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# Additive Manufacturing of Casting Tools Using Powder-Binder-Jetting Technology

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Daniel Günther and Florian Mögele

Additional information is available at the end of the chapter

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## Abstract

This chapter presents the use of the additive manufacturing (AM) method powder-binder-jetting (PBJ) for the generation of molds and cores for casting applications. Theoretical information on process steps and the binding of particles is given. For the based chemistry, examples are presented and the transfer from conventional production processes to powder-binder-jetting is explained. For sand as a material for metal casting, methods to determine key properties for the casting are in focus. The figures found by our research activities reach up to that of conventional production and indicate the readiness of the technology. These cavities produced by powder-binder-jetting can even be used for cold casting materials such as concrete. Several demonstrators show the impact of this application. A polymer process for the investment casting process is topic of an additional section. To understand this process, theoretical information and figures determined by measurements are presented.

**Keywords:** Additive manufacturing, powder binder jetting, casting, mold, cavity

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## 1. Introduction

Powder-binder-jetting (PBJ) technology, an important process within the additive manufacturing (AM) technology, may be considered as the standard method for the production of cores and molds for the foundry industry. Despite the enormous turnover volumes, the characteristic variables of the process and the process chain for metal casting are still relatively unknown. This chapter lists the main processes involved in this technology and provides extensive, application-relevant measurement values and results for foundry processes. Thus, the foundry world and the world of additive manufacturing (AM) are closely interlinked.

Additive manufacturing processes differ fundamentally from the conventional production process: The desired component, for example, a mold, is composed of layers. The production is directly related to the component data. In the case of the conventional manufacturing, the component data are at first realized as a model or tool, and this part is then further used for the actual production. The time required for an entire processing cycle is significantly reduced by applying additive manufacturing methods (see [1]).

This layer-based powder-binder-jetting technology produces porous material components by selective bonding of particle material. These characteristics (specifically strength) are disadvantageous for the direct use, but parts manufactured in this manner can be used in the foundry process. A temperature-resistant material, such as sand, is used as particle material for this process. The binder is also selected in accordance to its properties and temperature resistance properties are adjusted. Due to the porosity of the parts, the resulting gas can escape during casting, which eliminates casting defects by rising gas bubbles in the melt.

The particular process associated with powder-binder-jetting which makes this process highly efficient is the use of particle material as a basis and the use of a limited amount of binder. In addition, the automation process can easily be expanded. It is possible to produce component sizes that are specific for foundry technology. Scalability during production allows production rates that are economical for small series. Here as well, a lot of potential can be seen, and previously limited lot sizes increasingly move toward larger lot sizes (see [2]).

This chapter introduces the powder-binder-jetting method in detail and explains its suitability for the production of molds. Other additive manufacturing processes are briefly described and their different characteristics are shown. It is shown that powder-binder-jetting processes based on lot sizes and productivity are unique, and therefore hold a prominent position as an industrial means of production within AM.

The sand casting process plays an important role in the field of conventional casting technology. This sand casting process is carried out using three materials/binding systems, which can be directly transferred to AM production methods. The basic methodology of determining the characterizing parameters are explained further in the following sections. The data obtained for printed components using this method are compared with the data of conventionally manufactured components and an assessment is carried out.

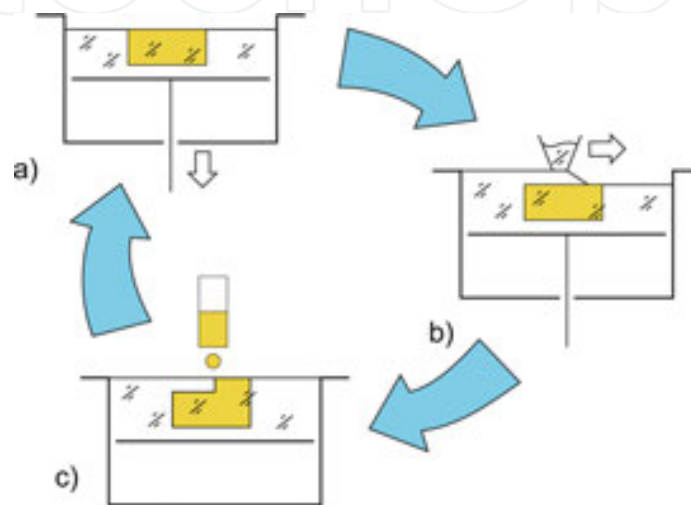
A subchapter deals with the application of 3D printed molds for metal casting in the area of cold-curing materials. Here, the problems arising out of de-coring are most crucial. The process of extracting the printed part from the mold is explained in detail using the examples of concrete casting. The results that are obtained in this area are presented in detail and discussed in the context of applications in structural engineering and architecture.

Another section presents the use of the particle material, PMMA powder, as a basis for the investment casting process. Here, the investment casting process is explained and its embodiment as AM process is explained using 3D-printed forms. Within this context as well, the property requirement necessary for the 3D-printed parts is also elaborated.

## 2. Powder-binder-jetting

### 2.1. Overview

This section provides an overview of the powder-binding-jetting technology. As in the case of several additive manufacturing processes, this process too comprises individual steps that are repeated continuously to form a three-dimensional component. **Figure 1** provides an overview.



**Figure 1.** Schematic representation of the powder-binder-jetting-process: (a) lowering the build platform, (b) layering with particle material, and (c) printing process using binder.

The PBJ process steps are as follows: applying a layer of particle material (powder) on a build platform, bonding of the powder particles by a liquid, and lowering the build platform by the height of the desired layer thickness (see [3]).

The process begins with an empty build platform. It is usually set up within a build box. A seal prevents leakage of powder between the moving construction platform and the static walls of the build box. The recoater spreads the powder on the build platform (see [4]). The powder can either be placed in front of the recoater or is moved along with the recoater across the build platform.

At the start of the construction process, the space between the recoater blade and the build platform is sequentially built up with multiple layers of powder to eventually form an even layer of powder.

In the next step, the inkjet print head moves over the powder layer and doses binder onto the layer. The current height of the built component corresponds to a cross-section of the virtual component. The inside part of the cross-section is filled up by print data. Depending on the data processing process, the sliced images are eventually converted into a matrix, in this case in a bitmap structure (for data formats, see [5]).

The inkjet print head also represents a matrix-like arrangement and is guided across the entire built platform, depending on the size of the print head in a meandering motion or in one linear drive across the platform. In the simplest case, this matrix-like arrangement is a line of nozzles which correspond to the driving pattern as determined by the data matrix. During the drive, data change in rapid succession, thus forming the desired image.

The droplets are generated in the inkjet print head itself due to rapid pressure fluctuations and expelled through a micronozzle. Thus, a drop formed in the micronozzle is pressed out and leaves the nozzle as a free-flying independent droplet. Due to this process, certain restrictions are placed on the material range that can be applied (see [6, 7]).

The upper limit for the viscosity is currently approximately 30 mPa s. The surface tension should be substantially below that of water, so less than 50 mN/m. The printable material can include solvents, aqueous solutions, oils, or monomers. The media should not expel particles larger than approximately 1  $\mu\text{m}$  so that no blockages are formed in the microjets.

The final step in the construction process is the lowering of the build platform. After lowering, the resultant space is again filled with the help of the recoater. The layer thickness corresponds to the vertical distance the build platform moved while lowering. An alternative process is the continuous 3D printer. According to this method, the printing is performed on an inclined plane and the powder-bed movement takes place via a conveyor belt at an angle to the plane (see [8]).

## 2.2. Distinction from other processes

The MultiJet modeling process works similar to the PBJ process. The focus of the method is also an inkjet print head that works on matrix basis. Contrary to the method described above, powder is not used, but the desired shape is composed by the medium expelled from the print head. Here, the medium is cured in layers with the help of a UV source. Overhangs can be achieved by using a support medium that is applied over a second print head. Curing is done using UV technology (see [9]).

Under the vector-based methods, the fused deposition modeling is the only method that is not based on energy beam technology and is thus similar to the PBJ process. As opposed to the two procedures mentioned above, this method does not involve free-flying droplets. The model is constructed using an extruded filament (see [9]).

In the beam-based method, there is no additional mass involved during construction process, reflecting the total mass of the finished model. Existing volume is modified. During stereolithography, resin is cured by a laser beam [10]. When laser sintering process is applied, a powder is used as a base which is similar to the PBJ process and a high-energy beam is used to fuse the powder; Currently, the most widely used methods are the ones making plastic or metal parts. Materials such as ceramics, concrete, or biological materials are the subject of research on an industrial scale but not yet main stream (for ceramic see [11]). **Table 1** provides information on the different distinction possibilities.

Method	FDM	LS	SLA	PBJ
Vector based	X	X	X	
Matrix based				X
Powder based		X		X
Beam based		X	X	
Size	++	0	+	++
Performance	0	+	+	++
Costs	++	0	0	++
Direct application	++	++	+	0
Material diversity	+	+	0	++

**Table 1.** Characteristics and categorizations of various AM methods.

**2.3. Scalability**

Among all processes, the powder-binder-jetting process is considered the most scalable. This has an impact on possible component sizes and system performance. Different categories of scalability are discussed and evaluated as below.

In the PBJ process, the build size is defined by the distances covered by the linear axes. In principle, these axes can be extended as required. Merely the axle supporting structure needs to be adjusted according to the increased point of deflection. Limitations are generally not posed by the device, but by the strength of the product produced relative to its weight. This ratio largely determines the handling of the parts and is therefore size restricted.

The performance of a system is often quantified on the basis of the time taken to print one layer.

During the PBJ process, the pixels of a layer are printed by individual parallel controllable nozzles. Here, the number of the nozzles is proportional to the print performance. When measures are taken to parallelize the coating process, the number of nozzles is often nearly proportional to the time per layer. The performance of the printing system can thus be easily scaled by increasing the number of nozzles.

Within PBJ process, there is another option to improve the performance: Several spatially successively arranged coating and printing units are able to generate quasiparallel layers. The applicable layer time is then the layer time of such a “layer unit” divided by the number of the active “layer units” [12].

For procedures having a vector control, such scales cannot be realized. In laser-based methods, the radiation field cannot be expanded indefinitely. This is mainly due to the flat field lens required for a focused exposure. Similarly, it is not possible to use arbitrarily many laser sources simultaneously since the beam path would rapidly become complicated, particularly due to the necessary deviation.

In the case of FDM, axis scaling is possible as which the PBJ processes. However, due to the mass inertia of the print-head discharge, speeds are limited. A parallelization of several print-head discharges is possible albeit only with considerable effort.

The parallelization described by several “layer units” is not possible in the laser sintering process and the SLA process. Both methods use contour procedures that require a complete “visibility” of the current layer. A parallelization would require at least the simultaneous formation of a new layer and the laser exposure of an old layer. The FDM method combines the shaping and layer formation. In this case, this principle can also not be used.

