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3D sand mould printing: a review and a new approach

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Abstract

Purpose – The purpose of this paper is to review available technologies, analyse their features, propose a new approach of 3D sand mould printing based on line forming, introduce the manufacturing principle and show advantages of this approach, especially for larger parts with large Z steps in the build, such as 2 mm stepwise.

Design/methodology/approach –The paper introduces 3D sand mould printing, compares and analyses technological process and existing fabrication approaches among available technologies first. Then, a new approach of 3D sand mould printing is proposed to improve build speed. In addition, the proposed system will be analysed or benchmarked against existing systems.

Findings – By reviewing and analysing available technologies, a new approach based on line forming of sand mould printing is put forward to improve build speed from the aspect of basic molding movement instead of optimization of molding method and process parameter. The theoretical calculation and analysis shows that build speed can be improved greatly and it is more suitable for the manufacture of large scale casting's sand mould when considering dimensional accuracy and printing error, as well as uniformity of each layer.

Research limitations/implications –The specific implement scheme of line forming and nozzle's specific structure of this new approach needs further study.

Practical implications – Much higher build speed of 3D sand mould printing with new approach brings evident implication for moulds companies and manufacturing industry, having a far-reaching influence on the development of national economy.

Originality/value – This paper reviews available technologies and presents a new approach of 3D sand mould printing for the first time. Analysis of new approach shows that this new method of sand mould printing can boost build speed greatly. So, its application prospect is great.

Keywords: 3D sand mould printing, AM, 3DP, SLS, PCM, line forming

Abbreviations

3DP Three Dimensional Printing

AM Additive Manufacture

CAD Computer Aided Design

CAMTC Advanced Manufacture Technology Center of China Academy of Machinery Science and technology

CNC Computer Numerical Control

CTI Casting Technology International

DLP Digital Light Processing

FDM Fused Deposition Modeling

IJP Ink Jet Printing

LOM Laminated Object Manufacturing

PCM Patternless casting manufacture technology

RP Rapid Prototyping

RE Reverse Engineering

SL Stereo Lithography
SLS Selective Laser Sintering
SM Subtractive Manufacturing
STL STereo Lithography

1. Introduction

1.1 3D sand mould printing

3D sand mould printing, as an application of AM in foundry industry and one kind of modern mold manufacturing technologies, is based on the combination of Computer Aided Design (CAD) and digital control technology to produce sand mould without wooden pattern. And sand mould usually has complex geometry and intricate cavity as well as high accuracy [1-3]. AM is a powerful tool for manufacture molds, also known as rapid prototyping (RP) [4]. AM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies and the ASTM F42 Committee classifies AM processes into seven areas ,as listed below[4, 5]: Stereo lithography (SL), Fused Deposition Modeling (FDM), Ink Jet Printing (IJP), Three Dimensional Printing (3DP), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Selective Laser Chemical Vapor Deposition. While in terms of basic molding movement, AM relays on addition between adjacent layers and movement of point to form line, then build surface in the layer. At present, the technology of rapid sand casting is widely used in so many fields including development, research and a lot of industries, having a far-reaching influence on the development of national economy.

During a long cycle of research, development and use, the prototyping industry goes through enormous scientific and technological progress. Lots of science researchers have been attracted into this field. Singh and Rupinder classified technological development of prototyping as three phases, respectively, manual prototyping by a skilled craftsman, soft prototype by aid of computer software around mid-1970s and rapid prototyping (RP) applied to casting applications in early 1980s[3]. Usually, as shown in **Fig**. 1, there're two main approaches, additive manufacturing (AM) and subtractive manufacturing (SM) for the manufacture of sand mould [6, 7]. And the typical rapid sand casting approaches include: Stereo lithography (SL), Selective laser sintering (SLS), Fused deposition modelling (FDM), Laminated object manufacturing (LOM), Drop-on-powder deposition inkjet printing technology (3DP) and Drop-on-drop deposition inkjet printing technology[3, 7-9], as well as Patternless casting manufacture technology (PCM)[1-3]. While for SM, Rapid manufacturing of sand molds by direct milling on sand block with Computer Numerical Control (CNC) is one representative [10, 11]. Patternless Casting CNC Manufacturing Technology [12-14] and digital precision forming technology without pattern casting from CAMTC [15, 16] both refer to this technique whereby moulds are directly machined out of blocks of sand. The companies applying this technology include CTI in England [17] and ACTech Company in Germany [18]. Besides, there's a hybrid rapid pattern manufacturing system for sand castings based on a combination of additive and subtractive manufacture in order [7, 19]. Here, further subdivision on sand mould fabrication based on AM is shown in **Fig**. 1. It mainly includes direct tooling approach, indirect tooling approach and direct fabrication of sand mould, also known as pattern less moulding [8] or 3D sand mould printing. The first two approaches generates objects that can be used as a pattern, a substitution for wooden pattern. In addition, the difference between these two ways is that the former is more suitable for small or medium volume casting production while the later can be efficiently employed in case of large-volume production and when great durability of pattern is required [8]. As for the third and latest approach is the use of AM technique to fabricate sand mould directly without pattern [8].

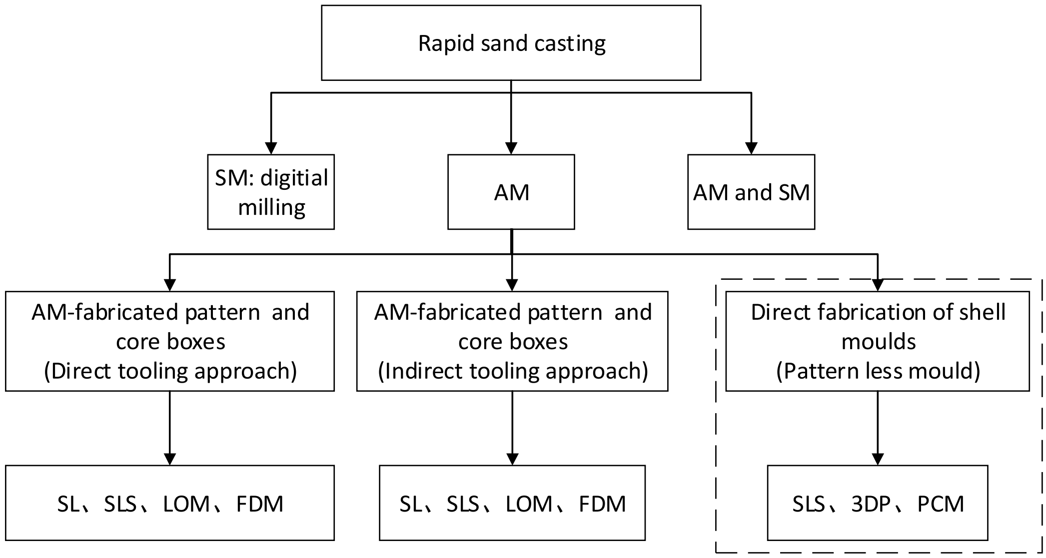

Fig. 1 approaches for rapid sand casting

Modified form source: Chhabra, Munish; Singh, Rupinder (2011)

3D sand mould printing fabricates pattern and core boxes without pattern mould, which is different from direct and indirect tooling approach. Existing technologies of 3D sand mould printing mainly are the following three methods: SLS, 3DP and PCM[3, 7, 8] and companies applying these methods include EOSINT-SLS, Soligen-DSPC, Generis (GS), ProMetal rapid casting technology (RCT), ZCast 501 and Fenghua Zhuoli-PCM and etc[6, 8]. At present, accompanied with the popularity of these technologies, there are plenty of research and relevant applications on this field. Those research most focuses on technology itself, such as molding material properties improvement and its cost reduction and molding speed increase, further optimization of molding method and process parameters, and performance improvement of product, as well as application range extension and so on. Concerning study of molding material , its cost and molding speed, Sunpreet Singh and Rupinder Singh [20], Eujin Pei [21], Benjamin Weiss et al[22], Wen, Shifeng et al[23], Rodríguez, Adrián et al [24] and so on all did relevant work. The adhesion of polymer materials printed directly onto fabrics using entry-level FDM machines was investigated by Eujin Pei. Benjamin Weiss et al researched the improvements in speed and precision achievable using straightforward closed-loop control for the gantry motion in AM machines. Wen, Shifeng et al proposed materials and method for material optimization and post-processing of sand moulds manufactured by SLS. For improving performance of product, like surface quality and manufacturing accuracy, related studies about process parameters optimization and methodology improvement are researched by some scholars. Such as H. Chen, et al worked with 420 stainless steel power material to improve the product quality, and optimized process parameter as well [24], and W. D. Yang suitable planed contour path of PCM for better forming accuracy and efficiency [26], and to improve surface quality of wax injection tool fabricated by FDM, C. Kuo and S. Su used aluminum filled epoxy resin as a filler [27]. Besides, to extend the application range of 3D printing, such as education and medical science, some researches carried out study on these issues. D. Eujin Pei, et al evaluated how the direct access to

AM systems impacts on education of future mechanical engineers [28], J. Corney et al investigated medical RP technology applications and methods based on reverse engineering (RE) and medical imaging data.[29], F. P. Melchels, et al gave a review on stereolithography and its applications in biomedical engineering [30].

