ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2024
Issue 1/2024

32 – 39

5/1

10.24425/afe.2024.149249

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

The Use of 3D Printed Sand Molds and Cores in the Castings Production

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Received 10.11.2023; accepted in revised form 22.12.2023; available online 04.03.2024

Abstract

As a part of this work, an analysis of the current state of knowledge regarding the use of additive technology - binder jetting in the production of castings was made. The binder jetting (so-called 3D printing) has become the leading method of sand mold and core production. Within this paper types of molding and core sands with organic and inorganic binders that are and can be used in technology were analyzed. The need to carry out works aimed at developing pro-ecological molding / core sands with inorganic binders and organic binders with reduced harmfulness to the environment dedicated to binder jetting technology was noticed. The influence of technology parameters on the properties of molding / core sands and the properties of cast components was analyzed. It was shown that thanks to the unlimited shapes of the systems obtained with the use of additive technologies, it is possible to influence the rate of heat dissipation through the mold, which positively effects the process of solidification and crystallization of the castings.

Keywords: Additive technologies, Molding and core sand, 3D printing, Mold technology, Castings quality

1. Introduction

Metal casting is one of the oldest technique of making components that serve man. From prehistory to the present, people are looking for modern solutions to significantly improve the quality of castings. New solutions like 3D printing coming from the development of additive techniques allow for not only the creation of complex shapes of casting patterns, but also for the production of sand molds and cores [1-9]. Currently, additive techniques (AM) have become part of Industry 4.0 and one of the Rapid Prototyping methods. In accordance with observed trends, in the future, the classical methods of molds and cores production may be partially replaced by printed components. Among many additive technologies, the binder jetting (so-called 3D printing) has become the leading method of sand mold and core production. The process is similar to classic 2D printing, including printers using ink. In the binder jetting technology a drop of binder falls on the prepared layer and locally binds nearby grains and then another layer of material is applied. The layer of material is fine-grained sand. The process of 3D printing of molding sands is shown in Figure 1 [3]. Nowadays the use of 3D printing in molds and cores production is the subject of numerous research. The technology may be a breakthrough for modern foundry engineering. Within this paper literature data concerning types of molding sands dedicated for 3D printing technology, the possible changes in mold construction and finally the impact of the technology on castings properties were analysed.

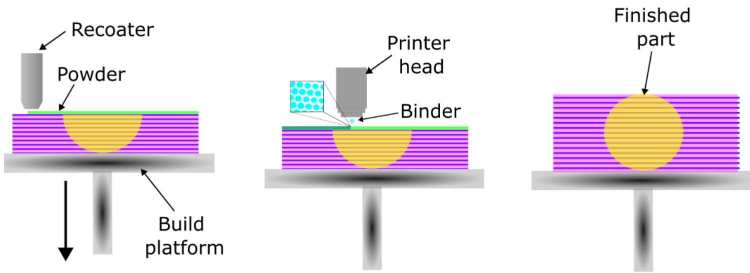

Fig. 1. Scheme of the process of 3D printing of molding sands using the binder jetting method [3]

2. Molding and core sands in binder jetting technology

Casting molds and cores manufactured by the additive method are mainly produced with the use of organic binders and quartz sand as a matrix [3-6]. However, there are solutions in the manufacturers' offers where chromite sand can also be used, and sometimes synthetic and ceramic sands are also used [6]. The grain size is 0.14 - 0.25 mm [5-7] and the commonly used binder is furan resin in the amount of 1 - 2% [4, 8] in relation to the printed molding sand mass. However, according to P. Szymański and M. Borowiak [9] the concentration of furan resin in the molding sand is 2.4%, and the thickness of the printed layer is 0.28 mm. The second most popular binder used in binder jetting technology is phenolic resin, dosed to the molding sand in the ratio of 2.2 - 2.4% [7].

According to trends observed in modern foundry engineering regarding molding and core sands, low environmental impact is one of the main conditions which must be met. The need to comply with high environmental protection requirements is the dominant factor in the development of molding and core sands. This is done even at the expense of reducing their technological properties.

It was proved by H. Shangguan et al. [4] that binder jetting technology allows for the reduction of used furfuryl resin to 1.6 - 1.8% and by S. Mitra et al. [9] to 1 - 3%, which may be considered as a pro-ecological effect of the technology.

However, as the binder jetting technology is developing rapidly and the environmental friendly binders are noticed to be rarely used in it, the importance of elaborating appropriate molding systems using inorganic binders and organic binders with reduced negative environmental impact should be considered as a priority. This is very important from the point of view of reducing the harmful organic compounds emitted during the production of castings and also from the point of view of waste management. The problem of post-regeneration dust disposal from molding and core sands with organic binders is still not solved. Works on environmentally friendly molding and core sands in both above mentioned aspects are the subject of many the authors' own research [10-18].