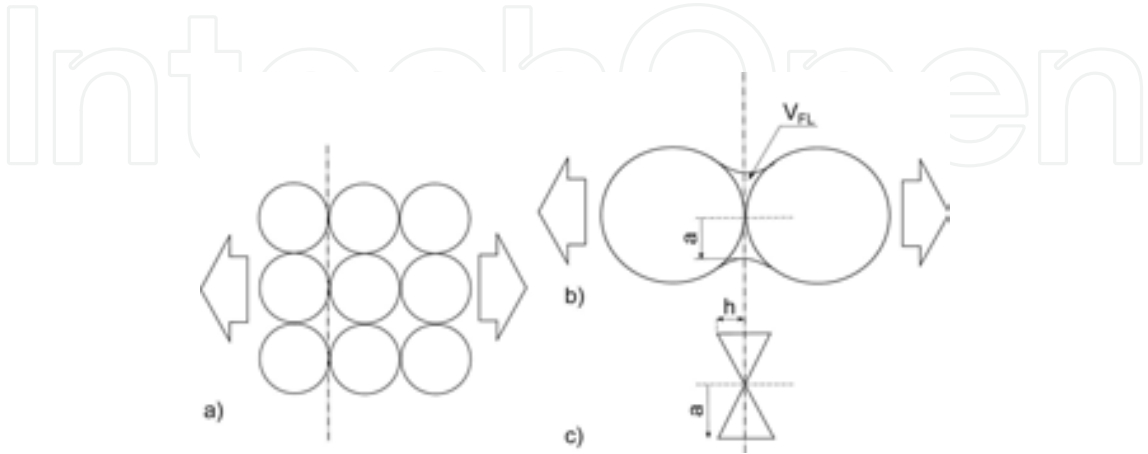
The PBJ method thus provides unique opportunities to improve performance. A summary of these bearings can be found in **Table 2**. Thus, applying this technology as a production process within established production procedures seems to be realizable.

Process	Size	Layer speed	Z-speed
PBJ	++	++	++
FDM	++	0	-
SLS	-	+	+
SLA	0	+	-

**Table 2.** Assessment of the scalability of different processes.

2.4. Basic modeling

The mechanical properties of the PBJ processes are, apart from the cohesion of the binder and the adhesion of the binder to the particles, essentially determined by two variables: the grain size and the relative amount of binder. During the model forming process, the particles are thought to be stronger than the bond.



**Figure 2.** Schematic representation of the model particles/bond: (a) illustration of a particle cluster under tension, (b) illustration of two particles under tension, and (c) highly simplified model for calculating the volume of the bond.



A model of the bond can be represented as in the following simplified diagram: Between two particles that are considered as ideal for the spherical model, there exists an external nearly cylindrical binder bridge (see **Figure 2**). This bridge is formed by capillary action shortly after application of the binder by the print head and the respective strengthening mechanism freezes this condition. This form of connection is similar to the sintering process. Basic deviations, necessary for the basic understanding of the conditions, can be obtained by simple considerations.

If the binder bridge is small in relation to the radius of the sphere ( $h = \text{const}$ ), then considering the above assumptions, a model of a cylinder minus two cones describes

$$V_{Fl} = 2 \cdot \frac{2}{3} \cdot a^2 \cdot \pi \cdot h \quad (1)$$

the volume of the bond or the printed quantity of liquid. If the model is modified to determine the influence of the volume, it can be assumed that a constant distance of the particles exists. Only the radius of the cylinder varies. Thus, the relation holds true:

$$V_{Fl} \sim a^2. \quad (2)$$

The contact area  $A$  and the maximum mechanical tension  $\sigma_{Max}$  are accessible via simple equations

$$A = a^2 \cdot \pi \text{ and } \sigma_{Max} \sim A. \quad (3)$$

The relationship of the printed amount to the mechanical stress at break is thus linear:

$$\sigma_{Max} \sim V_{Fl}. \quad (4)$$

The strength is thus linearly dependent on the volume of the printed material. The printed volume corresponds to the organic or inorganic binder content minus the evaporated solvent content.

Considering the influence of the particle size, the model must be mentally expanded to form a particle cluster. As a minimal model, a cubic packing may be used and a voxel as observational volume. A voxel is defined by the smallest possible volume that can be produced with a PBJ system. The dimensions of a voxel are made up of layer thickness and the resolution of the inkjet print head together in two directions. For the number of binding areas per voxel  $N$  holds true:



$$N = 6 \cdot N_p = 6 \cdot \left( \frac{l_v}{D_p} \right)^3 \quad (5)$$

with the number of particles per voxel  $N_p$ , the dimension  $l_v$ , a cubic voxel, and the grain diameter  $D_p$  of the considered perfect monomodal particle size distribution.

For the volume of a single bond  $V_B$  and the total binder volume per voxel  $V_v$ , the following equation applies:

$$V_v = V_B \cdot N = V_B \cdot 6 \cdot \left( \frac{l_v}{D_p} \right)^3. \quad (6)$$

As with the approximation of the print volume, in this case only one-half, it is again assumed to form a binding as shown below:

$$V_B = \frac{2}{3} \cdot a^2 \cdot \pi \cdot h. \quad (7)$$

For calculating the bond area, relevant for the maximum mechanical stress at break, the following equation applies:

$$A = a^2 \cdot \pi \cdot \left( \frac{l_v}{D_p} \right)^2 \quad (8)$$

and by applying the above relationship for  $V_B$ , we obtain

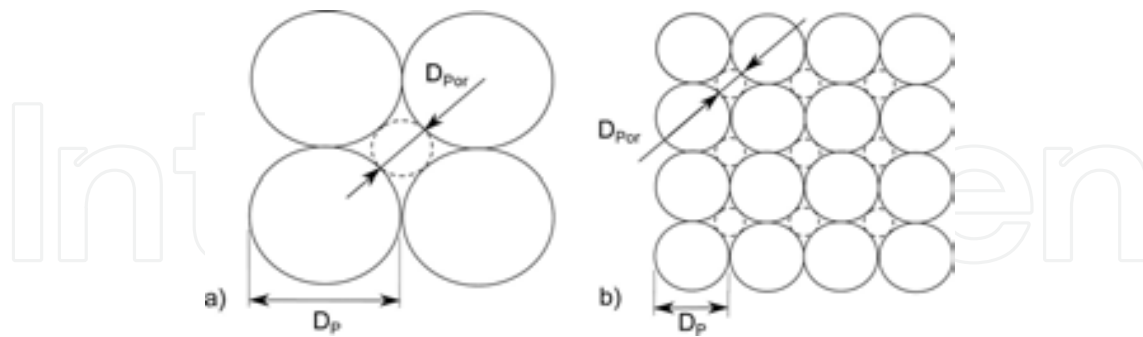
$$A = \frac{3 \cdot V_B}{2 \cdot h} \cdot \left( \frac{l_v}{D_p} \right)^2 = \frac{3}{2 \cdot 6 \cdot h} \cdot V_v \cdot \left( \frac{D_p}{l_v} \right)^3 \cdot \left( \frac{l_v}{D_p} \right)^2 = \frac{V_v}{4 \cdot l_v \cdot h} \cdot D_p. \quad (9)$$

The relationship between  $\sigma_{Max}$  and the particle diameter  $D_p$  is therefore, at  $V_v$ ,  $l_v$ , and  $h = \text{const}$ , almost linear:

$$\sigma_{Max} \sim D_p. \quad (10)$$

The particle diameter is directly proportional to the breaking stress value in the same way as the amount of liquid. This implies that the use of finer particles leads to a reduction of strength. Similarly, when particle size is reduced (improving the surface properties), the amount of

liquid printed needs to be adjusted. In the given model assumptions, the density is not affected by changes in the particle diameter.



**Figure 3.** Diagram of the pore-channel diameter at different particle diameters: (a) diameter of an average particle cluster with inscribed minimum passage diameter and (b) particle cluster with half a particle diameter for comparison.

The dimension of the size of the pores is changed by changing the particle diameter (see **Figure 3**). In this example, the diameter of the respective largest circular diameter  $D_{por}$  is inversely proportionate to the particle diameter. This can be roughly described as

$$D_{por} \sim \frac{1}{D_p}. \quad (11)$$

According to this relationship, the resistance of a gas flowing through such channels greatly increases because the volume flow is proportional to the diameter to the fourth power. A change in the particle diameter (for example to influence surface finish) has a strong influence on the behavior of the gas penetration in the printed model.

### 3. Production of casts by powder-binder-jetting

#### 3.1. Theory, chemical, and physical basics

The introduction describes the conventional process—to produce metal parts by casting. Sand casting or the combined use of molds and sand cores is explained as follows.

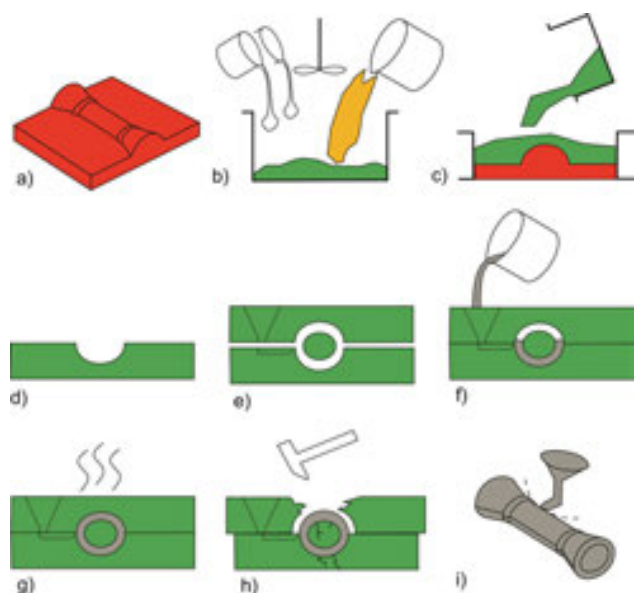
Casting provides important components for industrial production because they provide high functional integration densities with cost-effective implementation. The production of castings is carried out in two steps: First, to create a multipart mold having a cavity which corresponds substantially to the later casting. Second, the casting where the mold is filled with molten metal and after its solidification forms the actual part.

Depending on the complexity, quantity, or cost requirements, the mold can be designed as a disposable or reusable form. Simple structures can be produced using reusable forms. Complex shaped channels in the casting are only possible using disposable molds to realize

such complex cores. Often the techniques are hybridized with each other to take advantage of the required assembly (see [13]).

Thus, the cavity of a casting for metallic molds, and molds and cores, may be surrounded by sand. These different parts are mounted before they are cast, some with a large degree of automation (for process steps, see **Figure 4**).

Disposable molds and cores are made from a base molding material that is a particle material using a binder. The binder is often a fluid, which is mixed with the particle material. This mixture is then added to the model and solidifies. The model is shaped in such a way that the model or the core can be removed from the model without being destroyed. Thus, high complexities cannot be achieved using this method. More complex mold sets have to be assembled from individual parts by mounting (see [14]).