Especially in the field of improving molding speed of 3D sand mould printing, as described above, most studies focus on the research for new and efficient molding material [31], or using print head with a plurality of nozzles [32]. Compared with traditional manufacturing, 3D sand mould printing technology as a new mode of production, has a huge boost in terms of production. Nevertheless, for the manufacture of large pieces of cast, production is relatively slow. Overall, in the process of sand mould fabrication, lots of attention has been paid to aspects referred above instead of its basic molding movement. There's a single scanning nozzle or head with a plurality of nozzles to realize scanning movement at current. Both of them in essence belong to movement of point. Based on this, this paper puts forward innovative line forming principle, to provide a theoretical research basis for the future development of 3D sand mould printing and industry application.

1.2 The content of research

In the following part, based on approaches of 3D sand mould printing for rapid sand casting this paper introduces available technologies at first. Then, referred to respective characteristics of each approach, analysis of them were made in theory. Finally, according to analysis above and to promote molding speed of 3D sand mould printing radically, a novel approach——principle of line forming and relevant prototype in concept are proposed. In addition, molding precision, theoretical build speed and volume demand and recycling of sand mould of prototype are given out as a further argument of its advantages. The new proposed approach of 3D sand mould printing, radically different from available sand mould fabrication equipment at market in molding methodology, possesses higher molding speed in theory.

2. Available technologies of 3D sand mould printing

In the following section, discussion focuses on technological process of 3D sand mould printing and relevant molding principle, as well as existing fabrication approaches.

2.1 Technological process

The detailed process involved in 3D sand mould printing technique is illustrated with the following flowchart **Fig**. 2 and described as follows.

1. First of all, design the part's 3D model and with the help of 3D modelling software get 3D model of sand mould by means of Boolean operation.

2. After that, export the document into the format of STereo Lithography (STL).

3. Then, apply some slicing software such as slic3r or Cura to make the data of 3D model become layer by layer's contour and the filling path of nozzle, or control code of nozzle jet array, or laser trajectory so as to plan molding movement of each kind of equipment. No matter which approach is chosen to fabricate sand mould directly, SLS, or 3DP, or PCM, because the linking up reacts on resin sand's surface where binder and curing agent come across, powder laying roller paves sand evenly, and the nozzle scans the preplanned tracks to jet binder precisely, or laser moves according to laser trajectory, which is provided by the slice up software to sinter precoated sand to make sand bond together, ensuring strength and producing the sand mould layer by layer until all the layers are finished.

4. Sometimes later when all layers are finished, clean out the crude sand which hasn't been

formed into entity and do some post processes on sand mould to strengthen it further.

5. Finally, pour the molten iron into the sand mould.

6. After a series of heat treatments, get the sand casting part which is initial design [1, 3, 33].

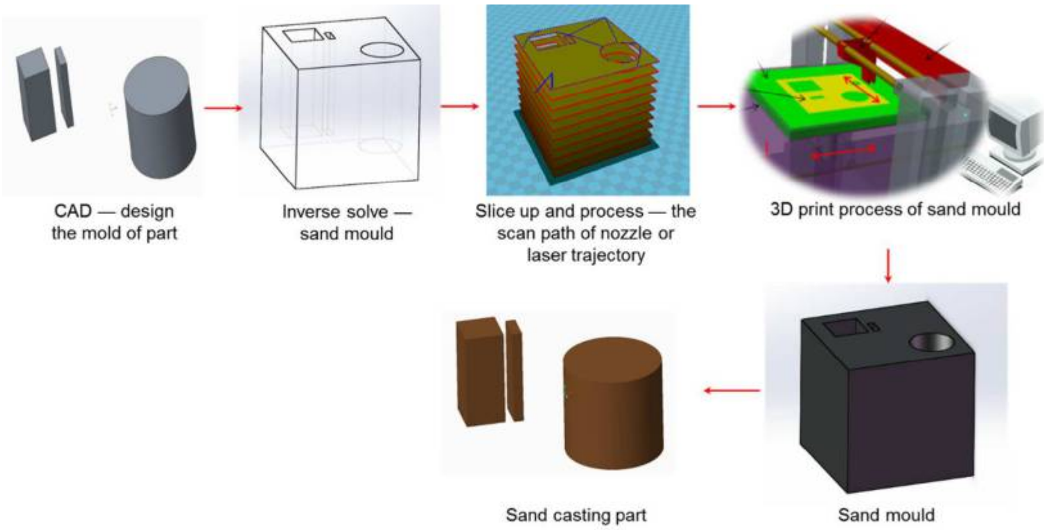

Fig. 2 technological process of 3D sand mould printing

3D sand mould printing, as application of RP in traditional foundry industry [3] and from sand mould manufacture process introduced above, it can know that the most basic molding principle of direct sand mould manufacture is based on AM technique. Hence, the process of forming can be classified into two main parts——forming in the layer and forming between adjacent layers as well. About forming in the layer, the crude sand is solidified by the reaction of binder and curing agent, also known as horizontal diffusion. And concerning forming between adjacent layers, adjacent layers are bonded with the help of vertical permeability of the binder and curing agent, or even other materials to realize laminated solidifying. All in all, the whole sand mould relies on these two kinds of forming principles basically.

It is known to all that the continuous movement of point forms line and in a similar way the continuous movement of line forms area, plane and even curved surface. Because the sand is bonded together with binder's horizontal diffusion in build surface and with binder's vertical penetration between adjacent layers, here as shown in **Fig**. 3, we divide sand mold construction process into two parts, construction in the layer and construction between adjacent layers. To some extent, the small area of binder's horizontal diffusion in build surface is much more like a point. In this way, continuous movement of this point forms a line, area, and the whole build surface in the layer. Therefore, under normal circumstances, when considering the relative movement between nozzles and build platform, or laser and build platform to form the final printout, there are two kinds of print methods on the basic forming principle in the layer, just as **Fig**. 4 shows. One methodology is that single nozzle or laser moves in the two dimensional surface following the contour path and the filling path planned in advance to form area, plane and even curved surface, while the other is that printing head with a plurality of nozzles or lasers laid out in array, which is close to a line or area, moves in parallel in one or two directions with the build surface divided into several subsections. As shown in **Fig**. 3, we can skip the first step in the dashed box. In that way, it's very different when people design the control system of the equipment, because the former movement only needs one nozzle or laser moving along with the planned path while the latter needs print head with a plurality of nozzles or laser array to move simultaneously and to make control of large amount of them on and off constantly in the meantime according to molding demand. In general, all those methodologies are based on the mode of point-line-area-layer-solid, as shown in **Fig**. 4 (a). Applying the mode of line-area-layer-solid, as shown in **Fig**. 4 (b), instead of beginning with the movement of point to form line, the build speed will get a huge ascension in terms of basic forming principle. Between adjacent layers, those molding principles rely on the bind of binder and curing agent, also known as vertical penetration.

