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CRITICAL REVIEW

A review of the influence of sand properties on parts manufactured by rapid sand casting through additive manufacturing

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Abstract
Sand casting remains widely utilized in both small- and large-scale production due to its simplicity, especially for small parts manufacturing. Recent innovations, such as rapid sand mold and core creation through additive processes, have significantly reduced lead times compared to traditional pattern-making methods, which often require weeks or months. However, products from rapid sand casting frequently exhibit defects, including poor surface finishes and inconsistent mechanical properties. This review critically examines key sand properties such as size and shape distribution, chemical composition, surface area, packing density, flowability, microstructure, and thermal behavior that influence the quality of rapid sand casting. Understanding, addressing, and optimizing these properties are essential for enhancing casting efficiency and improving product quality. Moreover, future research will explore cutting-edge technological advancements to enhance these properties and meet the growing demands of modern industry.

Keywords Sand casting · Molds and cores · Sand properties · Rapid sand casting

1 Introduction

One of the primitive techniques applied for producing casting with modest dimensional accuracy is sand casting [1, 2]. In history, sand casting stands out as the ancient casting technique, and in the foundry casting field, it still has an immense portion in production [2]. The continual recognition of sand casting is credited to its cost-effectiveness and capacity to manufacture castings from diverse materials, spanning from minute grams to higher tons in weight. In the process of sand casting, liquid metal is discharged into molds and cores developed from a particular sand mixture, majorly consisting of silica, about 90%, with binding substances, like clay, that glue the sand particles [3, 4]. Sand casting is often applied for a huge percentage of production, although in situations where dimensional accuracy and surface finish are unimportant. This technique is appropriate for casting any alloy or metal regardless of the casting's varying size, shape, or load [5]. The core disadvantage of the technique is that it requires machining operation to achieve a better surface finish of the parts, specifically huge casting with rough surface quality [6, 7]. Hence, the establishment of rapid production of cores and molds has nullified some of the challenges encountered in traditional casting methods. The rapid production of cores and molds are made of sand, ceramic, and some other materials [7]. This ensures quick production of cores and molds for casting, consequently eliminating the long duration of conventionally making them because the process, which could take weeks or months, can be shortened to 2–3 days [8]. The equipment used to produce these molds and cores are ExOne, ZCast, and Voxeljet. This process of sand production of sand cores and molds for casting is referred to as rapid sand casting [9–12].

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Experts or specialists are developing new AM techniques and materials for the high demand for 3D-printed parts for casting. The present innovation has minimized the cost of 3D printers, consequently stretching their use in homes, schools, laboratories, and libraries [13–15]. At first, 3D printing was hugely applied by designers and architects to fabricate functional and aesthetic prototypes because of its quick and cost-effective prototyping ability [16]. The recent application of 3D printing has reduced the added costs that are induced in the product development process. Although in the past years, 3D printers have been used in diverse industries, from models to products [17]. Product customization has been a problem for a manufacturer because of the high cost of fabricating designed-tailored parts. This is particularly important in the biomedical sector, whereby exclusive patient-designed parts are normally needed. Wohlers associates predicted that tailored functional products are presently emerging as the new development in 3D printing [18–20]. They projected that 3D printing will account for about 50% of the production of commercial parts in 2020 [21, 22]. This technique has attracted the consideration of those in medical institutes because of its capacity to fabricate a huge, diverse medical implant from computerized tomography (CT)-imaged tissue models [23]. Presently, this technique has been used successively in the construction industry. An assembly of comparatively inexpensive houses ($4800 USD per unit) in China was effectively reproduced by WinSun in less than a day [24, 25]. Therefore, developing an agreement to acclimatize the 3D fabrication method over the conventional techniques is attributed to the diverse importance of optimum material savings, developing difficult geometry with maximum precision, personal customization, and flexibility in design. A huge material range that is presently applied in 3D printing comprises sand, ceramics, polymers, metals, and concrete. Acrylonitrile butadiene styrene (ABS) and polyactic acid (PLA) are the major polymers applied in 3D composite printing [15, 17]. Enhanced metals and alloys are classically applied in the aerospace industry because using conventional counterparts with similar materials is costly, difficult, and time-consuming [26, 27].