**Figure 4.** Diagram of the conventional sand casting process: (a) model, (b) preparation of the molding material mixture, (c) molding of the model and solidification of the molding material mixture, (d) part of mold (drag), (e) mounting of molds and cores, (f) pouring liquid metal, (g) solidification and weakening of molding material, (h) extraction, and (i) casting with gating.

For the production of series, the molding material is often mixed with the binder and activated in an automated process (**Figure 4**). This reactive mixture is then injected via a pneumatic conveyor into a model form and gets coated alongside the walls. The component thus produced is cured in the model form. After curing, the part is often automatically removed by a robot and is deburred by an automated process as well. Thereafter, the mold for the actual casting process is again mounted with the help of the robot. The casting process too can thus be carried out fully automated.

The method described requires several basic materials properties for the individual process steps. The particle material must be free flowing to fill the model form. The binder must have

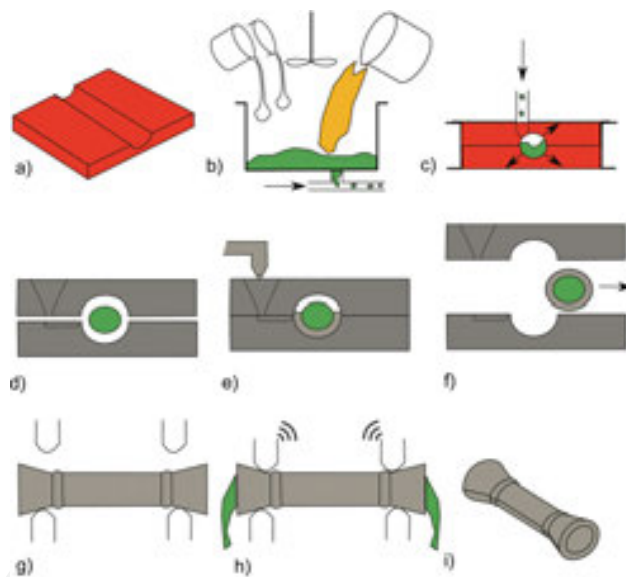
very low viscosity for metering and for the resulting molding material flow characteristics (Figure 5 ).

Both properties are also a basis for processing of materials in machines within the PBJ process. Therefore, the materials can be used in 3D printers without major modifications in their physical or chemical properties.

Both methods can also be combined. Forms created with conventional tools or molds are able to support PBJ-printed cores (compare [15] or [16]).

The heat occurring during casting is used to weaken the molds and cores to such an extent that after solidification of the casting the molding material can easily be removed from the casting. This is called de-coring and is significantly defined by the binder.

Among the additive manufacturing methods, the laser-sintering process is the only other AM method by which it is possible to create cores and molds for the foundry industry. In this method, resin-coated sand is melted with a laser and thus selectively bound. The technique is similar to the Croning® method (see [17]).



**Figure 5.** Brief overview of highly automated core production: (a) half section of a core model, (b) preparation of the molding material mixture, (c) core shooting process, (d) inserting the core in the mold, (e) casting process, (f) removal of the casting with the core (gating is not shown), (g) clamping the casting, (h) shake-out of the core, and (i) casting.

Metals that can be used in the sand casting process, in certain cases, exhibit very different properties (see Table 3). As far as weight goes, cast iron is the most widely used material for casting. It is characterized by a low melting point of about 1250°C and excellent mold filling properties. Less common casting is the use of steel whose melting point is about 1700°C. Here, form filling is much more difficult. Due to the ready availability of a variety of cast iron types having high ductility, the ductility of the material is only a weak criterion for choosing the appropriate casting material. Therefore, cast steel has become less important. Aluminum is superior due to the lightweight requirements of modern products and has thus become

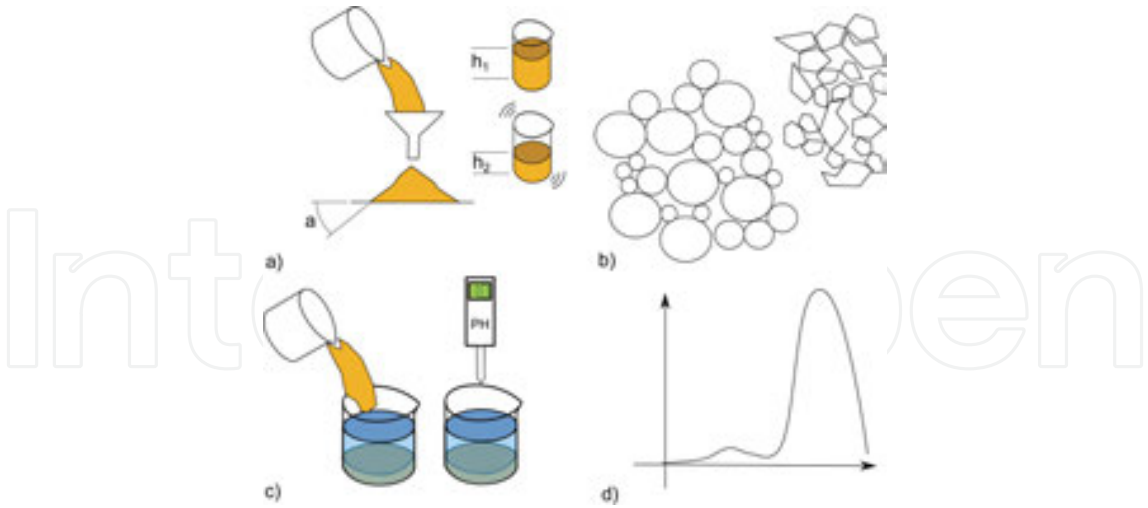
increasingly popular. Aluminum–silicon alloys are excellent for mold filling and melt at around 700°C. In sand casting processes, there are plenty of other metals that can be used. These include the nonferrous metals such as copper, brass, and bronze. Similarly, other light metals or alloys can also be used, for example magnesium (see [18]).

	Aluminum	Cast iron	Steel
Strength	0	+	++
Elongation at break	0	0	++
Damping	0	+	–
Corrosion behavior	+	–	–
Machining	+	+	0
Density	~3	~6.5	~7
Market importance	+	0	–

**Table 3.** The most important metals in the foundry industry.

3.1.1. Sand and particle material

Particle material is the basis of the powder-binder-jetting process. Therefore, the properties of the particles and the particle clusters are of particular importance and are described below (see **Figure 6**).



**Figure 6.** Methods for the characterization of particulate matter: (a) angle of repose and density determination, (b) microscopy, (c) pH value determination, and (d) particle size analysis.

Different groups of sand types are available for sand casting processes. The natural sands are characterized by low cost. The main group forms the quartz sand whose purity permits predictable behavior in the casting. The contents of SiO<sub>2</sub> often exceed 95% in weight. The other

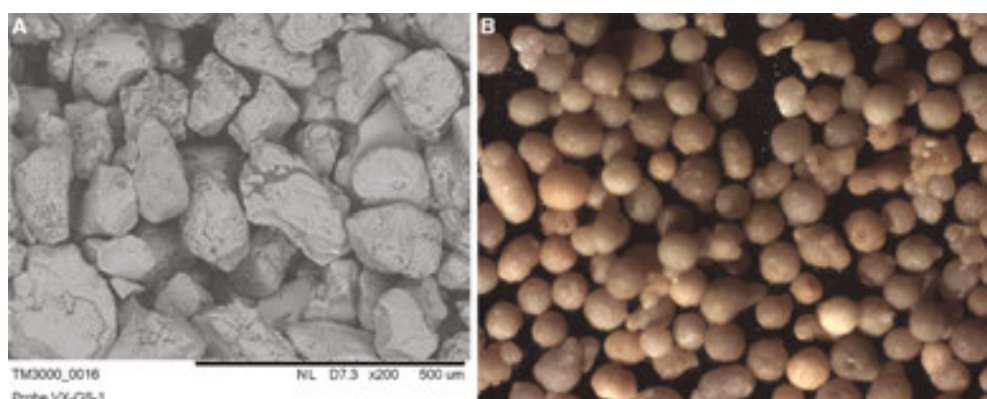
components are usually also oxidic in nature such as  $\text{Al}_2\text{O}_3$  or  $\text{MgO}$ . Since the sand prior to use is strongly heated in order to dry, organic admixtures are usually excluded.

For special applications, there are also natural sands which are a mixture of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ . Here, the costs are not as low as with pure quartz sands. Other minerals, for example chrome ore or zircon sands, are common when a high density of the molds or cores is required (see [19]).

Artificial sands, although substantially more expensive, are also common. Here, mostly  $\text{Al}_2\text{O}_3$  or  $\text{SiO}_2$  are used as the base. These sands are chemically highly pure and the particle spectrum is precisely adapted to the requirement (see [20]).

In the case of natural sands, the grain structure depends on the origin of the sands. Cracked products are made up of sharp-edged grains that are generally more square shaped than spherical in shape. Sand qualities can be obtained from natural deposits such as rivers, whose particle shape is nearly spherical. These sands also often exhibit particularly favorable microtopology for binding reactions (see [20] and **Figure 7**).

Depending on the production process, the form of artificial sand is usually spherical. This property allows these products to flow very well and there are smooth surfaces.



**Figure 7.** Various mold raw materials: (a) SEM picture of natural sand and (b) optical microscopy artificial molding material.

The sand particles react with various chemicals. Many oxides react alkaline in an aqueous environment. Therefore, the pH value of the applied media changes, which is especially significant for PBJ processes when the sand is premixed with a liquid.

A measurement of the chemical properties can be carried out by measuring the pH of the wash solution for the sand. For example, for an amount of water of 100 g, 10 g sand is given and after a waiting period of 10 min the pH value is determined with a pH meter with a glass electrode or is determined titrimetrically against an alkaline solution.

Natural sands have a significantly broad particle size distribution. Here, often a noticeable amount of fine particle distribution of up to  $<10\ \mu\text{m}$  particle size can be noticed. This affects various properties, among other things, the flow property, but also the bond because the



micrograins attract the binder in a capillary manner and thus withdraws from the binding region of the mold-forming grains (find different qualities in **Table 4**).

Undesirably large grains are often separated by sieving. This leads to a sharp divide in the grain size range. The bulk density of the sieved as well as unsifted materials falls way behind theoretical possibilities. With natural sand, about 50% volume space filling can be achieved. Targeted blends can positively affect the bulk density (see [21]).

Artificial sands are nearly monodisperse, i.e., they have essentially only one grain size. This property and the round grain often lead to an increased bulk density. Again, this effect can be enhanced by adding further monodisperse powders having different grain size.