2.1. Influence of printing parameters on the properties of molding sands

The mechanical properties define for which alloy the molding sand can be used. The use of binder jetting technology forces more and more research into both the parameters of the printing device and the binder properties. The printing device affects the mechanical properties of molds and cores by:

- distribution of sand grains - 3D printing allows for more accurate distribution of layers, which has a positive effect on strength properties [19];
- print plane - the best strength values are achieved by samples printed on the X-Y plane (90° printing angle) [20-23];
- thickness of the printed layer [24].

N. Bryant et al. [25] showed that the system settings affect the transverse strength of the sands, losses during firing, print density and resolution. Changing the settings of the heater shows a change in the properties of molding sand density and permeability. In the same work attention was put to the permeability at elevated temperature. The research proved that permeability decreases with temperature increase [9].

On the other hand the binder may affect the molds and cores properties by its gel time (resin cross-linking) which was proved by P. Hackney et al. [26] and Y. Wang et al. [27]. The effect of the gel time of the resin with different amount of sulfenic acid as a binder was examined [20]. Therefore, there were conducted comparative studies for molding sand prepared in no-bake technology and in 3D printing technology. It was shown that the tensile strength after 24 hours is lower in the case of using 3D printing. It was also proved that the gel time for the same amount of hardener is extended in the case of 3D printing technology. In addition, studies have shown that the gel time affects the surface of the printed cores. The longer the gel time was, the more deformed side surface was observed, which affected the strength results. Figure 2 shows the comparative results of cores made using the classic method (no-bake sand) and 3D printed sand. The relationship between the compressive strength after 24 hours of curing and the time of gelation was presented. A short gel time for no-bake technology negatively affects tensile strength values. It was proved that the strength values increase after five minutes and then stabilize. In 3D printing technology, a short gel time allows to achieve higher strength values. A longer gel time for the resin used in 3D printing technology results in a decrease in tensile strength values [27].

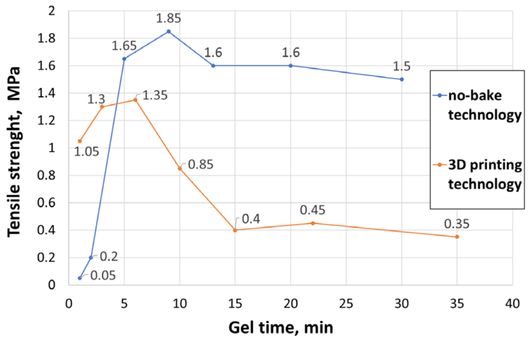

Fig. 2. The influence of gel time on tensile strength tested after 24h of hardening [20]

Fig. 3. Casting with a visible stepping effect on the surface [20]

The use of additives to printed molding sands may have a beneficial effect on their strength properties. Z. Fa Zhang et al. [7] proposed the use of a poly(vinyl alcohol) (PVA) additive as water-soluble and fully degradable at 220°C material, which, according to the authors, allows for easier reclamation. The use of PVA in the amount of 4.5% improves the mechanical properties of the printed parts. In addition, the authors showed that in the case of binders based on resins, the strength properties of the sands are affected by the saturation with the binder and the alcohol content of the sand.

It was also proved that in case of cores made in additive technology their basic parameters were kept better while storing at ambient temperature in industrial conditions than cores produced in classic technology [25]. From practical point of view it is important that pre-prepared cores or mold parts keep their strength and permeability after storage.

A characteristic feature of printed sand molds and cores is so-called stepping effect [28]. Characteristic steps appear during printing and are formed on the casting surface (Figure 3). The effect is caused by applying successive layers of sand and may force additional surface treatment of the produced casting. The main causes of the stepping effect are:

- layer thickness,
- local surface inclination,
- material used,
- size and distribution of the joined particles [29].

C. Hartmann et al. [30] proposed a proprietary solution in which there were significant changes on the surface. In the research, it was concluded that the binder concentration significantly affects the disappearance of the stepping effect. Decreasing the binder content below 5% in Z-axis eliminated the problem. The printed surface was examined in terms of droplet penetration in a given voxel. According to authors, in the future it will be possible to print cores and molds in more dense XY grids, which will completely eliminate stepping effect [30].