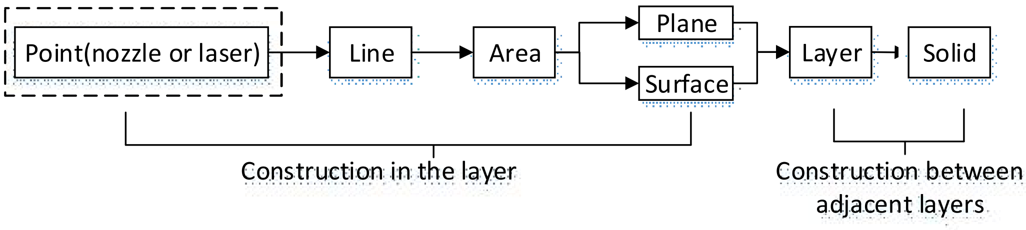

Fig. 3 molding principle in the layer and between adjacent layers

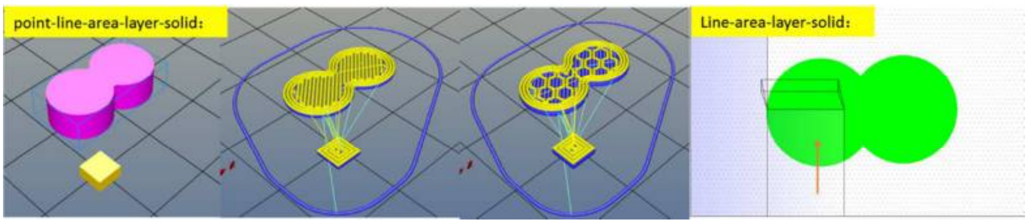

Fig. 4 molding mode of point-line-area-layer-solid in the layer (a) and molding mode of line-area-layer-solid in the layer (b)

2.2 Existing fabrication approaches

Fabrication approaches of sand mould mainly include SLS, 3DP and PCM, and the following section will give a brief introduction of these technique firstly.

SLS is a procedure of sintering molding material according to the shape of required prototype. The brief principle is to pave powder uniformly and selectively sinter these powder in accordance with CAD model in sequence until all layers finished. Usually, these sand are precoated sand [6] crude sand coated with binder and a certain amount of curing agent. At last, the final prototype is surrounded by un-sintered powder [3, 34, 35].

3DP was developed at Massachusetts Institute of Technology (MIT) and licensed to Soligen Corporation, Extrude Hone and Z Corporation of Burlington. The brief principle of this technique is by depositing drops of binder from jet nozzle to selectively harden molding powdered material layer by layer so as to form the final entity, which is similar to tradition 2D ink jet printing (IJK), and then blow out those unused molding powdered material to get sand mould [3, 36].

PCM was developed at Tsinghua University and successfully applied at Chinese company Fenghua Zhuoli [37]. The brief principle of this technique is to spry sand, catalyst, also known as curing agent, and binder in order by following the contour and filling path generated by STL file of CAD model to realize additive manufacture, and blow out those unsolidified sand to get sand mould [1-3, 37].

Generally, regardless of SLS, 3DP and PCM, sand mould manufactured by equipment of 3D sand mould printing is the reaction result of silica sand, furan resin binder and P-toluene sulfonic acid or dimethyl benzene sulfonic acid curing agent or other materials with similar properties [11]. In especial, for SLS, powder of silica sand procated with binder are sintered into the shape of the required prototype by heat curing[3], which is distinctly different from the other two approaches by self-hardening, reaction among silica sand, binder and curing agent. What's more, the binder and curing agent is under research to be further optimized by researchers. And they are also dedicated to finding new material with much better performance to manufacture sand mould [3, 19]. Here, the binder makes sand particle to link with each other to form sand mould while the curing agent as catalyst makes the link more tighten. At certain degree, the content of binder determines the performance of formed part such as final sand mould strength, the thermal conduction efficiency and the amount of gas evolution and so on[37].

About how to make use of molding material, crude sand, curing agent and binder to produce the final sand mould directly with the control of computer, there are three different methods respectively being SLS, 3DP, PCM and steps are described in **Table** 1 below. All these three molding processes of 3D sand mould printing and their composition are illustrated. For SLS, as depicted in **Fig**. 5 (a), it paves precoated sand powder uniformly and selectively sinters sand powder by laser, and repeats this process until completeness of the final sand mould. One representative of SLS is EOSIN-SLS [8]. For 3DP, as **Fig**. 5(b) depicted, it paves the mixed powders of crude sand and curing agent and then selectively jets binder, which Exone's S-max [38, 39] and VX4000 from Voxeljet [40] employs this theory. For PCM, as **Fig**. 5(c) depicted, it paves crude sand uniformly on build surface and selectively jets curing agent and binder in turn, which Fenghua Zhuoli applies with PCM-1200 and PCM-800 [41, 42] and is firstly proposed by Yang Weidong et al [43]. And **Table** 3 presents existing approaches of 3D sand mould printing and corresponding equipment with respective technical features more specifically.

Table 1 existing fabrication approaches of 3D sand mould printing

Method / Step	SLS	3DP	PCM
1	Roller spreads the precoated sand powder	Pave powder mixture of crude sand and curing agent uniformly	Pave crude sand powder uniformly
2	Laser sinters the powder selectively according to layer slice information	Spray binder selectively according to layer slice information	selectively spray binder and catalyst in order according to layer slice information
3	Do step 1 and step 2 until final part finished	Do step 1 and step 2 until final part finished	Do step 1 and step 2 until final part finished
Composition	Precoated sand (crude sand and curing agent) + layer sinter	Mixture of crude sand and curing agent + binder	Crude sand + binder +curing agent
Typical manufacturer	EOSINT - Germany	Exone- America, voxeljet- Germany	FHZL- China

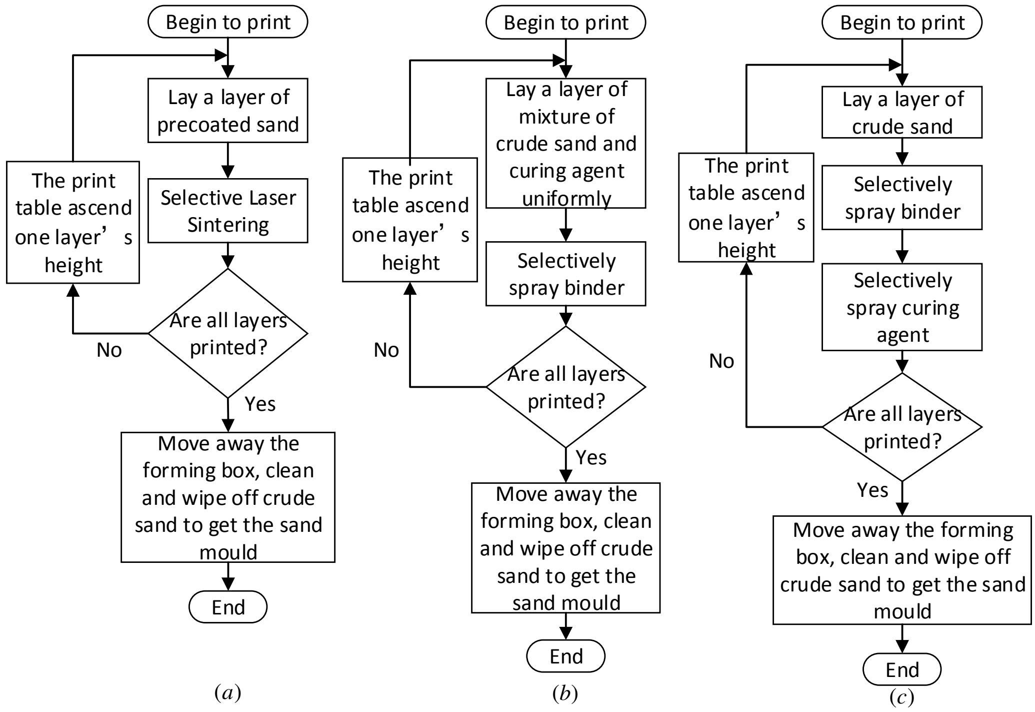

Fig. 5 Flow chart of 3D sand mould printing (a) SLS, (b) 3DP, (c) PCM

3. Analysis of existing fabrication approaches of sand mould

In previous section, this paper introduced 3D sand mould printing technique in detail and in the following part research and analysis on existing fabrication approaches of sand mould referred above are studied in following aspects: application status and molding movement composition, as well as key technology.

3.1 Application status

Combined with introductions above and according to existing approaches for 3D sand mould printing, **Table** 2 presents the application status and future trend of 3D sand mould printing. In this table, it can been known that traditionally ink jet printer, laser printer or application of SLS, 3DP and PCM all apply scanning with single nozzle or head with a plurality of nozzles to form in principle. It can be known that the primary deciding factor affecting building speed is scanning mode through analysis above. Nevertheless, there’re few researchers involved in application of line forming in 3D sand mould printing. . Obviously, scan with line to form molding area is much faster than scanning just with single nozzle or head with a plurality of nozzles, which simulates line forming as far as possible with lots of nozzles laid out in array. So far, there’s laminated object manufacturing (LOM), and with help of carbon dioxide laser it cuts the sheet material to the shape of each layer and bonds adjacent layers by pressure and heat application [9]. Besides, digital light processing (DLP) is also based on area molding [44]. There’s 3D scanner with laser line scan [45], while line forming hasn’t been applied to manufacture of sand mould. Thus, it is the trend that 3D printing is line based, area based and solid based, to make build speed of 3D printing with a remarkable improvement.