Natural sands are often preferred because of their low cost. However, especially with quartz sands, a change in the crystal structure of the elementary cell (quartz inversion) takes place at a temperature of 573°C. These stretches abruptly produce a sudden increase in volume of the core or mold. This often leads to flaking of layers close to the mold cavity, thus causing casting defects (see [14]).

For artificial sands, this effect is usually only minimal. Here, additionally a high density is often implemented in order to reduce the buoyancy of cores in the melt.

In the PBJ process, much finer sands are used compared with sands used in the standard foundry. This is necessary in order to achieve surface qualities that are comparable to the conventional process because the grains are not aligned toward the surface of the component as is the case while using a model.

	Quartz sand GS14RP	Cera beads AFS100	Kerphalite HA
Chemical base	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>
Purity/contents (%)	>98	62/38	60/40
Medium grain size (µm)	140	150	200
Specific surface (cm <sup>2</sup> /g)	176	172	105
Sinter temperature (°C)	>1550	>1660	>1660
Residual water content (%)	0.2	0.7	0.7
pH of washing solution	6.3	6.7	6.4

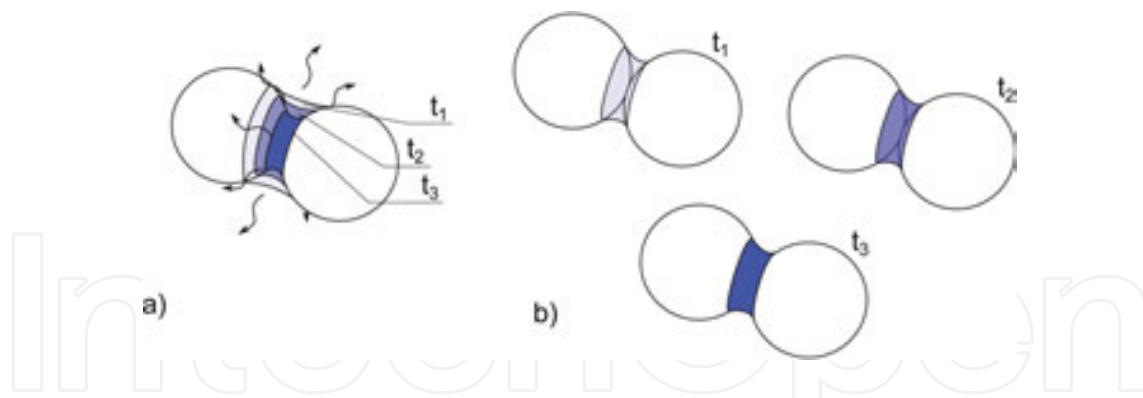
\* the shown figures are simplified and do not take account of the small amount of additional oxides.

**Table 4.** Examples of data for sand systems which are suitable for the PBJ process.

3.1.2. Binder systems

The bonding strength between particles is caused by the binder. In the case of PBJ, the binder is selectively applied with the help of an inkjet print head.





**Figure 8.** Basic binding mechanisms: (a) solidification by evaporation of solvent and (b) curing by polymerization.

Basically, two binding mechanisms can be used for the above-mentioned PBJ process (as depicted in **Figure 8**).

The material may be dissolved in liquid binder. The adhesive effect of the material is obtained by drying. Often plastics or inorganic binders are dissolved in water or suitable solvents. The drying must take place as long as the layer is exposed and the parts lie covered in powder during the construction process. A variation on this procedure is to dissolve the particle material with the help of a solvent which is part of the printing liquid and then to let it dry again. Thus, a binder-free medium can be printed. This is favorable for the life of the print head. But the problem is often the long setting time.

Polymerizing binders can also be used. Polymerization is a chemical reaction where mostly low molecular weight substances react in longer chains of molecules. Thus, a transition between low viscosities, i.e., good printability and extremely high viscosities (solid), is made possible.

Usually, it is not only necessary but also useful to use both methods as a hybrid. This allows moderate reaction rates that safeguard all the machine components and support a drying process deep inside the large powder cake.

The properties of the binder which are suitable for the PBJ methods are very similar to those of the conventional molding production. In the following, the most common systems are described according to their chemical and physical characteristics (**Table 5**).

Furan resin is a polymer binder which is derived from corn cobs. The resin system is available in the form of a resin and an activator component. The resin itself is made up of monomers and oligomers, for example, furfuryl alcohol, bisphenol A, and resorcinol. In addition, adhesion promoters are included. The activator is an acid, usually a mixture of several acids. It has a catalytic effect on the reaction, but is itself also consumed in the process. The polymer which is produced through polycondensation is a cross-linked, high-strength thermoset which is highly temperature resistant due to furan groups in the molecule (see [14]).

In contrast to furan resins, phenol resins consist of phenol units, which are preferably linked to each other in *para* and/or *ortho*-positions via methylene groups. No continuous conjugated system is formed. The curing process is carried out using formaldehyde depending on the

prepolymer. For example this can be made available for the process by the thermal decomposition of the substance Urotropin. A thermoset plastic is again formed. The temperature resistance is even higher than that of furan resin (see [14]).

Inorganic binders are gaining importance not only because of their historical importance, but also because of new requirements for environmental-friendly production. They are characterized by very low and harmless cast emissions. For this process, liquid water glass is of particular importance. It can achieve high strengths. However, the de-coring process after casting requires more effort with this binder system than with the organically bound varieties (see [14]).

	Furanic resin	Phenolic resin	Inorganics
Bending strength (N/cm²)	250*	350*	300*
Temp. stability	Sufficient	Very stable	Extremely stable
De-coring	++	+	–
Shelf life (months)	12	6	Unlimited
Emissions	High	High	No

Table 5. Relevant binder systems and properties, \*typical figures, depending on the amount of binder.

3.2. Methods for the characterization of PBJ generated parts for foundry purposes

Using PBJ printed components as tools for casting processes requires a special range of characteristics for the parts. The porosity of the parts is essential for the process. Similarly, the strength values are important to ensure safe handling, as well as safe and easy de-coring after casting. In this process, some values are linked and, under certain circumstances, represent contradictory optimization criteria (Figure 9).

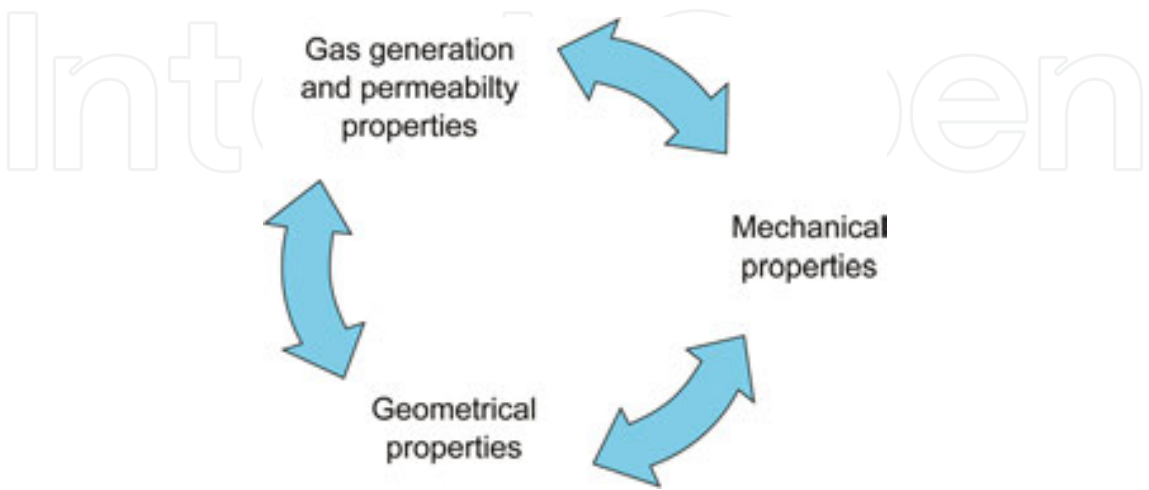
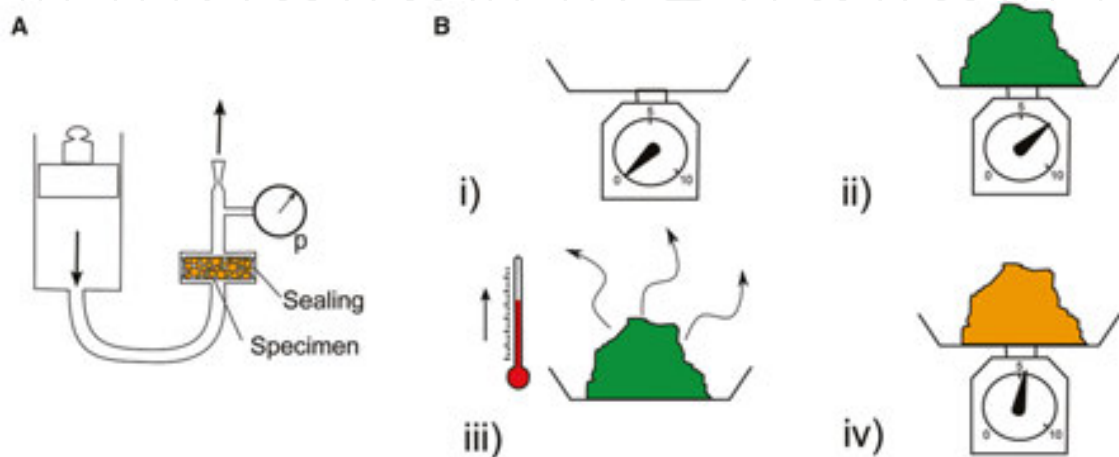


Figure 9. Schema of interdependent properties.

The resulting amount of gas emitted from the burning binder during casting must be diverted through the porous structure of the molds and cores. The volume of the gas impact will depend on the proportion of the binder. This in turn significantly affects the strength. The strength is dependent upon the particle size, the related resolution, and the achievable surface quality of the process in relation to the geometry. Similarly, high strength often means the tendency for shrinkage and thus distortion. The geometry works once again due to the effect of the grain size on gas permeability, as the finer particles cause the gas channels to become narrow.

