Improvements on the design of sand structure additive manufacturing

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Abstract—Additive manufacturing has been widely used in the industry in recent year. Among a range of applications, printing sand structure for cast ing die or the structure in the construction industry has become more and more popular, since it is cost-effective by using powder printing technology without laser sintering. This paper has explored the additive manufacturing technology used for printing sand structure. To achieve cost-effective and saving materials, methods have been exploring through requirement analysis, materials selection, and design optimization in terms of the mechanical performance of the sand structure. Through 3D modelling, design optimization, and performance improvements, an optimal sand structure for 3D printing is created. This proposed method gives a general way to produce sand structure through 3D printing in the construction and casting industry.

1. INTRODUCTION
Additive manufacturing is also called 3D printing, which has become more and more popular in a range sectors, including manufacturing and construction industry [1]. Originally, this method is invented by Hideo Kodama in 1981 to fabricate plastic models with photo-hardening thermoset polymer [2]. After that, 3D printing has been widely used in various sectors, including manufacturing, healthcare, construction, architecture, even food sector (such as chocolate). There are several reasons for that. Firstly, 3D printing has simplified the manufacturing process. Since it can print a 3D object directly, there is no need to create a mould for the product. Also, some complicated shapes, which are difficult to manufacturing using traditional method, can be easily printed through additive manufacturing. Besides, 3D printing provides an efficiency way of creating prototype, which allows designers to quickly communicate and test their ideas by printing a real object.

In the construction industry, there is also a large potential to apply 3D printing technology [3]. Comparing to traditional methods, the 3D printing technologies could be more environmentally friendly as the waste construction materials can be significantly decreased. Moreover, there are increasing printed materials can be used in building construction, e.g. concrete, gypsum, sands, foam, etc. The remarkable advantages of 3D printing in faster speed, lower labour cost and less waste make it have increasing large market in the construction industry. Among various types of building construction materials, contour crafting is one of them which is suitable for 3D printing. This technology is originally developed by University of Southern California.[4] Applying this method can certainly
reduce manual labour significantly. However, the material used for its printing, as well as the cost-efficient way of creating the printable 3D model need to be explored.

In this case, this paper aims to study the sand materials for the 3D printing used in construction industry, and also explore a systematically way to create the computational model for printing in terms of low cost and good mechanical performance. Since the materials used in construction industry require higher mechanical strength, the viscosity of the sand materials needs to be study together with experiments. To reduce the weight and save materials, a design optimization is required on the 3D modelling of the sand structure to be printed. Therefore, this paper focuses on these two aspects and proposes a solution, together with a case study proving the feasibility.

The rest of the paper has been constructed as follows. Section 2 reviews current methods used for 3D printing sand structure. Section 3 demonstrates the methodology of this study, and Section 4 describes the details and results. A discussion and conclusion are drawn in Section 5.

2. LITERATURE REVIEW

Sand material is widely used in different areas, especially in the construction industry. The 3D printing has provided a novice way to create sand structure. Since the sand structure can be printed directly without laser sintering, it has been used in producing casting die, as it is cost-effective and time-efficient. The principle of printing sand structure is basically using powder printing technique, which is to print sand structure through printing a mixture of sand powder and depositing binder liquid selectively into powder bed layer by layer [5], as shown in Figure 1.

There are more and more attempts to apply 3D printing technologies into the construction industry. Among them, D-shape technology, GRG/GRC printing, and contour crafting are the key technologies used. Specifically, D-shape technique is a type of powder printing, used in construction 3D printing [6]. D-shape is a large three-dimension printer that uses the powder printing technology to print a stone-like item with the sand and binder [7], with a dataset showing the mechanical and physical properties of the D-shape processed stone specimens in Table 1.