Table 2 Application status and future trend of 3D sand mould printing

Forming method	Point based	Line based	Area based	Solid based
Molding principle	Point->line->area->layer->solid	Line->area->layer->solid	Area->layer->solid	Tiny solid->solid
Method and relevant typical manufacturer	**SLS** EOSINT-Germany **3DP** Exone-America, voxeljet-Germany **PCM** FHZL-China	**Respectively pave crude sand and furan no-bake sand with scanning in line**-SJTU	**LOM**(Laminated Object Manufacturing)	**None**
Advantages	Higher molding precision; Higher build speed; Time and cost saving	Higher molding precision; Much higher build speed, Time and cost saving	No post processing and supporting structures; No deformation or phase change during the process; The possibility of building large parts	Higher molding precision; Much higher build speed and time and cost saving
Disadvantages	Consume higher power for SLS based on laser to sinter the sand; Higher cost for manufacture nozzle with high resolution	Molding precision up to the nozzle's capability of following contour	Wasting molding material; Models with papers, composites, and metals which are directional dependent for machinability and mechanical properties	Molding precision up to the size of tiny solid

And from **Table** 1 and **Table** 2 and **Table** 3, it can been learned that Exerial from Exone is with the fastest build speed 300 to 400 L/h. In structure it applies the scanning mode by layout plurality nozzles in head with array. In order to improve build speed of sand mould, the Exerial adopts two boxes to print at the same time. This way makes the printer with the capability of double build speed, and so is its build volume. While build speed of most other printers concentrates upon the speed less than 100 L/h. Although, their print resolution can be up to 0.05 mm and layer thickness can be up to 0.12 mm, if adopting these printers to construct sand mold for heavy casting, it will cost lots of time. Towards manufacture requirements of heavy casting, 2 mm layer thickness would be acceptable. Nevertheless, with available sand mould printers, production time is relatively longer. So, build speed is another bottleneck problem of 3D sand mould printing for heavy casting, which requires attentions from R&D institution and equipment manufacturer.

3.2 Molding movement composition

Generally, as **Fig**. 6 shows, the equipment system's movements of 3D sand mould printing mainly include relative horizontal scanning movement of nozzle or laser, vertical jet of nozzle, droplet flight process from nozzle and penetration process of binder or curing agent, as well as build platform descends periodically after each layer is printed. All these movements should be well organized to guarantee normal operation of the system so that the molding precision is within the scope permitted. So this equipment's various movements need high accuracy response control with the aid of motion controller.

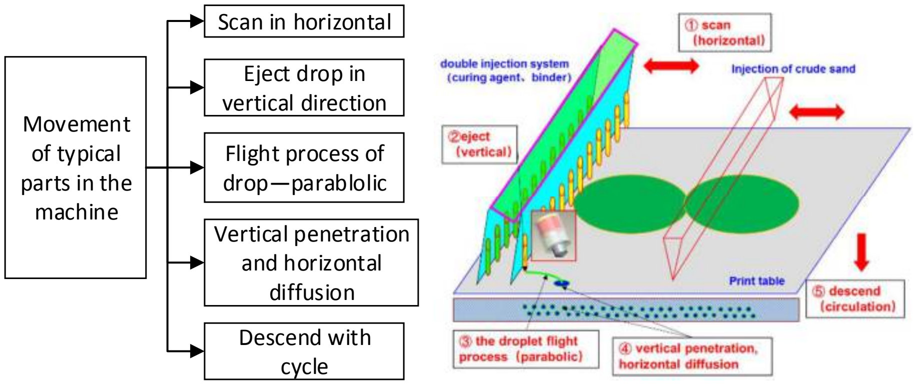

Fig. 6 molding movement composition

According to technique of 3D sand mould printing and combined the introduction of typical molding movement composition, it allows further refinement of those movement as shown in **Fig**. 7. In layers, scan in horizontal direction is up to molding principle and different ways need different motions, mainly including eject drop in vertical direction, flight process of drop and horizontal diffusion, as well as flight process of molding material and auxiliary molding material. While between adjacent layers, movement in vertical direction includes vertical penetration and laminated solidifying, as well as descent with cycle in vertical direction. **Fig**. 7 shows the key influence factor of molding precision as well.

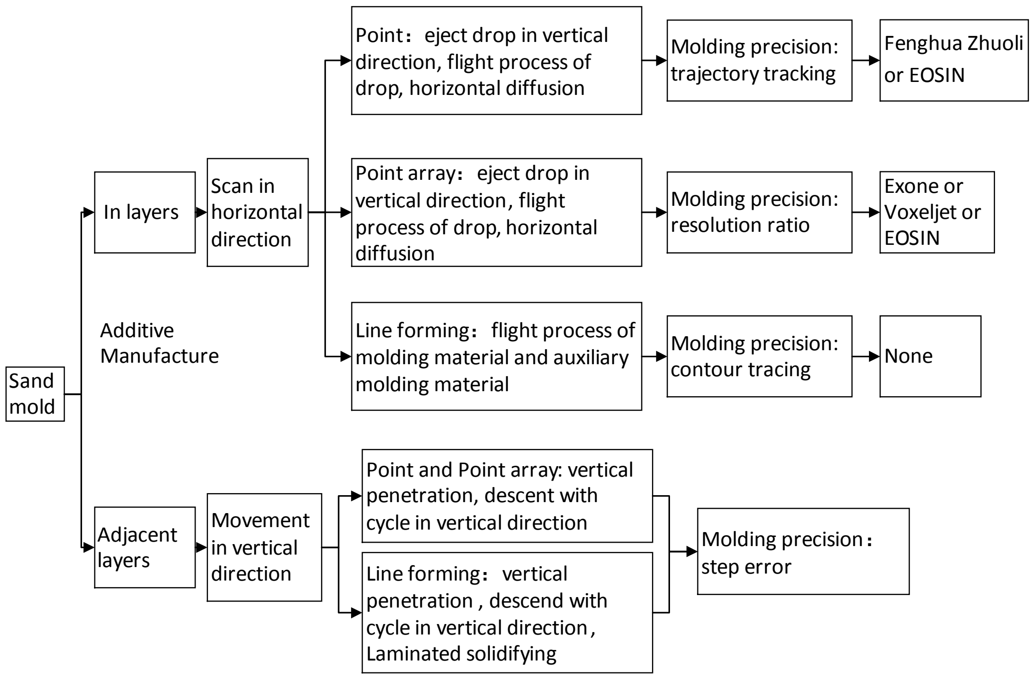

Fig. 7 molding movement composition of different approaches

3.3 Key technology

Molding precision, as a key factor influencing sand mould quality, may be distinct for different molding principles. As shown in **Fig**. 7, in layers, if the most basic element of forming is point, molding precision depends on the error of trajectory tracking. While if it is point array, molding precision lies on resolution ratio, nozzle number or laser number in unit area. Hence, the molding precision is in direct proportion to the resolution ratio. And if the most basic element of forming is line forming, molding precision depends on the error of contour tracing. About the molding precision between adjacent layers in longitudinal surface, there are print surfaces' deficiency or overlap between adjacent layers, also known as step effect [46]. Of course, there are lots of other factors having influence on molding precision which need attention when designing prototype.

In addition, to a large extent, the performance of the material, binder and curing agent itself or the quality of precoated sand determines sand mould strength, its surface quality and dimensional accuracy. For example Yang, Wei Dong and Liu, L B consider the quality of scan lines has important effect on sand quality, while the quality of scanning depends on gap between the droplet caused by frequency and duty ratio of nozzle jet [47]. Also, on contend of binder, Yang, Wei Dong thinks binder function as a bridge and its content determines the performance of strength, gas evolution and mobility, so it has a great relationship with sand mould's property [37]. For SLS, with appropriate input laser power, powder ratio and overlapping, as well as post processing, it can improve surface accuracy and dimensional precision [35].

4. A new approach of 3D sand mould printing

Through above introduction of sand mould fabrication technique and analysis of existing approaches, a new approach based on line forming was proposed.