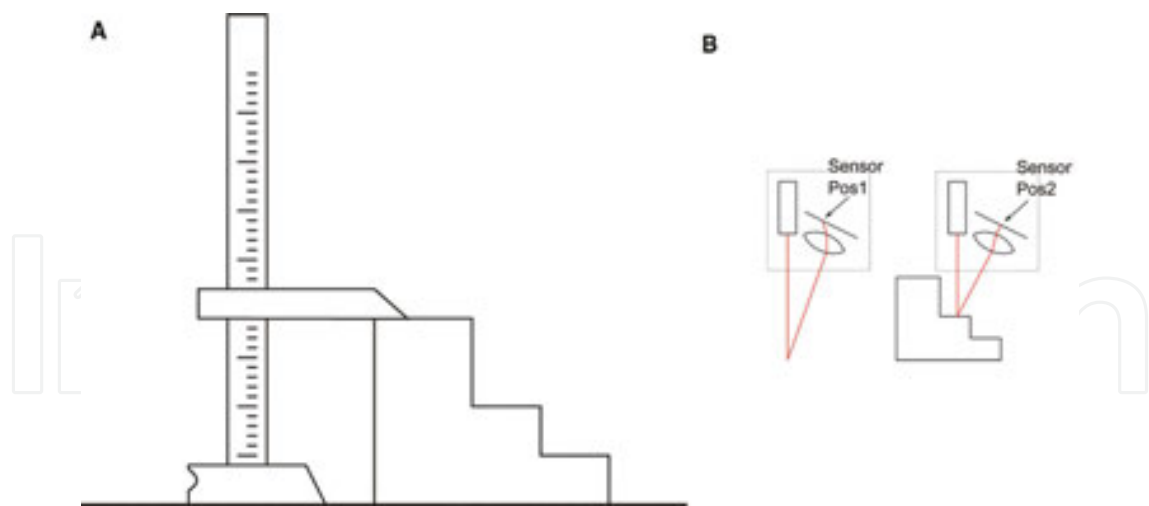


**Figure 10.** (a) Diagram showing the arrangement to determine gas permeability and (b) process cycle during the determination of ignition loss: (i) taring process, (ii) (initial) weighing material, (iii) glowing, and (iv) weighing material.

The range of printed applications as well as conventionally manufactured cores and molds is affected by gas permeability. To determine the behavior of the gas, the flow rate can be measured with the help of a test specimen at a given pressure. In this case, a tester of the type SPDU of + GF + is used. A cylinder having dimensions 50 mm × 50 mm is used as test specimen (for schematic, see **Figure 10a**).

The second important parameter characterizing the moldings with respect to the gas problem is the loss on ignition. This is determined by taking a sample from a bound form or a core. A furnace of type KLS 05/11 from Thermconcept and scales of the type of PCB2500-2 core were used in the above-described experiment.

According to the standard method for determining the loss on ignition, about 30 g pulverized molding, usually from test bars, is weighed and put into a ceramic bowl. Before the bowl is filled, it is constantly heated to constant weight in an oven to extract moisture and organic residues. Before and after filling, the bowl is weighed. The binder or moisture in the components is burned out or expelled at about 900°C for approximately 30 minutes. After cooling, the weight is determined again. The difference between the weight of sand sample before and after heating is the absolute loss on ignition which is usually expressed in percent by weight on the initial weight (see **Figure 10b**).

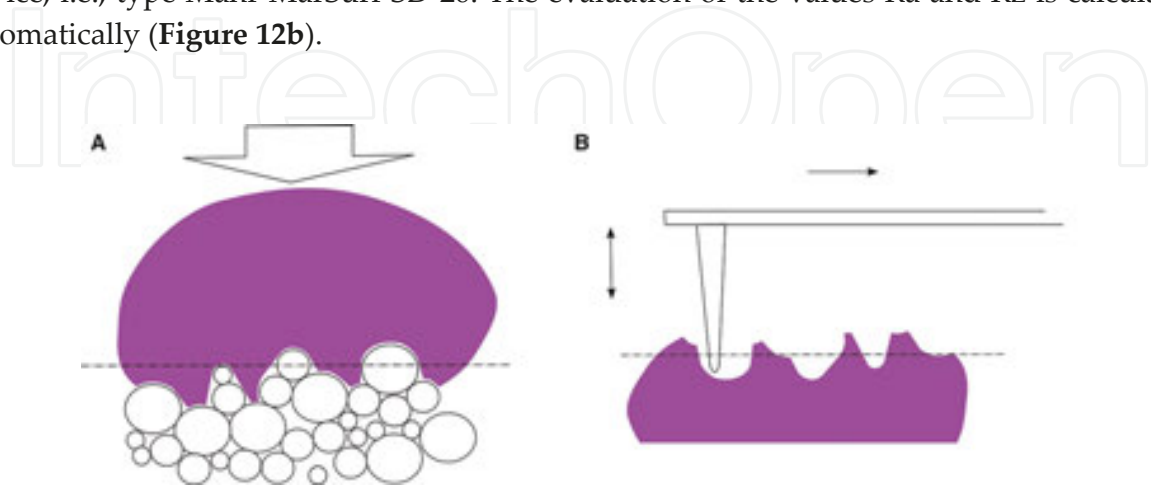


**Figure 11.** (a) Detecting the main dimensions with a vernier height gauge and (b) basic determination of triangulation.

The accuracy of the construction method is determined based on test specimens. These determine the scope of the machine. Rods measuring up to 500 mm can be measured in this manner. The simplest and most common method is the direct measuring with a caliper or vernier height gauge. More complex shapes can be determined using optical methods. Some of them are based on the principle of triangulation. Here, a device of the type MICRO-OPTRONIC optoNCDT is used (ref. overview [22]) (see **Figure 11**).

The surface parameters of the molds and cores are determined by a tactile measuring method. Here, the extreme microstructure and the weak binding of the grains are taken into account so that an imprint of the surface is made before measurements are carried out (**Figure 12a**).

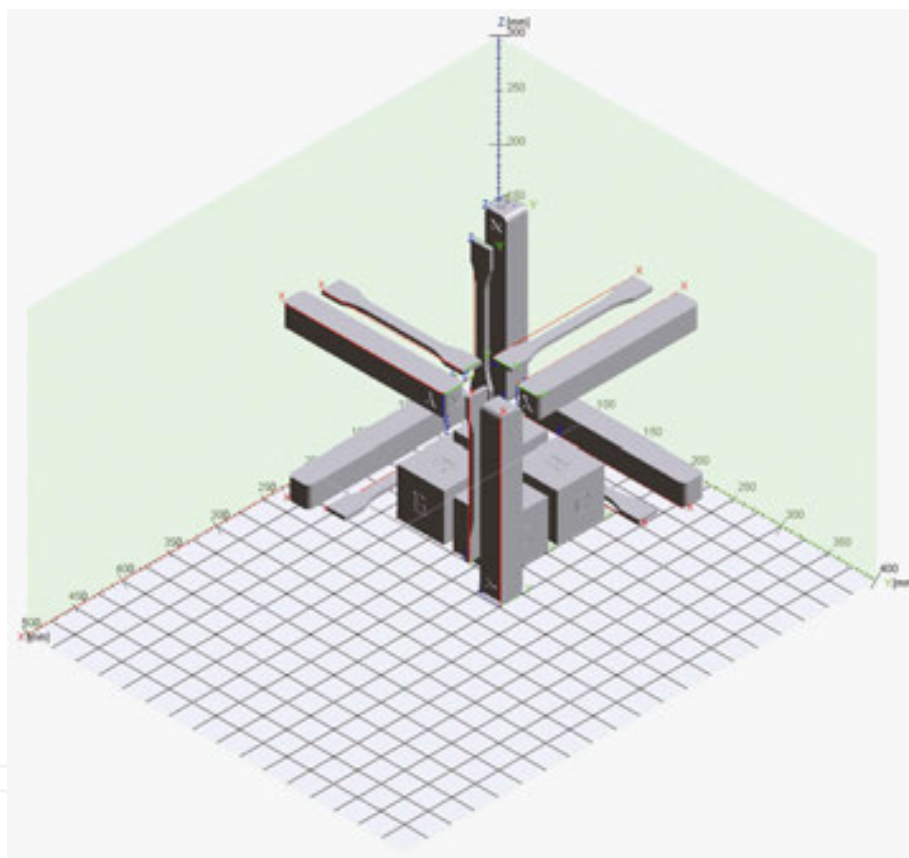
For the purpose of forming an imprint, plasticine may be used as a quick means yielding good accuracy. Plasticine is soft and produces a clean and accurate imprint. The impression thus obtained is cured at 100°C in the oven. The imprint is then scanned with a surface measuring device, i.e., type Mahr MarSurf SD 26. The evaluation of the values  $R_a$  and  $R_z$  is calculated automatically (**Figure 12b**).



**Figure 12.** (a) Creating an imprint of the surface and (b) determination of the surface finish using a tactile device.

The strength of 3D printed parts is determined using destructive testing just as in conventional production methods. Conventional test equipment is used. A universal type ZMART.PRO of the company Zwick is used for the determination of the  $E$  modulus, the elongation at break, and the tensile strength. For a three-point bend test which is commonly used in the foundry industry, a test device of the type +GF+ PFO is used.

A test job is specifically built having the appropriate material system for recording the measured values. This includes all relevant tests specimens in different variations for the described tests. The material system furan is processed on a Prometal S15 system. The phenolic resin and inorganic binding material are processed on a voxeljet VX1000. **Figure 13** represents a test job on a VX1000.



**Figure 13.** Arrangement of different test samples within a test job.

### 3.3. Results for PBJ printed parts

Within PBJ, the furan resin system is the most common and long-term proven system. The measured values refer to a system with the sand type GS 14 RP Strobel quartz sand. As sand binder, a binder from ASK type ASKURAN with the corresponding hardener is used.

The test samples show a strength with an average of  $270 \text{ N/cm}^2$  at a density of  $1.35 \text{ g/cm}^3$ . The scattering of 20% within an orientation can be measured. The maximum anisotropy of the

strength values is shown in a deviation of nearly 40% in strength for bending-test samples built in the Z-direction (see **Table 6**).

Orientation	X			Y			Z		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Density (g/cm <sup>3</sup> )	1.33	1.37	1.41	1.33	1.36	1.41	1.32	1.33	1.36
Ultimate bending strength (N/cm <sup>2</sup> )	222	276	326	236	278	331	219	245	268
Modulus of elasticity (GPa)	1.4	1.3	1.1	1.1	1.3	1.5	1.0	1.1	1.2
Ultimate tensile strength (MPa)	0.6	1.1	1.3	0.8	0.95	1.2	0.2	0.4	0.6
Elongation at break (%)	0.05	0.06	0.08	0.04	0.07	0.09	0.02	0.06	0.16

**Table 6.** Mechanical properties of PBJ-printed parts.

The measurements of the length of the bars exhibit low scatterings in the range of about 0.2%. The surface quality of differently arranged surfaces widely varies from each other. In this case, the surface roughness Ra of the top surface with 19.8 μm is the lowest. Subsequently, parallel to the XY plane, surfaces having a Ra of 22.4 μm follow. The area with the roughest surface is oriented in the Z-direction (Ra = 25.2) (**Table 7**).

Orientation	X			Y			Z		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Surface quality Ra (μm)	19.8	22.0	25.7	21.4	24.3	25.6	22.4	25.2	29.1

**Table 7.** Geometric characteristics of PBJ-printed parts.

In the settings used for the test job, a loss on ignition of 1.8% can be measured. The gas permeability of the material system is 68 l/h. **Table 8** provides the gas permeability of more sand systems. It is assumed that each system has a for the strength reasonable compaction, and thus also a reasonable density.