3. Binder jetting in mold technology

The use of 3D printing technology allows for the production of cores and molds with shapes that were not possible to achieve with the use of conventional molding methods. S. R. Sama et al. [28] proposed casting the brake disc in a vertical position. A computer simulation was run which showed less porosity of casting produced in such a position. The use of vertical orientation also allowed for a higher yield. The authors [29] also considered using an unconventional gating system in the case of casting a complex handle. The proposed solution enabled to homogenize the speed of the metal in the gating system.

As mentioned earlier, the technology of 3D printing of casting molds and cores enables achieving previously impossible, due to the limitations in the classic methods of mold technology, shapes. The use of 3D printing allows to focus on the subject of longer heat retention in order to better supply heating nodes that are particularly vulnerable to casting defects such as shrinkage porosity or shrinkage cavity. Researchers [4, 31, 32] first created a mathematical model of the mold in which the air cavity appeared, and left a thicker layer of molding sand near the main sprue. Simulations showed that this type of mold is better suited to alloys with a lower melting point, such as aluminum alloys. The casting of the frame for testing casting stresses was examined. A shell-truss mold and a classic mold were printed from molding sand with resin as a binder (Figure 4). The prepared molds were poured with AlSi7 aluminum alloy. The conducted research showed that the proposed type of mold has a beneficial effect not only on the cooling rate, but also allows for adjusting the local cooling conditions. In addition, the use of this type of mold allowed to save two-thirds of the molding sand and shortened the cooling time by 25% in comparison to the traditional type of mold.

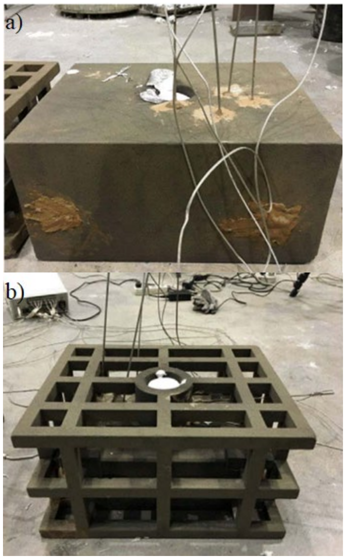

Fig. 4. Printed molds: a) classic type of mold b) mold with cavities (shell-trus mold) [4]

Casting cores also play a special role in the cooling process. In the first phase of pouring, the core can absorb a large amount of heat, the dissipation of which is low, which causes a low cooling rate. X. Wei, Y. Wan & X. Liang [33] suggested that a core with cavities could provide better heat dissipation. Three types of cores were designed: solid core, a core with a cavity and a core with a truss structure (Figure 5). The prepared molds together with the previously printed cores were poured with alloys: aluminum alloy AlSi7 and cast steel No. 35. The carried out research allowed to reduce the cooling time by about 20%. In addition, the use of a core with a cavity enable to reduce the defects associated with improper feeding of castings. In the case of steel No. 35, the obtained results allowed the authors of the work to advance the thesis that the hollow core does not expand as much as the solid one, which reduces the likelihood of cracks on the inner wall of the casting.

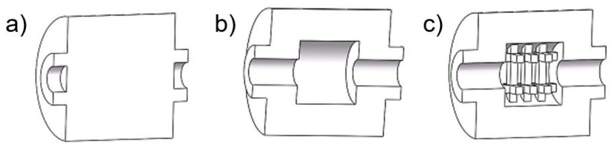

Fig. 5. Diagram of cores: a) solid b) with a cavity c) with a truss structure [33]

The solidification process itself is affected by the thickness of the mold wall. M. ben Saada & M. el Mansori [34] conducted research related to the influence of the thickness of the printed wall (from 3 to 30 mm) on the solidification time of aluminum alloys. First, the conditions were simulated, which allowed to determine that the smallest wall thickness for conducting the experiment was 5mm. AlSi13 alloy was cast into the printed molds. Simulations showed that the solidification time of the alloy decreases by 40% with the increase of the thickness of the mold wall from 3 mm to 30 mm. The authors determined that the wall thickness for the tested element was characterized by the optimal solidification time and the thickness of printed material was 15mm. It allowed to obtain a good compromise between solidification, mechanical properties and manufacturing cost [35].

The use of modern technologies in one of the oldest component production processes allows for the development of advanced methods of testing the impact of mold technology on the quality of the casting obtained. Modern simulation programs are used for such research, however traditional molding techniques did not allow to verify the results of the simulations under experimental conditions. The 3D printing technique makes it possible to carry out such experiments thanks to the possibility of designing mold elements of unlimited shapes. Based on the literature on simulation studies using main sprues of various shapes [35], S. Sama et al. [36] and D. Martinez et al. [37] produced castings using sprues with the shapes suggested by the authors [35] of the simulation. Three types of main sprues were compared: classic, parabolic and spiral, which are shown in Figure 6 [38]. The conducted research allowed to determine that the liquid metal flowing through a parabolic and spiral sprue contains fewer non-metallic inclusions and is characterized by better bending strength. The use of a spiral sprue allowed for a significant reduction in the occurrence of casting defects [35-37].