Ceramics are majorly applied in 3D-printed scaffolds, while concrete is the vital component used in the AM buildings, although the intrinsic anisotropic performance and mechanical features of AM-printed products still restrict the large-scale printing capacity. Thus, an improved AM priming pattern is vital to regulate anisotropic performance and flaw sensitivity. Likewise, modifications in the printing environment affect the quality of the finished products. AM is excellent at producing components of diverse dimensions from micro to macro scales. However, the precision of printed materials relies on the printing scale and applied method accuracy [25]. For example, micro-scale 3D printing induces problems with surface finish, resolution, and layer bonding, which occasionally need post-processing methods like sintering. Contrastingly, the incompetency of 3D printing induces some problems in diverse industries [28, 29]. Therefore, there is a requirement for fabricating appropriate materials that have the efficiency to be applied to 3D printing. Additional mechanisms are also required to improve the mechanical features of 3D-printed products [30, 31]. The importance of 3D printing technology will continue to arise via incessant research, which must be initiated to comprehend and decrease the challenges that restrict this technology application in certain areas.

Furthermore, beyond the 3D printers employed in producing sand molds and cores, one critical aspect to consider is the sand itself, particularly the factors influencing the properties of molds and cores. Recent observations have shown that specific sand properties significantly affect the outcomes of rapid sand casting. These findings have sparked debates regarding the efficiency and reliability of techniques used for producing rapid sand molds and cores [32, 33]. To address these challenges, it is essential to examine various sand properties, including size and shape distribution, chemical composition, surface area, flowability, packing density, microstructure, and thermal properties. By understanding and optimizing these properties, rapid sand casting can achieve a comparative or competitive edge over other sophisticated manufacturing techniques.

The role of sand properties in conventional molds and cores development has been extensively studied, focusing on factors such as bulk density, microstructure, shape distribution, packing density, surface texture, grain shape, flowability, chemical composition, and size distribution. For instance, bulk density has been found to influence molds and cores porosity, strength, and surface finish [34], while packing density affects dimensional accuracy and the occurrence of casting defects [35, 36]. However, the interactions between these properties, particularly in the context of rapid sand casting, remain inadequately explored. Most research has predominantly focused on conventional molds and cores development [31–35]. This gap in knowledge contributes to inconsistencies in casting outcomes, particularly in dynamic industrial environments striving for high-quality and precise cast products. This review aims to bridge these gaps by critically analyzing the existing literature on sand properties in both conventional and additive manufacturing contexts. It also proposes innovative methodologies to optimize these properties for enhanced casting efficiency and product quality.

2 Direct tooling

Direct tooling processes ensure that the production tools have a high capacity for quicker response to market demands, thus establishing a modern competitive advantage [37, 38].

The aim of direct tooling is not focused on the development of final components but rather on the preparation of mass production tools for final components (such as dies and molds), enabling easier and faster production. Additionally, integrating direct tooling with rapid prototyping in an organizational framework fosters the adoption of concurrent engineering in industries [39, 40].

The major challenge the manufacturers face has been the minimization of time-to-market components. The rapid tooling process can be categorized into two, depending on the measure associated with the number of procedures:

1. Processes needing no in-between routes in the tools manufacturing, for instance, stereolithography (SLA), directly produce the prototype. This type of process can produce the tool directly. Hence, it is designated as a “direct tooling process”.
2. Processes needing a master pattern (for example, an SLA) to produce the final component using more standard techniques, like resin tooling and investment casting. This process can be designated as “non-direct tooling routes” because they entail at minimum one intermediary phase in the tooling process [41–43].

With the above categories, it is clearly observed that the first category possesses a far higher influence on time-to-market than the second one, which is more associated with certain usages. The “direct tooling process” category provides the origin for defining the “direct rapid tooling concept” [21, 44–46].

In rapid sand casting, the production of mold and cores using Voxeljet equipment significantly reduces the traditionally long time required to create molds and cores. Rapid sand casting serves as a direct tooling approach for making sand molds and cores. A pattern is first designed using a CAD system, and this design is integrated into the equipment, enabling the system to produce the sand molds and cores. These sand molds and cores are subsequently utilized for casting the desired parts [47, 48]. Some instances where rapid sand casting have been used successfully are in automotive parts [49], sand molds, and cores specimen with hollow structures [50], 3D printed cores [51], rotary gating system [52]. Figure 1 describes the direct tooling categories for a specific rapid sand casting.

3 The categories of sand properties that influence rapid sand cast products

Figure 2 showcases key properties of sand, such as bulk density, microstructure, shape distribution, packing density, surface texture, grain shape, flowability, chemical composition, and size distribution. Each of these factors plays a crucial role in determining the quality of rapid sand casting products, affecting characteristics like surface finish, mold strength, and the development of defects such as porosity and rough surfaces.