	GS14	GS19	GS25
Grain size (μm)	140	190	250
Gas permeability (l/h)	65/75	140	250

**Table 8.** Gas permeability of PBJ-printed parts using different grain sizes.

A comparative measurement of different chemical binder systems is performed on the basis of a variety of systems, and in each case an optimized configuration for the intended use is applicable. **Table 9** provides a brief comparison of the results.



	Furanic resin	Phenolic resin	Inorganics
Density (g/cm <sup>3</sup> )	1.29–1.31	1.29–1.31	1.2–1.25
Sand grain size (μm)	140	140	170
Loss on ignition (%)	1.6–1.9	2.2–2.6	0.2–0.3
Bending strength (N/cm <sup>2</sup> )	220–330	350–450	250–350
Surface quality (μm)	24	28.5	23
Length (mm)	172	172	172

**Table 9.** Properties of PBJ-printed parts using different binder systems.

### 3.4. Discussion

The special characteristics of the printed components relative to the conventionally manufactured components are the smaller grain size, the alignment of the grains, and built-layer characteristics unique to each method. Thus, the 3D printing itself exhibits different values. At a comparable grain size, the surface finish of 3D printed parts is substantially lower compared with that of the conventional parts. Similarly, the loss on ignition is higher at the same strength, as the conventional methods have a greater densing effect on the material.

The methodology for measuring the properties can be well transferred to the PBJ process. But there are special considerations to be observed. Most dimensions are anisotropic. Additionally, the artifacts “stair steps” have to be considered for an objective surface quality comparison and each surface orientation has a different surface finish.

The use of 3D printed cores is by now widely spread. Even complex cores can be produced by this method with a suitable choice of the binder system, although some characteristics of the conventional production may not be achievable. To produce challenging cores, it is possible to find good compromises for test series. The material systems described above provide such processes, material and binder combinations.

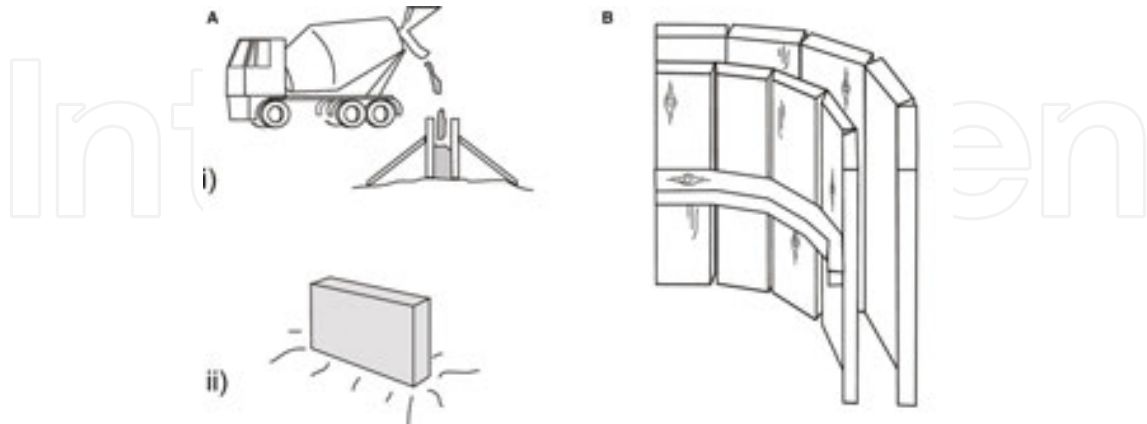
## 4. Forms and cores for cold setting materials

In addition to metal casting, several important casting processes exist for the production of molds. For example, thermoplastic resins are injected into molds under high pressure. Commodities thermosets usually have very low viscosity and can be poured just like liquid metals. Casting of concrete is also relevant. Here, large volumes and tonnage can be cast. These molds can be built as forms and also be constructed using PBJ-printing technology (see [23]).

In concrete casting, carpenters are often involved in preparing the formwork. The castings are mostly simple geometries. Pillars, walls, and ceilings are predominately made by this casting process. But more complex forms such as curved stairways are poured into wooden molds (see **Figure 14** and compare [24]).



In prototyping, even large components are cast with reactive resins. Here as well, large molds are necessary to give the casting the correct geometry. The casting process is essentially analogous to the conventional concrete pouring.



**Figure 14.** (a) Conventional procedure in construction: (i) pouring concrete into formwork, (ii) finished de-cored wall and (b) construction made by a carpenter: curved wall structure.

Concrete casting usually consist of smooth walls, which can be used repeatedly, and hand-crafted wooden construction, which is often used only for one part. After the mold is set up, the reinforcement is usually built from iron. Then, the previously mixed concrete is poured. After curing, the formwork is cut off and the concrete can be surface treated.

In concrete construction high complexity is seldom realized due to the formwork technology. In contrast to metal casting, the heat of the cast material cannot be used for de-molding.

A high degree of complexity can be achieved with printed forms. Molds may be used once or several times depending on their geometries, for example, whether forms have undercuts or not is a relevant criterion.

The printed forms have to be surface treated irrespective of the base material used (**Figure 15**). There are two essential points that need to be considered. Firstly, it is important to prevent cement from entering the pore space of the mold. This would also lead to the mold sticking to the form and to cement leaking around the peripheral regions. Both these factors mean that the outer surface of the casting will be damaged.

Secondly, the separation of casting and form must be made easier if the form is to be used several times. In this case, the adhesion of various materials to each other is to be considered as well as the exact arrangement as lack of air circulation results in high adhesive forces during the separation process.

Hydrophobic substances such as fats are usually used as release agents. These can be applied directly onto the forms. A free-flowing greasy substance thereby allows through-flow of air from the pore space and enables easy removal from the mold.

In case strong forces are created during unmolding, the forms can be strengthened prior to use by infiltration. For example, this can be done by epoxy.

In some cases, the integration of ejectors into the mold is advisable. These can be implemented as jacking screws. Targeted stresses can be built up in the area of the form in order to reduced bending stresses while separating the mold.



**Figure 15.** (a) Printed form mounted (form for casting upside down) and (b) designer sink made from concrete.

The mechanical properties are relevant for multiple phases in the application of these processes. Strength is desirable during the handling phase and while filling the mold. While demolding of disposable forms, low strengths are desired. Particularly suitable are shapes and forms whose strength can be influenced after casting. These can be water-soluble forms with a hydrophobic coating or forms whose binder loses strength even at very low temperatures.

The thermal behavior of the forms plays a subordinate role in this process. Similarly, loss on ignition or residual ash is not relevant.

In this process, accuracy and surface quality are just as relevant as in the metal casting. However, the proportions of the surface features of the component dimensions are often so extreme that the surface finish plays only a subordinate role. The achievable accuracies usually do not greatly exceed the general requirements in the construction industry.

See **Figure 16** for an experimental casting of a large-scale structure.



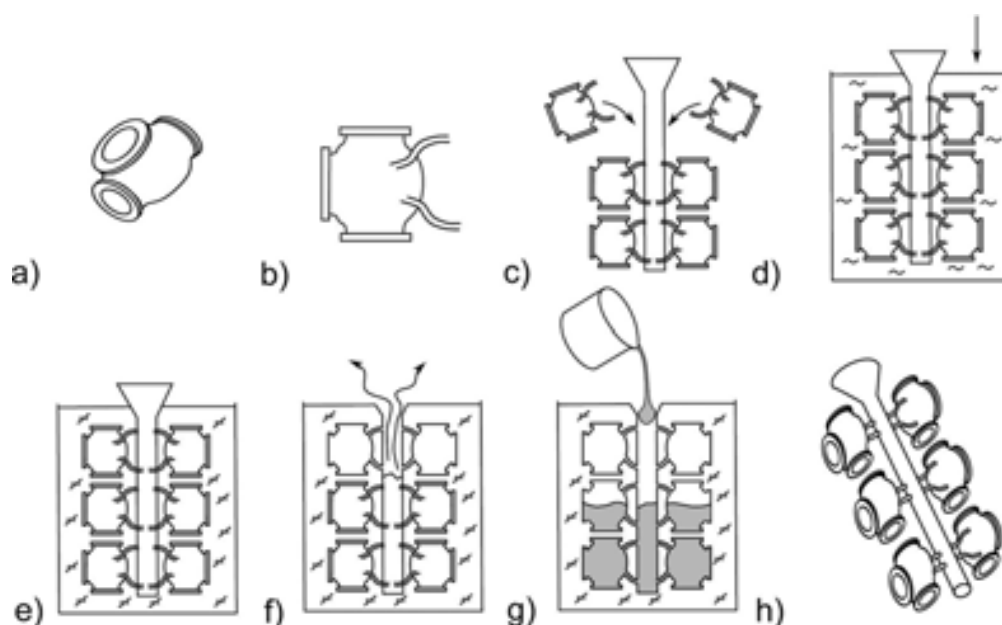
**Figure 16.** (a) Composite mold from 3D printed formwork elements and (b) resulting large-scale concrete member.

## 5. Investment casting with positive molds using PBJ printed material

### 5.1. Theory, chemical, and physical basics

#### 5.1.1. Conventional investment casting

The investment casting process is used to produce metal parts that have finer details, thinner wall thicknesses, and superior surface quality compared with parts generated by the sand casting process. Since the foundation of the process is a positive model, the process differs in its substantial process steps from the sand casting process. See **Figure 17** for details. In this section, various methods are described to create cavities which can then be applied in the metal casting process (compare [18]).



**Figure 17.** Steps of investment casting: (a) positive model, (b) fixed gating system, (c) mounting of the (wax) cluster, (d) embedding in plaster or ceramics slurry, (e) setting of the shell, (f) burn-out of the model and the gating system with hardening of the shell, (g) casting, and (h) production result.

The basis of the investment casting process is a positive model, which are always lost models in contrast to the models used in sand casting. These models can be produced by artisans manually using the traditional way or by applying industrial mass-production technology.

The models are often produced by injection molding out of wax. As in the plastics processing, the wax is injected under high pressure into a metal mold and removed from the mold after cooling. In order to increase the dimensional stability and to change other properties, the wax is often filled with microgranules. The granules themselves are mostly plastics such as polystyrene or polyethylene.

The individual wax models are attached to further wax model in the production cycle. This wax model serves as a carrier and defines the gating in the subsequent casting of the liquid

metal. The individual models are connected using thermal wax to the gating. The upper part of the gating widens conically and later represents the pouring funnel.