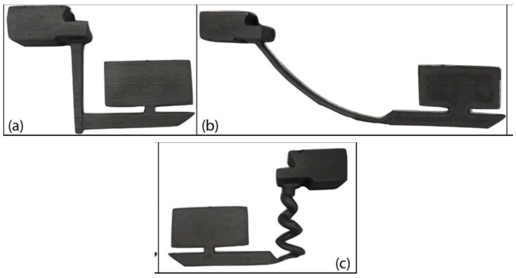

Fig. 6. Types of tested sprues a) classic b) parabolic c) spiral [38]

4. The influence of 3D printed molds and cores on the castings properties

Numerous phenomena occurring at the metal-mold interface are significant for the quality of the castings obtained. Therefore, the use of 3D printing technology for the production of molds and cores from molding sands requires determining its impact on the castings properties. D. Snelling et al. [39] presented a comparison of the properties of AlSi7 aluminum alloy castings into molds produced by conventional methods and printed on ExOne and ZCast® printers. In the case of the parameters: distance between dendrite arms, porosity, roughness and tensile strength, the obtained test results were comparible. They different in tensile strength, hardness and density. These parameters were obtained on an ExOne printer, which provides better control over the distribution of sand grains [39].

Binder jetting allows the use of reverse engineering, which makes the preparation of the CAD model and then the preparation of the mold much easier. In the case of an attempt to make the impeller made of cast steel [40], similarity was found at the level of 99.6% to the original, with differences only in grain refining. In the mold made by the additive technology, finer grains and a homogeneous surface were observed, which means that the shrinkage porosity is below 0.5% [40].

The surface quality of the obtained casting is an important element during the production of the casting. Very low roughness is even desired by the foundry industry. P. Szymański & M. Borowiak [41] conducted research to determine the effect of the type of sand and binder on the roughness of various casting alloys. As part of the research, 5 different molds were made: 2 with organic binders based on furan resin with different types of sands; with phenolic and cold curing phenolic binder and with inorganic binder. The following alloys were cast into the prepared molds: cast iron GJL-250, cast steel X5CrNi18-10, tin bronze CuSn10P and aluminum alloy AlSi11. The tests showed that the type of used binder has a significant impact on the roughness of the obtained castings. In the case of the inorganic binder, the roughest surface was obtained when pouring bronze and cast iron alloys, while in the case of cast steel, the most unfavourable surface was obtained when molds with furan binder were poured. In addition, the researchers proposed to remove the stepping effect by placing the flat surfaces perpendicular to the printing surface [41].

Low roughness and very well reproduced dimensional accuracy obtained thanks to 3D printing allows for the preparation of molds for precision and artistic castings. 3D printing technology also enables the preparation of gypsum molds that can be used for die casting of copper and noble metal alloys [42]. Appropriate development of material parameters allows for printing various types of molding materials. O. Na, K. Kim & H. Lee [43] developed a cement-based molding material for use in binder jetting technology. The matrix was quartz sand mixed with CSA type cement and gypsum, and the binder was hydrated sodium silicate with a viscosity modifier. Zhang et al. [44] proposed using printed water-soluble cores in the production of casting components that require cooling with water. A water-soluble molding sand based on sand with the content of Al_2O_3 (≥75%) and SiO_2 (12-25%) mixed with bentonite was used. The binder was pure potassium carbonate (K_2CO_3) dissolved in water. After the printing process, the fittings were sintered at 850°C for 10 min, re-soaked in K_2CO_3 aqueous solution and sintered again for 10 to 80 min at 750, 800, 850 and 900°C. It was shown that the most optimal leaching parameters were obtained using a 40% K_2CO_3 solution, for molds cured for an hour at 140°C, soaked in a 50% K_2CO_3 solution and re-sintered at 900°C for 10 min [44].

Mold printing has a positive effect on the surface quality of cast copper alloys. I. Goto et al. [45] compared printed molding sands made of artificial mullite sand with a furan binder: dried and undried, with molding sand with water glass hardened with CO_2 treated at 200°C and 400°C. The molds were poured with pure copper alloy, which was created based on high-purity refined copper scrap and industrial scrap used for producing pure copper castings (CC040A). before and after the deoxidation process. Molds made in 3D printing from molding sands with an organic binder caused the formation of gases that created porosity in the case of deoxidized samples. However, in the case of using a non-deoxidized copper alloy, the additive technology of molds production brought a satisfactory effect.