4.1 Principle and virtual prototype

Based on the analysis above and from **Table** 3, it can been seen that existing approaches all apply scanning mode with point-line-area-layer-solid in the basic forming method instead of line-area-layer-solid, which brings relative lower build speed of sand mould fabrication. Exone-America, voxeljet-Germany and some similar companies adopt paving the mixed powders of crude sand and catalyst firstly, and then taking advantage of head with a plurality of nozzles to selectively pave binder. While the company of FHZL-China adopts the way of paving crude sand, spraying binder and catalyst in order with single nozzle. And EOSINT-Germany adopts laser to selectively sinter precoated sand after the roller spreading the powder uniformly on the build platform layer by layer. In spite of the existence of known industrial solutions referred above, build speed of 3D sand mould printing is relatively slow when manufacturing heavy casting. Hence, build speed is another bottleneck problem of 3D sand mould printing for heavy casting. Today, most studies have focused on parameters optimization, methodology improvement, as well as new materials and performance improvement of available materials. However, there're few researches from aspect of the most basic molding movement to dramatically increase build speed of sand mold for heavy casting in particular. This paper proposes a new approach based on line forming with line scan innovatively, which is especially suitable for sand mould fabrication of heavy casting. So, this new method could be a solution to the bottleneck problems in 3D sand mould printing. Herein, the mixed powders of crude sand, curing agent and binder, also known as the furan no-bake sand, which is used to form the sand mould entity eventually, has some time before being hardened after mixed uniformly [48]. Usually, for the manufacture of furan no-bake sand, the typical process is as follows: putting silica sand and curing agent into sand mixer and blending uniformly, after a while, adding a certain amount of binder. Finally furan no-bake sand is used to manufacture sand mould before they are solidified. And the manufacture order of furan no-bake sand should not be turned over, otherwise, it will lead to severe hardening reaction at some local part of the mixing. Thereby, before furan no-bake sand is solidified there's a time interval which can be utilized to pave crude sand and furan no-bake sand according to molding demand of each layer's deposition area, thus realizing build speed promotion based on the way of line forming basically.

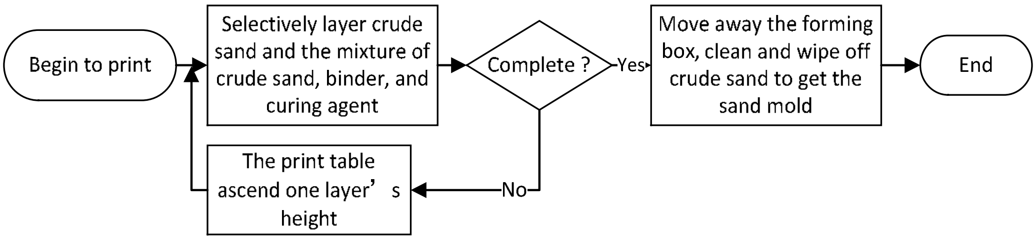

Fig. 8 flow chart of the new approach of 3D sand mould printing

The principle of this new approach of 3D sand mould printing is shown in **Fig**. 8. And the key part in procedure of 3D sand mould printing is application of selectively paving crude sand and furan no-bake sand layer by layer until the whole sand mould is manufactured. As shown in **Fig**. 9 (a) and **Fig**. 9 (b), build surface is segmented into several parts to further improve molding speed. These rows of nozzles print several parts simultaneously with line scan. They selectively pave crude sand to non-deposition area and furan no-bake sand to deposition area according to section of sand mould and nozzle's relative position to build platform in horizontal direction, which is shown in **Fig**. 10 (a). As is shown in **Fig**. 10 (b), crude sand and furan no-bake sand are stored in two hoppers separately and conveyed evenly through their respective channels to nozzles. In accordance with molding demand at current position, and with the help of high speed switch at nozzle's discharge gate or innovative design of nozzle's internal structure, nozzle selects one kind of material to make it through nozzle's discharge gate and lays it to the build surface, while blocking or recycling the other. Hence, this approach is distinct from the single nozzle moving along X and Y direction in molding movement composition, which is applied by most sand mould manufacturing companies. Here, furan no-bake sand is function as molding materials, and crude sand auxiliary molding materials. Furthermore, in the direction perpendicular to the scanning direction of nozzle in build surface, these two materials converge on the build surface simultaneously to fill one stripe area, including deposition area and non-deposition area, as is shown in **Fig**. 10 (a) and **Fig**. 10 (b). These rows of nozzles move back and forth, relative to build platform and paving one intact build surface layer by layer. For convenience of system to transport printing material, rows of nozzles are fixed to rack, while dolly with build platform moves back and forth, and its build platform can be raised or lowered. In this way, the new approach is much more efficient and effective, distinctive from existing approaches and applications from relevant manufactures on the market and with great advantage of improving build speed of sand mould in the basic forming method, thus it would make significant impact on national manufacturing.

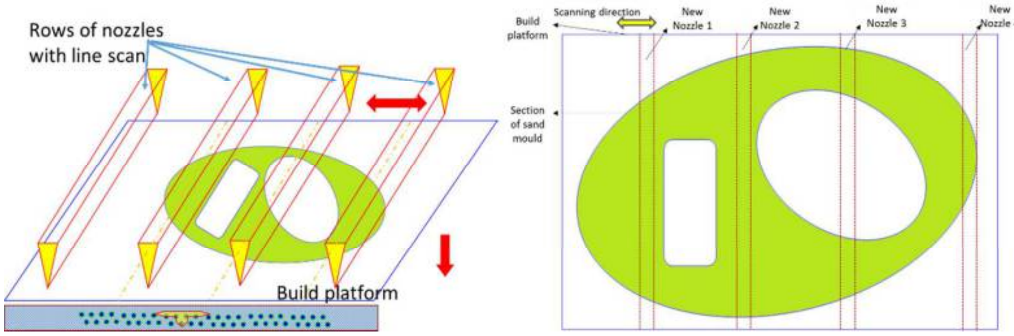

Fig. 9 nozzle arrangement (a) and top view of nozzle arrangement (b)

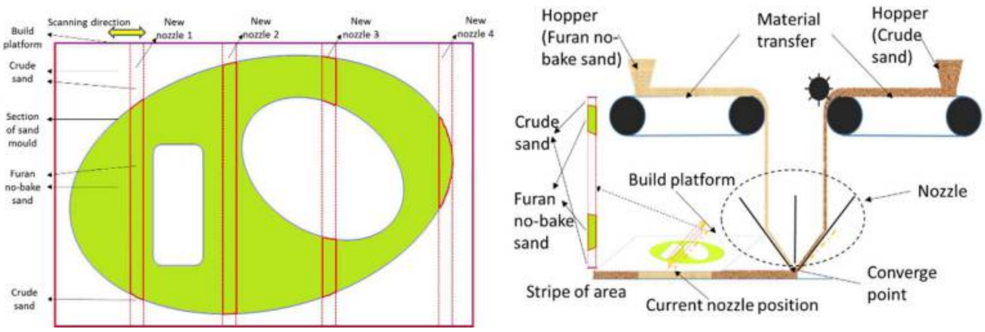

Fig. 10 deposition area (a) and sketch map of converge of molding materials and auxiliary molding materials respectively paving disposition area and none disposition in stripe area (b)

As is shown in **Fig**. 11, 1 represents furan no-bake sand and 0 represents crude sand. In the direction of scanning, nozzle outlet needs to quickly switch between 1 and 0 to keep consistent with laying requirement. Furthermore, in the direction perpendicular to the scanning direction, 1 and 0 converge on the build surface simultaneously to fill one stripe area. In this way, molding precision depends on grid mesh size of build surface and size of relevant nozzle's discharge gate. Hereby, considering molding error caused by boundary of deposition area and to eliminate this error, it is extremely urgent to design novel nozzle with ability to trace boundary between crude sand and furan no-bake sand in stripes so as to selectively pave two kinds of materials. Therefore, this new equipment's nozzle needs to be designed with novelty, and with the capability to quickly switch between two kinds of materials and dynamically trace and fill molding area and auxiliary molding area simultaneously according to molding demand of build surface. To meet requirements of line forming, there are two ways, respectively grids filling by means of micro switch technique, and dynamically tracing boundary and selectively paving molding material and auxiliary molding material with aid of novelty internal structure in nozzle. And the concrete structure of nozzle to fulfill those requirements mentioned above is still under research.