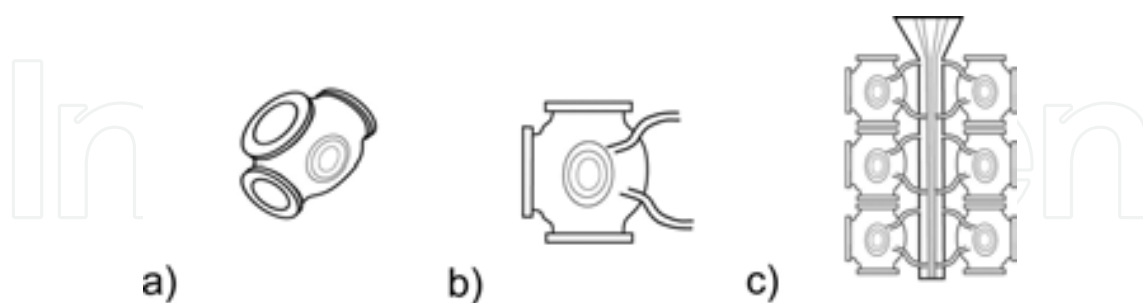
The shape thus obtained is further processed in the conventional method in two ways. The first method is to immerse the mold in liquid plaster. After the plaster has hardened, the mold is placed in an oven for heat treatment. Here, the wax evaporates or burns out and exposes the actual casting cavity. The second option is to generate a ceramic shell by repeated applying a coat of ceramic slurry. It is then fired in a kiln. During this process, the model evaporates or gets burnt out.

Both methods differ in the cooling rates which are attained later in the casting process. Especially, the simpler method using gypsum often produces an inferior metal structure and thus a casting of poor strength.

#### 5.1.2. A PBJ process for the generation positive burn-out models

In principle, several methods are suitable for the realization of the above-described investment casting process using additives manufacturing methods. These methods are wax or acrylate direct print processes, laser sintering of polystyrene, or stereolithography. Each method demonstrates specific characteristics which in turn make them the preferred method to apply depending on the production environment and related variables (see [25]). Different levels of components can be built by these technologies: from the single part model up to a complete cluster (see **Figure 18**).

An essential feature underlying all methods is the melt-out or burn-out property of the additive material that is being applied. Here, residue-free burn-out during the process (as far as possible) is important from an economic point of view as purification steps can thus be avoided. Individual melting is not sufficient, as the melt cannot run out from complex shapes and the material is able to leave the channels only in a gaseous state.



**Figure 18.** Production levels of components using AM processes for precision casting tools: (a) positive-model, (b) model with sprues, and (c) complete cluster with gating.

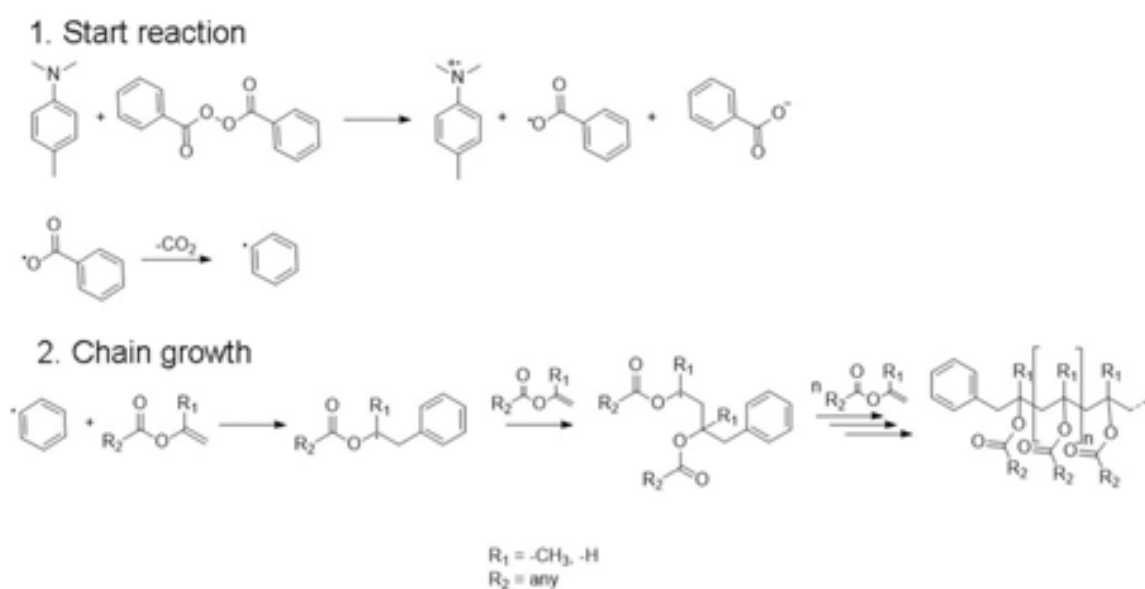
The PBJ method uses an acrylate-based printing process for investment casting. PMMA powder serves usually as base material.

The process is described in detail in the subchapter “sand casting.” After lowering the build platform, a layer of PMMA powder is spread over the built platform with the help of the

recoater. The achievable minimum layer thickness is well below that of the sand casting process and reaches 80  $\mu\text{m}$ . Through a binder system technology, the powder particles stick to each other whereby binder is applied on to the powder bed by an inkjet print head by using preprogrammed bitmap data. For this purpose, solvent-based adhesives can be used as well as polymerized adhesive. For the latter process, one component of a multicomponent adhesive system is added to the powder.

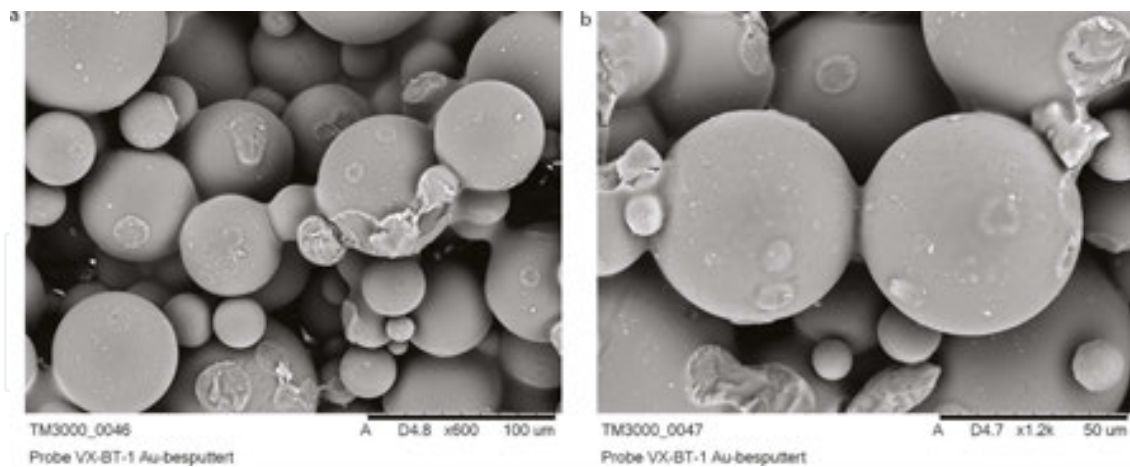
The basic chemical reaction of the polymerizing system is a free-radical polymerization. An initiator, for example, dibenzoylperoxide, is present in the powder itself. The concentration can be adjusted as required during powder production. At higher temperatures, the initiator decomposes into two radicals depending on the type of initiator used.

The actual ink contains monomers. These monomers have radically polymerizable chemical double bonds, which are the key reactants for the chain reaction in curing of such materials (**Figure 19**). In addition, the binder includes an activator which brings about the decomposition of the initiator and at the same time generates initiating radicals. In this case, the activator reduces the temperature of the disintegration under the room temperature. When ink penetrates into the powder, initiator from the powder is released and is activated by the activator. The radicals are bound to the monomers (chain initiation), whereby a new radical is formed, which reacts with another monomer (chain continued) in turn form further radicals. Thus, a chain reaction that leads to macromolecules is formed which makes up the strength of the bond (see micrographs of the bonds in **Figure 20**). The reaction stops (chain termination) if, for example, radicals react with each other (recombination) or the reaction mixture of reactive monomers increasingly reduces leading to a failure in reaction. The achievable strength depends on many factors, which in turn affect the chain reaction (see [26]).



**Figure 19.** Chemistry involved in the vx-acrylate process.



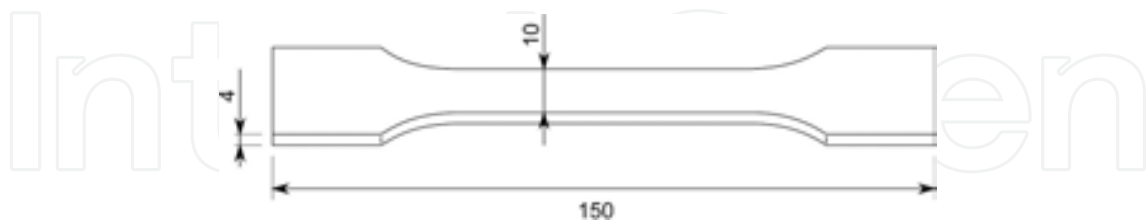


**Figure 20.** SEM micrographs of particles bound by the PolyPor method (a) magnified 600 times and (b) magnified 1200 times.

## 5.2. Methods for the characterization of PBJ generated parts for investment casting

In investment casting processes, just as in the case of sand casting, special component properties need to be achieved in order to support further processing steps.

Material strength values are important in order to allow safe handling of the component. But too high material strength values and a high modulus of elasticity are in fact damaging and thus harmful for follow-up processes. Here as well, a low thermal expansion coefficient is important. The mechanical characteristics are determined with a tensile testing machine of the type ZMART.PRO from the company Zwick. Here, the tensile testing program is carried out at room temperature at a speed of 1 mm/s. The measurement is carried out without displacement transducer. As a sample, a tensile testing rod is used with the cross-sectional dimensions  $10 \times 4 \text{ mm}^2$  (see **Figure 21**). The load cell has a measuring range of 2 kN.