M.A. Castro-Sastre et al. [46] studied the effect of two different types of molds (classic mold and 3D printed mold) on the microstructure and corrosion behaviour of aluminum alloys. The material used to print the binder jetting mold was a commercial powder plaster, $CaSO_4.1/2H_2O$ and to manufacture the sand casting mold, commercial silica sand was used. The authors [46] explained that the differences in corrosion behaviour of castings produced in both molds were related to the differences found in their microstructure. Figure 7 shows the microstructures obtained during the tests [46].

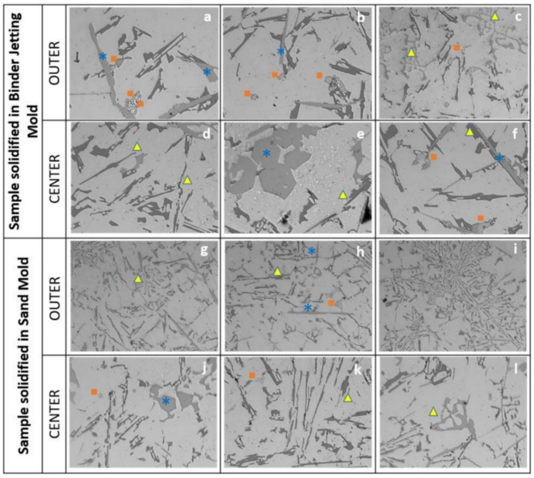

Fig. 7. Microstructures of the samples, outer layers of the casting (a-c) in the mold created in the binder jetting technology, and the center of the casting (d-f), the outer layer obtained in the sand mold (g-i) and the middle part of the casting (j-l),* - phase Si, ■ – $AlCu_2$, ▲ – Al-Fe-Si [46]

The enhanced corrosion resistance of alloy solidified in the binder jetting mold compared with the alloy solidified in sand mold, according to the authors [46], could be associated, with both the reduced area ratio of eutectic silicon particles to eutectic aluminum phase and the presence of coarse silicon particles visualized in the eutectic of binder jetting alloy that can originate a lower number of micro-galvanic couples. The alloy microstructure achieved by the binder jetting technology showed galvanic pairs of silicon and α-Al-Fe-Mn-Si intermetallic precipitates that limited corrosion resistance. With the sand mold, the microstructure was rich in needle-like intermetallic compounds (β-Al-Fe-Si) that accelerated corrosion as the presence of Fe in Al-Si-Cu alloys originates the β-Al-Fe-Si phase in the form of longer and thicker needles, with the higher the iron content and the higher the cooling speed [47]. This phase has a nobler potential than the aluminum matrix and therefore enhances the susceptibility to localized corrosion [46]. The presence of Mn resulting in α-Al-Fe-Mn-Si in the form of the so-called ''Chinese script'', with lower potential reducing the galvanic corrosion compared with the β-Al-Fe-Si intermetallic phase [48]. The Fe-intermetallic compounds were more visible in outer sections of both samples. However, the sample processed by sand casting had a higher number of needles with larger size while in the sample derived from binder jetting technology, a greater amount of script phase was visible. It can explain the enhance corrosion behaviour observed for outer ceramic casting sample [46]. However, it should be emphasized here that in the above mentioned studies [46] not only various technologies of mold manufacturing but viorious types of molding sands were used as well. Molding sands components may also affect the microstructure of the surface layer of castings. Therefore, the observations require confirmation.

5. Summary and conclusions

Analysing the presented literature data, it can be concluded that additive techniques used for molds and cores production will have an increasing share in the production methods of molds. N. Hawaldar N. & J. Zhang [5] compared manufacturing both 3D printing and classic techniques and showed that the use of 3D printing can ensure more efficient work and less sand consumption. However, according to the authors, the technology is more efficient when producing a small number of molds. Better dimensional accuracy and less post-processing of the casting are ensured. In small-lot production, the use of 3D printing technology allows to reduce energy consumption by about 9% [49]. However, in the case of the production of a larger number of molds, a combination of traditional technologies with elements made using additive methods works much better.

Appropriate preparation of the optimal composition and curing time allows for printing molds and cores with various binding materials. Despite the fact that 3D printing technology has evolved from rapid prototyping technology, which is well known and used in the industry [50], there are still many challenges that 3D printing of molds and cores has to face.

It seems particularly important to develop pro-ecological molding sand systems that could be used in 3D printing technology designed for molds and cores production, which are not currently used in this technique. This will be the subject of further research.

Acknowledgements

The research was financed by AGH Research Project No 16.16.170.654

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