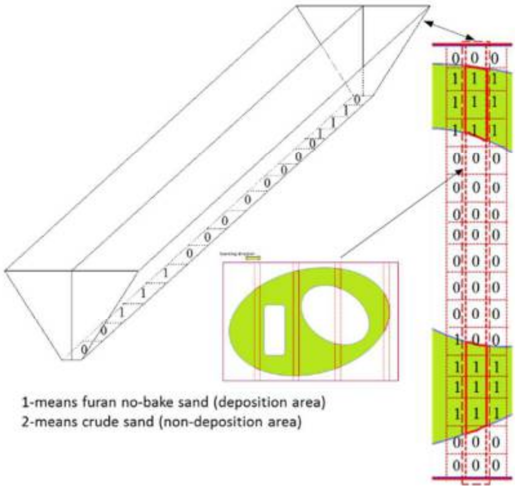

Fig. 11 Schematic diagram of selectively paving

On molding movement composition, as analyzed in **Table** 3, the new approach realizes line forming by selectively paving crude sand and furan no-bake sand. In this process, it has no eject drop in vertical direction, and flight process of drop and horizontal diffusion in layers, replaced with flight process of crude sand and solid-liquid mixed powders, namely, furan no-bake sand. And between adjacent layers, in addition to vertical penetration process of binder and descent periodically in vertical direction, there is another laminated solidifying process realized by press roll, to make sure degree of packing satisfies strength requirement of sand mould. Therefore, based on the new approach of 3D sand mould printing, the sketch map of proposed equipment in concept is depicted as **Fig**. 12, mainly including edge mill, material transmission system, hoppers of molding materials and auxiliary molding materials, selective laying mechanism and dolly with printing platform. For simplicity of this schematic, the recycling system of sand mould doesn't show in this figure. As shown in **Fig**. 9, **Fig**. 10 and **Fig**. 12, build surface is segmented into four rectangular regions to further improve molding speed. This requires four rows of nozzles printing these parts simultaneously, and four groups of hoppers of molding materials and auxiliary molding materials supplying materials as well. Two kinds of materials are respectively transported from edge mill to hoppers through material transmission system. Then, by means of selective laying mechanism and the relative movements between dolly and build platform, the equipment realizes selectively paving in the layer and construction between adjacent layers.

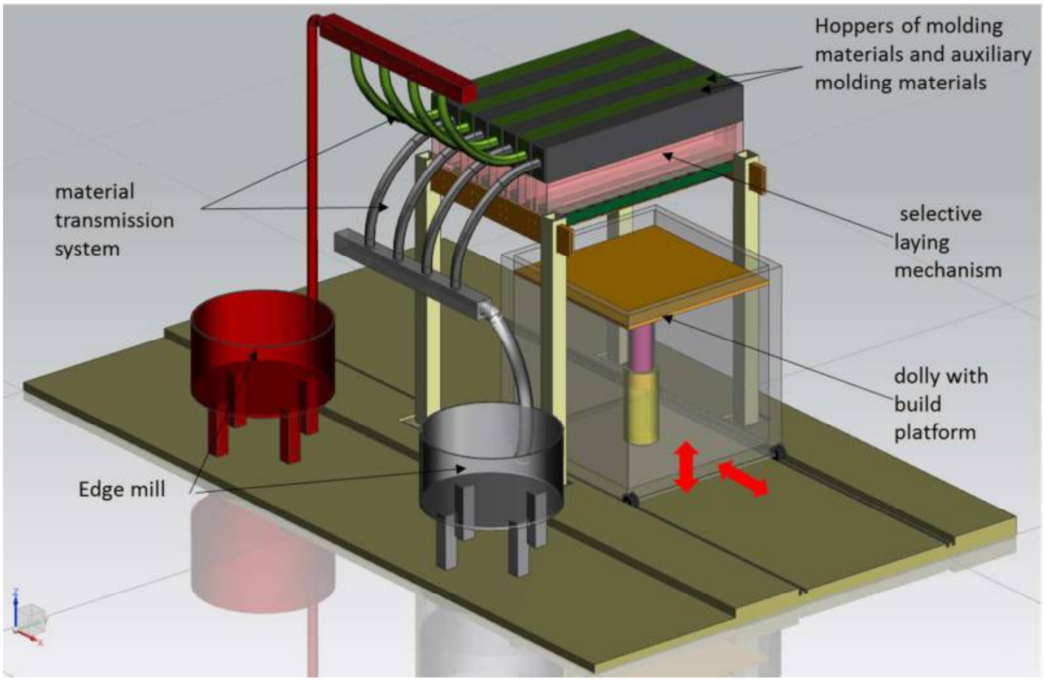

Fig. 12 sketch map of proposed equipment

4.2 Molding precision

Molding precision is a key point for the application and generalization of this new approach and equipment. Here, step effect, as molding precision between adjacent layers, needs further analysis. When the equipment begins printing, in the horizontal direction it needs considerations on the relative movement between the nozzle and the build platform. Given that those nozzles are still and the build platform moves back and forth, the drop of sand will have a speed relative to the build platform in horizontal direction. That is similar to the droplet deviation model of binder and curing agent as shown in **Fig**. 13, which was proposed by Yu-an Jin [49]. Since there's parabolic flight time of droplets, nozzle control needs high precision, ensuring that sands dropped from nozzle outlet arrive at exact position on build platform at exact moment. Otherwise, it will lead to step effect, as formula (1) and **Fig**. 13 show and result in poor performance of sand mould. Certainly, molding precision is in proportion to the horizontal nozzle scanning velocity and parabolic flight time of droplet. **Fig**. 14 shows relationships among molding precision, the velocity of build platform in the horizontal direction v_{scan} and interval delay or ahead Δt. The figure created by MATLAB illustrates that the molding precision is in direct proportion to the velocity of build platform and interval respectively. All in all, molding precision has relationships with various parameters, such as relative speed between build platform and nozzle in horizontal and vertical direction, as well as flight distance in horizontal and vertical direction.

$$\delta = v_{scan} \Delta t \tag{1}$$

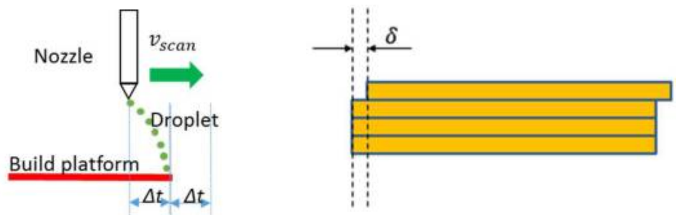

Fig. 13 scheme of parabolic trajectory of droplet (a) and step effect of sand mould (b)

Source: Jin, Yu-an (2014)

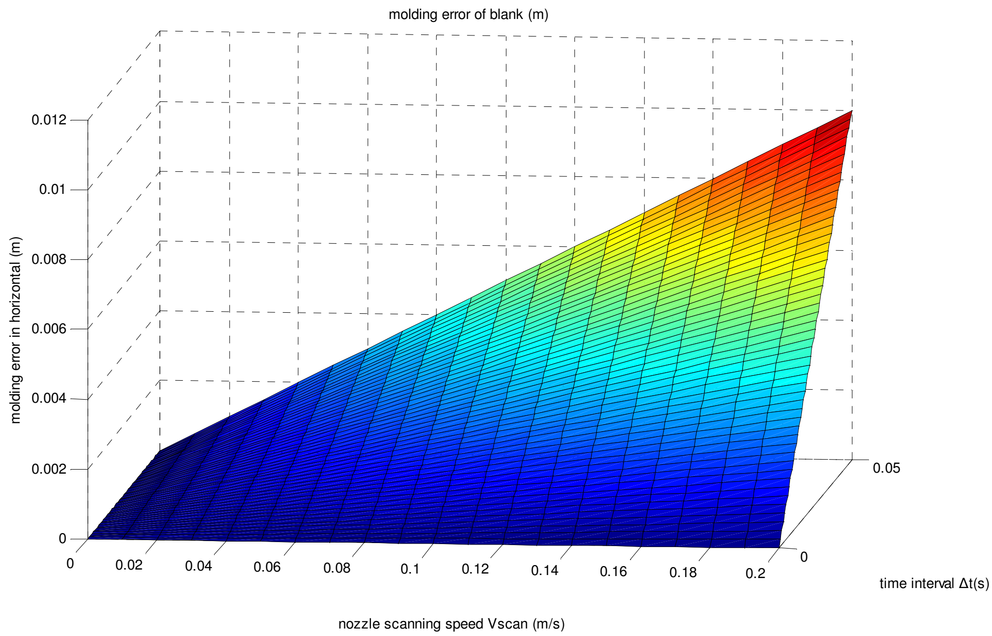

Fig. 14 molding precision related with nozzle scanning speed and time interval

In addition to the step effect, molding precision has lots of other sources such as mold design error, algorithm of slice up error, trajectory planning error, control error of equipment, molding material transformation error and so on. So, giving consideration to molding precision sources when boosting build speed is of great importance when in design and manufacture, as well as new porotype's debugging.

