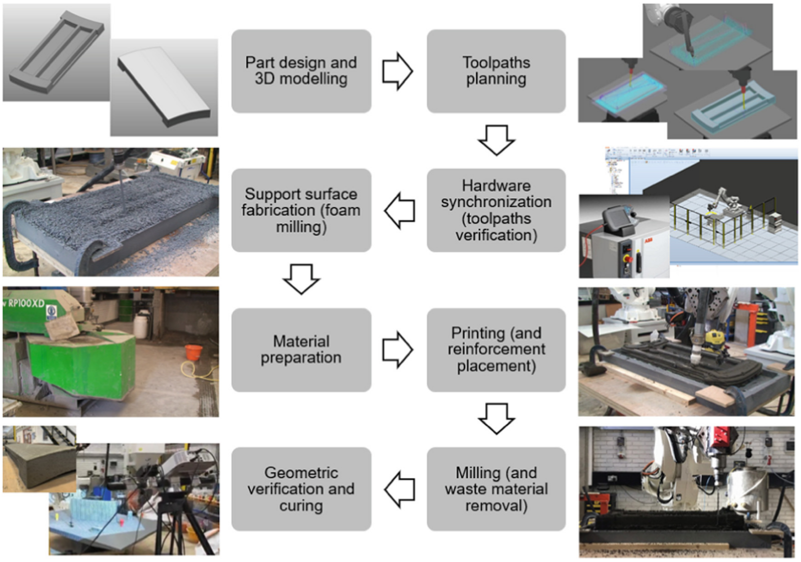


Fig. 2. HCP process workflow for trial panel manufacturing.

The material state is critical for the milling process as the material is required to be sufficiently rigid to withstand the milling force but also soft to allow cutting with milling tools [6]. In this case, the printed part (Fig. 3a – near net-shape) was allowed to cure in the ambient environment for approximately four hours to obtain an appropriately stiff surface. The milling operations used a 12 mm diameter, 283 mm long, 2-flute ball nosed cutter and produced the part shown in Fig. 3b (the net-shape).

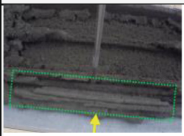
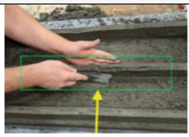
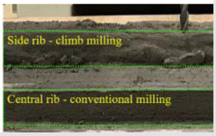
(a) (b)

Fig. 3. A) The printed part (near-net-shape) and b) the part post-milling (net-shape).

3 Results and Discussion

A number of the trial panel parts were manufactured to explore the process parameters that would yield good quality component. Several issues that affected process performance or generated failures were observed. These are presented as a matrix in Table 1 as examples arranged in three levels that improve the overall part quality by increasing degrees.

Table 1. Three-level 3DCP postprocess definition supported by the results of the experiment.

Process Level	**Level 1: Good Form Conformance**		**Level 2: Good Surface Quality**	**Level 3: Good Efficiency**
Observations of counter-ex-amples	 Plastic debris building up and forcing the side rib to collapse under the 'push' of the cutter	 Wrong milling sequence causing the central rib to collapse, saved by manual strengthening of the rib	 Comparison of rib side surface finish under climb milling and conventional milling	Postprocess took 10 times of the printing time (0.5h)
Key factors from evidence	Debris attachment	Milling path sequence	Milling direction; Debris attachment	Curing speed; Cut efficiency; Debris attachment
Correlation with material state	High	Medium	Medium	High

An uncontrolled curing environment (the four hours post printing) proved to be problematic. Estimates of whether the correct milling state had been achieved were based on the exposed surface of the part. For the majority of trials, once the milling cut beneath the first few millimetres of the surface, the material was too soft to cut effectively, creating some of the issues highlighted in Table 1. Controlling water loss and ensuring consistent curing through at least the milling depth is important to enable this approach to be applied effectively.

'Good form conformance' (Table 1: level 1) is achieved when the milling process does not cause any damage or detriment to the net-shape (the target geometric form). Two examples that prevented this from being accomplished were the build-up of debris (milling 'chippings') and the wrong sequence of applied passes with the milling tool.

Ideally, the milled material should form 'chips', or something similar, but the problems experienced when the material if not set sufficiently was that the wet material stuck to the surface of the part and the tool, where it would accumulate and be 'pushed' around the surface by the cutter as it made its subsequent passes. This is difficult to remove and can lead to damage to weaker features (Table 1, level 1: left hand image) and so management of debris is therefore very important.

Another factor that can lead to damage to the net-shape is that ability of the material to sustain the forces imposed by the milling, and this can result in a sensitivity to the sequencing of passes of the tool, particularly when creating fine features (Table 1, level 1: right hand image). Because each milling pass changes the object geometry (shifting the near net-shape a step closer to the net-shape) the rigidity and positional constraints, the path sequence needs to be carefully designed to ensure the tool forces can be sustained throughout manufacture.

'Good surface quality' (Table 1: level 2), is a primary motivation for adding milling to the 3DCP process. The attainable quality of the surface, and the ability to milling effectively is affected by the hardened state of the material [6], the milling direction and rotation and the manner in which the tool it applied to the surface are also all influencing factors.

The material state remains constant when machining typical materials in manufacturing [7], but here the material is transitioning from a plastic state into its final hardened state. Here, the direction of rotation of the tool proved to be important. A conventional milling approach (where the direction of the rotation of the tool goes with the direction of tool travel) tends to scrape debris from the surface to create a neat surface, whilst climb milling (with opposite rotation) was found to 'press' the plastic debris back into the surface, leading to a poor surface finish or even damage. This was most evident on the vertical surface of the rib (see image in Table 1: level 2). In addition, two consequences of the attachment of the debris to the surface were that: the attachment of the debris clogged the milling tool reducing the cut quality; and also the unremoved debris on the part surface could set further and damage the surface finish.

'Good efficiency' (Table 1: level 3) highlights the issues found over manufacturing time to implement the process. It took about one hour to complete the milling plus the four hours after 3DCP to allow the part to cure sufficiently. The printing operation, even with the placement of reinforcement, was around 30 min. There is, however, great potential to reduce this with the use of admixtures.

Some final observations were the trade-off between the softer material being (hypothetically) easier to cut and the resultant surface quality: it was found that several passes for the tool were needed to clean and improve the surface to achieve the required finish. In addition, removing the debris, which for this part largely fell onto the finished part because of its predominantly horizontal orientation, effectively doubled the milling time to allow stopping the machine to clean by hand.

4 Conclusions

This paper reports on early trials of milling 3D printed concrete prior to its fully hardened state. Observations and issues are discussed in terms of three levels of attainment required to deliver a good quality result. The key finding, and perhaps not surprisingly, is the importance of the control of the mortar hardening state. The material state dominates the success of the process effecting the consistency of the debris created during the milling, which can stick to the surfaces of the part and tools. This also has implications for cutting sequencing and the forces that can develop while shaping features leading to potential damage of the net-shape: the target geometry. The degree of material set also influences the ability for the printed structure to sustain the forces imposed by the milling operation and hence it becomes obvious to consider a material 'open time' for the milling in much the same way as the readily accepted principles of printing concrete.

Acknowledgements. This work was supported by the UK's Industrial Strategy Challenge Fund for Transforming Construction, UKRI grant number EP/S031405/1 and grant number EP/SO19618/1.

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