Table 1 Mechanical and physical properties of the D-shape process stone specimens.

| Property | Standard | Unit of measure | Value |
|----------|----------|-----------------|-------|
| Apparent density | UNI-EN 1936 | Kg/m³ | 1855.33 |
| Apparent specific weight | UNI-EN 1936 | Kg/m³ | 2200 |
| Total open porosity | UNI-EN 4016 | % | 13 |
| Uniaxial compressive strength | EN 12390-3 | N/mm² | 20.35 |
| Compression resistance | UNI-EN 1936 | Kg/cm² | 175-200 |
| Bending resistance | UNI-EN 12372 | Kg/cm² | 15-35 |
| Young’s modulus (E elastic) | PDE 14146 | N/mm² | 2150 |
| Poisson’s ratio (Strain Gauge Method) | ASTM D390 / D3809M | N/mm² | 634.5 |
| Flexural strength under concentrated load | UNI-EN 12372 | N/mm² | 710 |
| Linear thermal expansion coefficient | EN 14581-11 | c x 10^-6 | 68.3 x 10^-6 |
| Knoop microhardness | EN 14405 | Kg/mm² | 415-230 |
| Water absorption by capillarity | UNI-EN 1122 | % | 0.17 |
| Permeability resistance | prEN 12371 | Kg/cm² | 320-390 |
| Resilience | EN 10545-5 | cm | 50 |
Fibre reinforced gypsum (GRG materials) and Glass-fibre reinforced concrete (GRC) are two new materials used in 3D printing recently. Actually, these two materials have been used in construction and decoration engineering for several years. GRG material is simple installation with high strength for its compressive strength may be as high as 68.9 N/mm² [8]. The combination of GRG materials and 3D printing technology can improve the efficiency of producing the architectural components. GRC is used to produce many concrete architectural products for fountains, planters, status and also decorations. Several companies have tried and developed technologies to print the GRC objects. A construction company named Laing O’Rourke has been developed this technology in 2013 [9]. They can print the GRC materials with fast welding speed and low cost of labour and mould materials. The applications of 3D printing are most likely to reflect the GRC materials’ advantages: high strength, reinforcement, lighter weight, durability and other properties [10].

Besides, contour crafting is a significant method for 3D printing in the construction industry. This term was firstly come up with James B Gardiner in 2011 [11]. Basically, this technology uses the crane to create contour craft forms of the wall layer by layer with materials like concrete. This method can be used in municipal engineering even the structural components, plumbing and utilities.

3. METHODOLOGY

This paper proposes a method on creating a sand structure through 3D printing for the construction industry, which includes three steps, i.e. requirement analysis, material selection, structural design and optimization. Firstly, the requirements on the sand structure to be printed are analyzed, based on the customer’s needs. Various types of 3D printers and their capabilities are also considered. Then, the selection on the sand materials is undertaken, in order to choose suitable materials for the 3D printing sand structure. The microstructure of a range of printable materials, such as ceramic foundry sands, are compared and analyzed with normal sand using scanning electron microscope (SEM), in order to select a suitable one to the sand structure to be printed. In Afterwards, the sand structure is designed for 3D printing, and optimized considering both mechanical properties and cost. In this paper, a decorative Frieze is chosen as case study, and thus its engineering design has been undertaken all through conceptual design, embodiment design and detailed design. Together with a computer-aided design package Solidworks, the decorative Frieze’s 3D model has been created for the 3D printing. A finite element analysis (FEA) is also undertaken to optimize the design model in terms of good mechanical properties and cost-efficiency.

4. RESULTS

4.1 Demand analysis

In the construction industry, there is an increasing need on producing unique shaped structured which is difficult to make using traditional method. In this case, 3D printing is the proper method. Apart from that, using 3D printing can save building materials, time, and labour cost. Since unique shaped structured has more widely used, especially in large buildings like theatre or cinema. Among these materials, decorating Frieze is a popular one which is a decorated component usually used in European style buildings. This component has special and complex shape, and it is made of sand and cement gypsum. Traditionally, it is produced using film faced plywood and shaped by hand. Since plywood can only use once for each unique shape, it cost many materials. It also costs a lot of time and labour for its production. For the decorating Frieze made of gypsum, it has one disadvantage which is bad waterproof. These plaster materials are easy to damp, and may be fusty after a period of time. The new printing materials which can avoid these problems are required.

Previous research has shown that the 3D printing method is more cost-effective than traditional production method [12]. A comparison has been done between 3D printing and traditional production method [13] in regarding of the time cost for a building with 200 m², with result showing the method by 3D printing technology is three times faster than the conventional one.
In this paper, a representative construction component, i.e. decorative frieze, is chosen for studying its feasibility of production by 3D printing. Since decorative frieze has unique and complex shape, it is suitable and able to reveal the advantage of applying 3D printing in the construction industry. By using 3D printing technology, users can print and test their meet its requirements perfectly.