4.3 Theoretical build speed

In addition to molding precision, theoretical build speed is also a key factor. At present, considering dimensional accuracy and printing error, as well as uniformity of falling sand stream in experiment, 2 mm would be acceptable for heavy casting, which requires relative lower accuracy than small casting. When deposition rate is much higher and allowed printing error is greater, slice thickness could be thicker. Moreover, considering structure of nozzle, when technology of new nozzle and blanking technology get further improved, the slice thickness could be further reduced, and step effect as well, which will be suitable for small casting. Therefore, it's assumed that layer height is 2 mm, and width of build surface is 1000 mm*1000 mm, and the length of nozzle is 1000 mm, and scanning speed of nozzle is 100 mm/s, as well as four rows of nozzles are uniformly arranged with adjacent gap equal to 250 mm. Thereby, the volume of build speed is equal to 2880 L/h by multiplying data assumed above. In **Table** 3, Exerial's build envelop is 2200 mm x 1200 mm x 700 mm x 2 group and its layer thickness is 0.28 mm to 0.50 mm. If adopting build envelop of Exerial and with more rows of nozzles, the volume of build speed could be more than 2880 L/h. Despite layer height of proposed approach is thicker than Exerial's, theoretical build speed of proposed equipment with line scan is almost ten times of Exerial build speed 300 to 400 L/h. Therefore, the proposed new approach of 3D sand mould printing and relevant virtual prototype is much more suitable for the production of large casting's sand mould, especially with characteristics of relative lower molding precision and much higher molding speed. At present, the calculation of build speed is a theoretical value and in reality, there're lots of factors need consideration, such as mobility of mixed powders, minimum layer thickness within allowed dimensional accuracy and scanning speed of nozzle limited by molding precision and etc. Thus, further research is needed for the successful prototype manufacturing.

Obviously, when it comes to design of the control system of the prototype, it should integrate time interval of droplet flight process as shown in **Fig**. 13 and the activation/switch speed for the nozzles into account. Considering the gap between nozzle and build surface in horizontal and vertical direction, there is a droplet flight process requiring match of nozzle's state and print table's movement, which has a major impact on printing accuracy in the layer. Besides, the activation/switch speed for the nozzles also plays a key role on printing accuracy in the layer and build speed. Once the equipment runs and considering combing time interval of droplet flight process, the equipment should turn off and turn on nozzles at the right moment when building between adjacent layers. When building in the layer and in case the nozzles turn on, the nozzles are at selectively paving stage. They need to switch between two kinds of materials as quickly as the motors can, which depends on motor's characteristic. And the switch speed will play a key role in selectively paving which kind of materials, influencing printing contour accuracy between two kinds of materials. Therefore, Attention needs to be paid to those aspects when design the prototype's control system.

4.4 Volume demand and recycling of sand mould

Concerning molding materials, this new approach of 3D sand mould printing employs selectively paving crude sand and furan no-bake sand, which needs supply of molding materials and auxiliary molding materials all the time during printing. Because the former molding material does not have the problem coagulated into clump while the later does, it is not necessary to pay attention to the usage of crude sand. Therefore, it is indispensable to calculate the demand of furan no-bake sand and its recycle time precisely when supplying and recycling crude sand all the time until final sand mould finished. Otherwise, furan no-bake sand will coagulate into clump, influencing curing processing, affecting molding quality of sand mould resulting in transferring passage jam and even causing trouble in equipment maintenance, which lead to increase in the cost of equipment operation and maintenance in the future. Hence, aimed at arbitrariness of sand mould structure, one method based on calculus to calculate the volume of mixed powders was proposed so as to provide some reference for crude material feeding when equipment operates.

The relationship between scanning velocity, v_{scan} and width of paving furan no-bake sand area, $l_i(t)$ and height of each build surface, h_{layer} and cycle index, n and volume demand of furan no-bake sand at t moment, $V_{use}(t)$ can be described using the following computational model(2).

$$V_{use} = \sum_{i=1}^{n} A_i h_{layer} \\ = \sum_{i=1}^{n} V_{scan} l_i(t) h_{layer} \tag{2}$$

Where t refers to the present moment and $V_{use}(t)$ is total amount of furan no-bake sand needed during this period.

Formula (3) and (4)are respectively to further compute sand's volume demand from two aspects according to the formula referred. The former formula calculates area of paving furan no-bake sand directly while the latter calculates width of paving furan no-bake sand area indirectly. **Fig**. 15 below is one case of sand mould model to illustrate computational process.

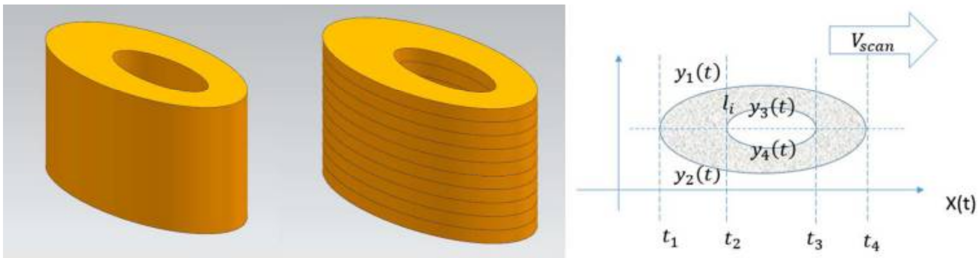

Fig. 15 case studied and analyzed

$$A_i = \sum_{j=1}^{n} \int_{t_{2j-1}}^{t_{2j}} y_{2j-1}\left(t_{2j-1}\right) - y_{2j}\left(t_{2j}\right) dt \tag{3}$$

$$l_i(t) = \lim_{\Delta t \to 0} \sum_{j=1}^{j=n} y_{2j-1}(t) \text{-} y_{2j}(t) \tag{4}$$

When sand's volume demand is calculated, to ensure the normal operation of equipment, it is of great necessity to guarantee that the volume of furan no-bake sand remaining in the hopper is more than needing at every moment and less than the capacity of hoppers, and these sand are not involved in the curing process.

Recycling of moulds and used sand is also an important element as postprocess of used sand mould. Casting output in china up to 46.2 million during 2014 and by the end of "The Twelfth Five-Year Guideline" [50, 51], it is much higher. More than 80% of total production are from sand casting, which brings millions of tons of used sand by manufacturing one ton of casting with one ton of used sand. In order to reduce consumption of new sand, manufacturing cost and pollution to environment, resin sand needs regeneration by removing adhesive coated on the surface of sands for reusing. With available technology now, more than 90% or even 100% of sand can be reused and resin saving exceeds more than 20%, which brings reclaimed sand with better performance and results significant economic benefits. Meanwhile, modification technology of the total reclaimed sand is researched by Du Hang and Qingzhou Sun to improve performance of casting process [52, 53]. With their process of "calcination of 700℃+ dry mechanical reclamation + micro-powder separation", the technical indicators of sand, such as size distribution, gain shape, mud content, are better than the same new sand, while the acid request is higher. Du Hang puts forward modification technology with process of "modification process + drying process +mechanical reclamation +separation of micro powder" to improve performance of casting process. On recycling of sand mould, there are three kinds of recycling system, respectively chemical recycling system, thermal recycling system and material recycling system. And material recycling system may be the most preferable due to no problem of atmosphere pollution [54, 55]. In China, reclaiming sand with method of material recycling is widely used since the technology is simple and perfect. And this method removes adhesive coated on the surface of sands by means of mechanical impact and friction with corresponding equipment. Process mainly divides into the following three phases, respectively preprocessing phase, regeneration phase and post-processing, as shown in **Fig**. 16 [54]. Combined with Chinese national standards GB/T 9442-2010-Foundry silica sand, key quality control indexes of reclaimed sand mainly include loss content on ignition, size distribution, acid demand value, angularity, PH, clay content, and refractoriness[56, 57]. Key quality control indexes listed above have a particular importance when determining properties of sand moulds, such as strength, permeability, flow ability, plasticity, toughness, gas evolution, deformability, and collapsibility [54, 57]. Herein, sand mould fabricated with the new approach and its used sand are going to be recycled by adopting available material recycling system.