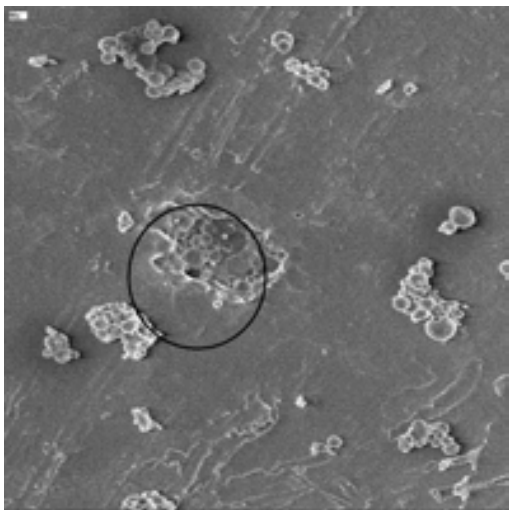


**Figure 21.** Test specimen dimensions for PBJ-parts used in investment casting.

For the embedding process, a closed surface is required. Without this closed surface, water can penetrate into the model. This could negatively affect the mold during burn-out in terms of cracks or disintegration of the shell. The surfaces of the PBJ-printed models are coated as porous surface adversely affect the follow-up processes of the above-mentioned processes. Thus, it is advisable to treat the model with liquid wax. The wax solidifies on the surface or penetrates by capillary action deep into the model, depending on the immersion conditions

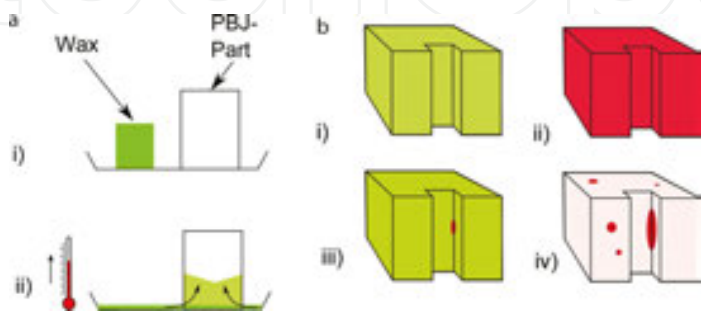
and temperatures of the wax or the component. A quick immersion of a cool component leads to a wax layer forming on the surface of the actual component. On the other hand, if a component is immersed over a longer period it gets almost completely filled with wax and has a significantly rougher surface.

The surface must be sealed for the follow-up process. If only a thin surface layer is obtained by the dipping method, there is a risk of microporosities causing surface damage during solidification and shrinkage of the wax (see **Figure 22**). This may lead to water seeping into the model. Thus, the model may be damaged during burn-out. The method of immersing components for a longer time poses the risk of component distortion due to the temperature reaction as well as the creation of rough surfaces.



**Figure 22.** SEM microscopy of a wax treated surface with pinhole defect.

This microporosity can be detected with the dye-penetration technique in accordance with DIN/ISO EN 571-1. Here, the dye accumulates in the microporosity and reveals the critical areas. Such critical areas must be reworked before the furnace process (**Figure 23**).

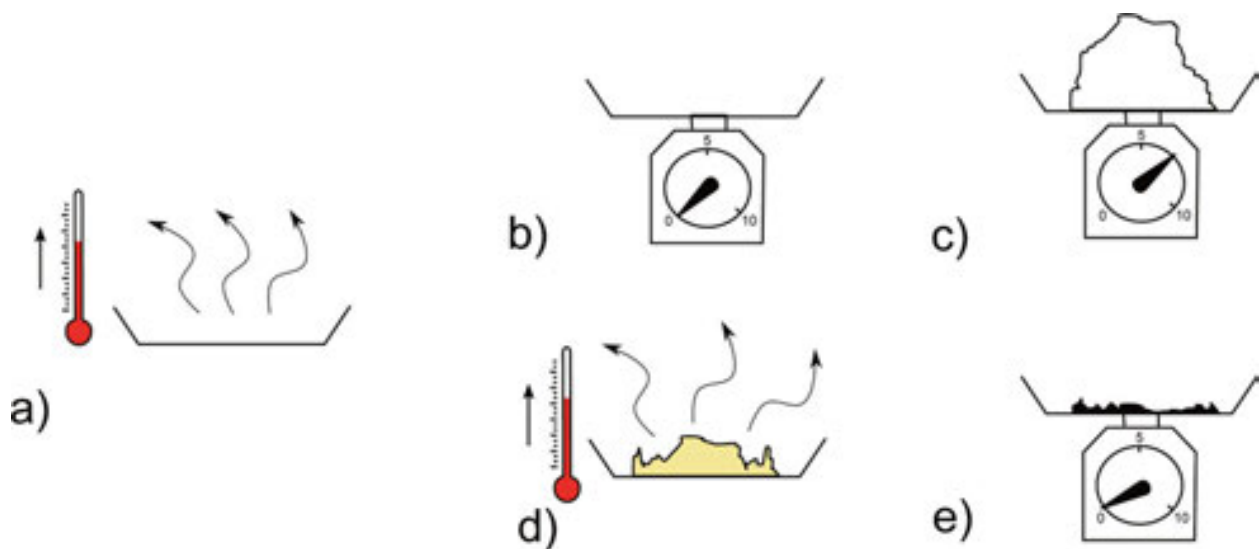


**Figure 23.** (a) Diagram showing after-treatment of porous components and (b) test: (i) waxed component, (ii) test color, (iii) the component after cleaning, (iv) the component after application of the developer.



After burning out, the residual ash is also an important factor for safe processing. In particular, undertaking cleaning steps after the casting cavity has been formed through burn-out is not advisable economically.

The residual ash is determined using the conventional ash measuring equipment. Since the quantities are very small, the procedure has to be performed with great care (see the steps in **Figure 24**). For the measurement at least 100 g bound material is required. These are added to a previously extensively heated bowl. After weighing, the plate is placed in an oven and heated up to 700°C. This temperature is maintained for at least 4 h. After cooling down for several hours, the dish is weighed again. The difference to the tare value will be read from the amount weighed. The quotient is thus residual ash. A residual ash content of less than 0.1% is considered as free of residual ash.



**Figure 24.** Methodology for determination of residual ash.

In this method, the properties are determined with a test job, just as in the case of the sand casting process. As material system, the PolyPorB system from voxeljet is used. The test job is built on a VX1000 machine from voxeljet. The surface quality is determined based on test blocks. Waxed as well as nonwaxed samples are used.

### 5.3. Experimental results

The density of the plastic components differs from the density of these parts because of the massively different density in relation to sand components. A mean of 0.63 g/cm<sup>3</sup> is measured. The scattering is relatively small with a range within a build direction of 0.02 g/cm<sup>3</sup>. The anisotropy follows the above-mentioned measures, but is less.

Orientation	X			Y			Z		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Density (g/cm <sup>3</sup> )	0.62	0.63	0.64	0.63	0.64	0.65	0.62	0.63	0.64
Modulus of elasticity (GPa)	0.34	0.35	0.37	0.28	0.30	0.37	0.26	0.28	0.29
Ultimate tensile strength (MPa)	3.3	3.4	3.5	2.2	2.6	3.5	1.7	2.0	2.1
Elongation at break (%)	1.4	1.5	1.6	1	1.2	1.5	1.7	0.9	2.1

**Table 10.** Mechanical parameters of components from the material PolyPorB for use in the investment casting process.

There is a close correlation between the modulus of elasticity and tensile strength for this material system. The tensile strength reaches a maximum of 3.3 MPa and a mean of 2.7 MPa. Here, the relative anisotropy of the strongest to weakest direction is 60%. The elongation at break is consistently less than 1.5%. Therefore, in the fracture behavior, it behaves similar to a glass-like material (refer to **Table 10**).

Orientation	X			Y			Z		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Surface quality Ra (μm)	15.9	18.8	22.4	18.1	21.4	25.8	17.2	19.5	22.2

**Table 11.** Surface characteristics of PolyPorB parts for investment casting.

The length deviation of the material depends in part on the storage and aging of the components. In compliance with the prescribed standard processes, the measurement shows an average percentage deviation from 0.7%. The deviation is always negative, and thus produced shrinkage. The shrinkage is anisotropic and reaches its minimum in the Z-direction. This shows a correlation to the direction of the weakest point.

On average, q roughness Ra of 19.9 μm is achieved. The highest roughness is an Ra of 25.8 μm. If parts are waxed, the roughness varies according to the waxing procedure. If the component is dipped briefly, an Ra significantly below 10 μm is achieved. The components that are dipped longer the roughness corresponds to that of a nonwaxed part (**Table 11**).

The thermal expansion of nonwaxed components largely corresponds to the base material PMMA. The measurement shows a thermal expansion coefficient of  $100 \times 10^{-6} \text{ K}^{-1}$ . In the region of low temperatures, the wax on the surface of the waxed components will melt. Thus, the thermal expansion seen in the investment casting process can be compensated during the burn-out of the printed component.

The test pieces which were immersed for a short time show a homogeneous image with no color inclusions along the surfaces during the penetration test. The edges of the component exhibit a slightly porous surface, which can be identified due to its pink color. Long immersed parts turn totally pink and penetrant testing confirms the (adverse) reading of the surface condition. In bodies having complex geometries, particularly the outer and inner edges are

placed where errors occur. Cracks and tears in the wax surface can be clearly observed by their distinct red color (**Figure 25**).



**Figure 25.** Results of the color penetration test: (a) short immersion, (b) long immersion, and (c) problem areas.

For the material system used, the measurement of the residual ash of samples indicates an ash content of less than 0.3 per thousand based on the initial weight.

#### 5.4. Discussion

In the case of investment casting processes, as opposed to the conventional sand casting methods, the finished models are not directly comparable with PBJ-printed models. In the first process, the part to be compared is built up by injecting a liquid, and in the second process the part is made using particulate material. The strength of PBJ-printed components is sufficient for safe handling during subsequent process steps. The high brittleness needs to be considered during handling. However, the lower density, which is present due to the porosity of the component, makes the parts easy to handle.

The geometry is strongly influenced by shrinkage. However, this shrinkage can be easily simulated and nearly completely compensated by an increase in the geometry of the raw data. The surface roughness of the models in the untreated state does not meet the requirements of a “precise casting procedure”. Through a postprocess procedure which is suitably adapted to the task (in this case wax treatment), the desired measurements can be achieved here as well.

The surface of the model has to be sealed, as during the post-treatment process it is immersed in a liquid. The surfaced can be sealed by immersing them in wax. The color infiltration method shows that special care is needed and further steps to ensure that the part is completely coated (sealed) may be necessary.

Thermal expansion of the basic structure of the particulate material can be compensated by applying a coating of wax. The type of wax selected and its melting point play an important role.

During burn-out which exposes the casting cavity, very little residual ash is left behind, this can be attributed to the combination of the raw materials, namely, PMMA and wax used in the process. By applying a suitable process, cleaning of the form can be avoided after burn-out and metal can be poured directly into the hot mold.

## 6. Summary

Models, e.g., molds and cores, for casting applications can be created using the additive manufacturing process PBJ. Liquid material can either be added directly into the mold after printing to obtain a cast part or a printed model is further processed using the investment casting process. The results show that the material properties meet the demands for a wide application in this field of application. Metals, as well as resins and thermosets, ceramic, or concrete fluids are processed. Quality assurance during production can be assured by applying the testing and measuring methods described in this chapter.

Due to the ongoing development in technology, the production quantities as well as performance can be enhanced. This advancement in technology and knowhow goes hand-in-hand with the reduction in costs, which makes it possible to produce even larger series using the PBJ method. At present, series comprising a few thousands parts are already economically viable. Through this ever-increasing advancement in technology, even larger series will be realized and thus inflexible production machines and dated technologies will eventually be replaced in several areas of production.

## Author details

Daniel Günther\* and Florian Mögele

\*Address all correspondence to: dg@voxeljet.de

voxeljet AG, Friedberg, Germany

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