4.2 Materials selection

To produce the decorating frieze through 3D printing, the materials selection is significant. Basically, the decorating frieze is sand structure, which consists of sand materials. However, it should be printable, and thus is different to the normal sand. The printable sand has been firstly studied to see its differences from normal sand, ensuring the mechanical properties of the sand structure to be printed.

The printable sand used in this paper is ceramic foundry sands, also called pearl coated sand with the chemical formula Al₂O₃. This ceramic foundry sand is a new material produced at 2300°C - 2500°C. And the normal sand is the silicon dioxide with chemical formula SiO₂. They are compared using scanning electron microscope (SEM) in different scale, with results shown in Figure 2.

Figure 2. Normal sand (left) and printable sand (right) in SEM

According to the results from SEM, there are three main differences between these two sand materials:

1. Size. The diameter of the printable sand is much smaller than the normal one. The diameter of the printable sand is approximately between 40 µm and 100 µm, while the diameter of the normal sand can reach 500 µm.

2. Morphology. It is obvious from the Figure 2 that the ceramic foundry sand is regular spherical or near spherical, and its surface is quite smooth. However, the silicon dioxide sand has rugged and irregular surface.

3. Uniformity. By measuring the dimensions in the figures, the uniformity of the ceramic foundry sand is fine and more average, but the sizes of silicon dioxide sands are in a wide range.

The comparison results have revealed that the ceramic foundry sand is much more smooth with perfect grain round shape, which can be mixed with binder evenly. In this case, the mixture of sand and binder can be tighter and with higher strength than normal one. Considering the expansion rate, the one for ceramic foundry sand is much smaller than silicon dioxides, which can effectively reduce the defects, such as deformation, cracks caused by high temperature expansion.
4.3 Design and optimization

The engineering design of the decorative frieze has been undertaken, in a process of conceptual design, embodiment design and detailed design. The first stage is conceptual design, which creates the sketches of the decorative frieze to give an overview on its size and shape, as shown in Figure 3.

![Figure 3. Conceptual design of the decorative frieze](image)

After several trial and modification, a general shape of the decorative frieze is determined, a dimension of 150 mm $\times$ 150 mm $\times$ 250 mm. Then, it comes to the embodiment design stages, where a computer-aided design package Solidworks is used to create a 3D virtual model of the decorative frieze, as shown in Figure 4.

![Figure 4. 3D modelling in SolidWorks](image)

Based on this model, design improvements have been undertaken in two aspects. One is to apply a ‘skin-frame’ structure solution, in order to reduce the weight and improve the strength of the decorative frieze, as shown in Figure 5. Another improvement is to use ‘combination reinforcement method’, which is used to find the worst situation in the model and then strengthen these positions. A finite element analysis (FEA) is used to simulate the stress concentration on the model in order to find out the weak point, and then several design improvements can be undertaken based on the FEA results, as shown in Figure 6. This FEA simulation is also used to ensure the mechanical properties of the designed decorative frieze is satisfied, and then this 3D model can be used for the 3D printing.

![Figure 5. ‘Skin – frame’ structural design for frieze](image)
5. DISCUSSION AND CONCLUSION

By undertaking requirement analysis, materials selection and design and optimization, this paper has explored a systematic process on creating a sand structure by 3D printing. A case study on the decorative frieze has shown its feasibility, and the results have proved that sand structure 3D printing design can be cost-effective, materials saving, and strength enhanced.

Also, this paper provides the methods to improve the sand structure 3D model and verifies the printability of the sand structure. A skin-frame method is explored and a network frame is created using a computer-aided design package, i.e. Solidworks. Skin-frame is a useful method original from the truss structure in civil engineering, which can achieve cost-effective and reduce weight significantly. The optimization based on this skin-frame structure is a useful method to reduce the materials used and enhance the strength of the structure.

Some further work can be done on developing software to design the skin-frame networks automatically. The software can be created as a module and integrated to SolidWorks as a plug-in component. In this case, engineers can easily design a sand structure with skin-frame for 3D printing only by inputting several basic parameters. This will make the process of design and optimizing the sand structure for 3D printing more convenient.

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