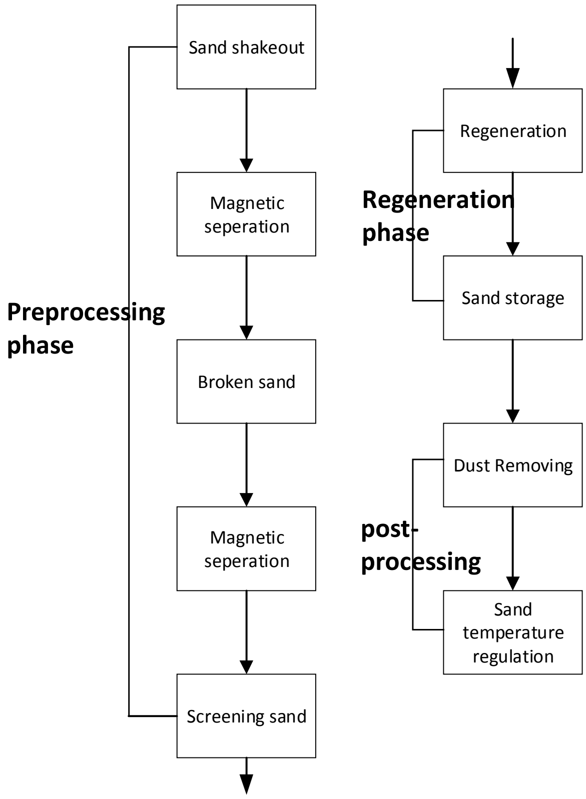

Fig. 16 Technological process of recycling of sand mould

Source: Zhensheng Cai (2010)

5. Conclusion

Based on AM and rapid sand casting, this paper did a simple introduction about 3D sand mould printing and existing technique in several aspects including technological process and existing fabrication approaches at first. Then, analyses of application status and molding movement composition, as well as key technology are made. Finally, according to analyses above, to boost build speed of 3D sand mould printing radically, a novel approach and relevant virtual prototype based on line forming and selectively paving molding material and auxiliary molding material respectively are put forward. Besides, analysis and calculation on molding precision and theoretical build speed, as well as volume demand and recycling of sand mould were also given.

Instead of selectively jetting binder or selectively sintering precoated sand or selectively jetting curing agent and binder in order respectively, the new approach and virtual prototype applies line forming. And it is realized by selectively paving crude sand and furan no-bake sand with line scan and new type of nozzle in concept. And the scanning mode of line-area-layer-solid with several rows of new nozzle arranged in parallel to boost build speed, is distinctive from available sand mould fabrication equipment. Technologies of new nozzle and blanking technology nowadays restrict its application to small casting piece's sand mould, which requires small stepwise like 0.3 mm, while theoretical build speed of large part show its great advantages. Therefore, equipment based on this new 3D sand mould printing method has magnificent prospect in promoting build speed and great industrial application value. The study in this paper will provide basis for the successful prototype manufacturing to greatly promote build speed of 3D sand mould printing from aspect of basic molding movement.

Nowadays, the specific structure of nozzle and the prototype equipment is under research, design and manufacture. Meanwhile, client software is going to be developed. It can be used to fulfill slicing up the STL file of sand mould and generate nozzle control data. Furthermore, on the basis of those data produced above, simulating the process of printing sand mould, as well as verifying data correctness are possible.

Beyond introduced above, taking nozzle or laser with three dimensional motion to realize printing with different direction and relevant 3D slicing into consideration is research orientation. Moreover, for high dimension accuracy, surface quality and making the material fiber of print with more superior directional dependent performance in machinability and mechanical properties, the nozzle might be based on Parallel Mechanism. Therefore, much more efforts would be devoted into this field to make sand mould and sand casting part with more superior performance.

Table 3 existing approaches of 3D sand mould printing and corresponding equipment with respective technical features

Manufacture principle	Company	Equipment	Nozzle or laser arrangement	Build envelop (x,y,z)(mm)	Build speed
3DP（DSCP, GS, ProMetal, RCT, Zcast）——firstly pave the mixture of crude sand and catalyst, then selectively pave binder.	Exone-America	Exerial	–	2200 x 1200 x 700 mm x 2group	300 to 400 L/h
		S-Max	nozzle array 4 lines*	1800 x 1000 x 700	60 to 85 cm3/hr
		S-Print	–	800 x 500 x 400	18 to 36 cm3/hr
		M-Print	–	800 x 500 x 400	
		M-Flex	–	400 x 250 x 250	30-60 seconds/layer
	voxeljet-Germany	VX200	256 Standard	300 x 200 x 150 mm	0.7 L/h
		VX500	2656 Standard	500 x 400 x 300 mm	3 L/h
		VXC800	2656 Standard	850 x 500 x 1500/2000 mm	18 L/h
		VX1000	2656/10624 Standard/HP	1000 x 600 x 500 mm	23 L/h
		VX2000	4096/13280 Standard/HP	2000 x 1000 x 1000 mm	47 L/h
		VX4000	26560 HP	4000 x 2000 x 1000 mm	123 L/h
PCM——pave crude sand, binder and catalyst in order	FHZL-China	PCM-1200	one nozzle for binder and one for catalyst	1200 x 1000 x 500 mm	400-600 mm/s
		PCM-800		800 x 600 x 500 mm	
SLS——sinter the powder selectively by sinter	EOSINT-Germany	EOSINT S 750	dual-laser *CO2	720 x 380 x 380 mm	0.25L/h
a new approach——respectively pave crude sand and furan no-bake sand	Institude of Design and Contorl Engineering for Heavy Equipment of SJTU	proposed a new type based on line forming	several nozzles layed out in paraller and with scanning in line	1000x1000x1000mm 3000x4000x2000mm	2880L/h (in theory) 3456L/h (in theory)

Table 3 existing approaches of 3D sand mould printing and corresponding equipment with respective technical features (continued)

Manufacture principle	layer thickness	Print resolution	molding material	system's motion composition of equipment and scanning mode
3DP（DSCP, GS, ProMetal, RCT, Zcast）——firstly pave the mixture of crude sand and catalyst, then selectively pave binder.	0.28 mm to 0.50 mm	X/Y 0.1 mm/ 0.1 mm	Silica Sand and a variety of manufacturing quality materials ;Furan Binder (no-bake),Silicate Binder and Phenolic Binder (microwave),Aqueous-Based Binder (sintering)	include all the five motions(scan in horizontal, eject drop in vertiacal direction, flight process of drop-parablolic, vertiacl penetartion and hozizontal diffusion, descend with cycle);point-line-area-layer-solid
	0.28 to 0.50mm	X/Y 0.1 mm/ 0.1 mm		
	0.24 to 0.38mm	X/Y 0.1 mm/ 0.1 mm		
	Variable with minimum 0.15mm	X/Y 0.07 mm/ Z 0.15 mm		
	Variable with minimum 0.15mm	X/Y 0.0635 mm/ Z 0.100 mm		
	150µm	300 dpi	SAND: Silica Sand, Inorfanic binder;PLASTIC: PMMA Partikel material (55 µm), Polypor B*. PMMA Partikelmaterial (85 µ m),Polypor C	
	80/150 µm	600 dpi		
	300 µm	600 dpi		
	100/300 µm	600 dpi		
	120/400 µm	200 dpi/600 dpi		
	120/300 µm	600 dpi		
PCM——pave crude sand, binder and catalyst in order	0.2-0.5 mm	±0.05 mm	Silica Sand, Inorfanic binder	include all the five motions;point-line-area-layer-solid
SLS——sinter the powder selectively by sinter	0.2mm	±0.05 mm	croning mould materials	not exist eject drop in vertical direction and flight process of drop;only scan in horizontal, vertical penetration and horizontal diffusion, as well as descend with cycyle;point-line-area-layer-solid
a new approach——respectively pave crude sand and furan no-bake sand	2mm	X/Y 0.1 mm/ 0.1 mm	Silica sand and mixture sand composed of silica sand, curing agent and binder uniformly	not exist penetration of drop ;instead of drop flight, it is flight of mixture; instead of jet binder, it is flow of silica or mixture;line-area-layer-solid

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