A. Bulk density of sand

The mass of granulated solid sand per unit volume is regarded as bulk density. It is applied to determine the mass-to-volume correlation for modifications and packing efficiency in aggregates [53]. For instance, about 2600 kg/m^3 is the bulk density of chromite sand [54]. The bulk density is affected by the sand size distribution, compaction, moisture content, and grain shape. Comparing the bulk density of silica and chromite sand, the latter has twice the bulk density of the former. The greater the bulk density, the more sand can undergo compaction into a specific volume and the total surface grain area in that volume. The significant range of sand bulk density applied for developing mold and cores is 1600–1800 kg/m^3 [55–57]. A study emphasized by Dinesh et al. [34] quantifies the effect of bulk density on gas porosity, showing that higher bulk density correlates with fewer casting defects related to gas retention. Their further investigation reveals that increased permeability can exacerbate casting defects like gas porosity, while a denser sand improves the quality of the final casting by reducing these defects.

B. Sand particle size

The differences in sand particle size influence the outcome of the products immensely. For attaining a desirable strength for a product, the particle size effect on bonding parts is significant [58, 59]. The packing dynamics in the sand are influenced by its roundness or angularity, consequently affecting the general strength and texture of the products. Also, sand having good workability due to smooth texture enables the sand for easy manipulation and handling during the mixing and development of mold and cores. Full comprehension of how the particle size influences the texture, and strength of the products is paramount in selecting the appropriate sand for certain uses, thus enabling optimum durability and behavior during service [60].

The sand particle size regards each sand particle’s diameter and is a vital feature that influences various sand properties and applications. The particle size influences the packing density, strength, texture, and some other properties of sand, specifically for rapid sand casting products [61, 62].

Sand particles, depending on their size, can be classified as follows:

1. Coarse sand: This type of sand varies in diameter from 2.0 to 4.75 mm. A typical coarse sand possesses a gritty

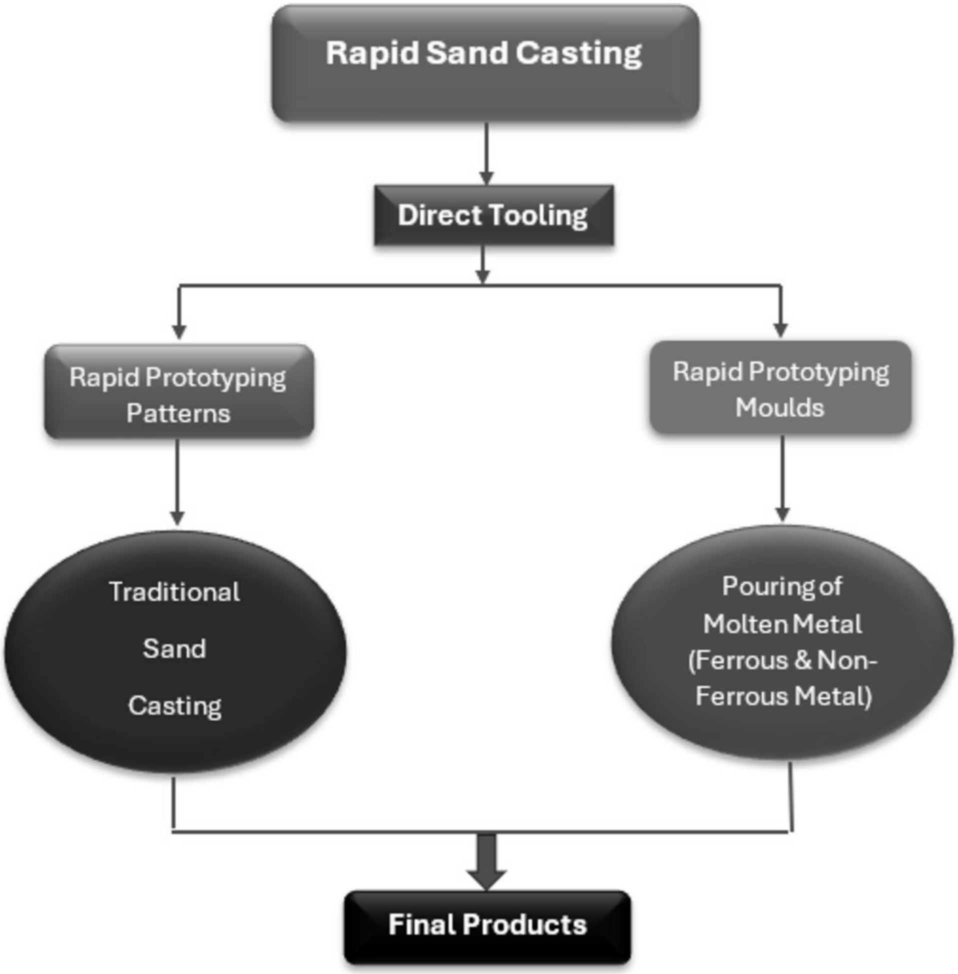

Fig. 1 Procedures of rapid sand casting, especially for direct tooling

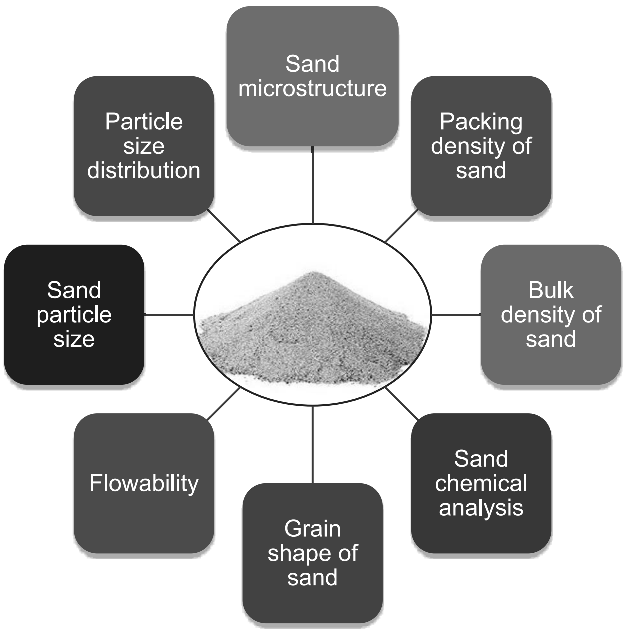

Fig. 2 Sand properties affecting rapid sand casting products

texture. The coarse sand for specific castings or molds and cores are used where improved ventilation, durability, stability, and strength properties are needed. However, on the compromise of compaction and surface finish. Coarse sand is applied in core and molds and cores making, bigger and heavy castings. Some examples of coarse sand are zircon sand and silica sand [63, 64].

2. Medium sand: This type of sand varies in diameter from 0.5 to 2.0 mm. Owing to its balanced features (particle size and granulation, good surface finish, and compaction and efficient gas escape and ventilation), this sand finds its application in different industries, hence making it appropriate for huge variety of metal casting procedures. The balanced features of medium sand give an efficient compromise between the strength of fine and coarse sands [39].
3. Fine sand: This type of sand varies in diameter from 0.0625 to 0.5 mm. Owing to its smoother texture, higher uniform texture and precision make it to be needed for casting parts in the automotive and aerospace industries. Fine sand applied to produce metal casting parts has

a better surface finish and dimensional accuracy than medium sand [65].

4. Very fine sand: This type of sand has a diameter below 0.0625 mm. The texture of this sand is often in powdery form, and they are normally applied in specific precision applications and also for creating detailed and smooth molds and core surface. Very fine sand can be used as additives or binder [66, 67].

Studies by Sahoo et al. [68] indicate that fine sands (with smaller particle sizes) typically improve surface finish but may reduce permeability, leading to defects such as gas porosity. On the other hand, coarser sands improve permeability but can result in rougher surfaces and decreased mold and core strength. Therefore, achieving a balance between these sand particle types is crucial for effective molds and cores development in casting.

C. Particle size distribution

This property of sand in casting is paramount since it influences the features and quality of the cast product. The various grain sizes applied in the casting processes influence the molds and cores permeability, strength, and surface finish [69]. The influences of particle size distribution on surface finish, permeability and molds and cores stability, and strength vary. For a surface finish, the finer the sands, the smoother the surface finishing on the castings, however, on the compromise of stability and strength [70]. In minimizing these compromises, a balance is required to endeavor enough molds and cores strength and excellent good surface. For permeability, fine sand has poor permeability compared with coarse sand, which has enough permeability for the escape of gases and steams in the molds and cores during the casting [60, 71], although at the compromise of bad surface finish and complexity in attaining fine specifications due to enormous coarseness. Hence, molds and cores with high permeability are excellent for casting, because they can easily eliminate air trapping in cavity of the molds and cores, consequently minimizing defects in the casting of parts [68]. For molds and cores stability and strength, the sand mix comprising different particle sizes often results in more stable and stronger molds and cores. Also, fine particles occupy the space between the larger particles, hence enhancing the molds and cores' general deformation resistance and density. In testing the particle size distribution of sand as well as controlling its quality, compaction test and sieve analysis are often applied [72, 73]. Pradana and Ariono [74] elaborated on the influence of grain size on the permeability of the sand molds and cores; it was discovered that the increasing permeability was achieved because of the increasing grain size; this is revealed in Fig. 3a. Hence, the lowest permeability was attained for 60 mesh size of sand, consequently

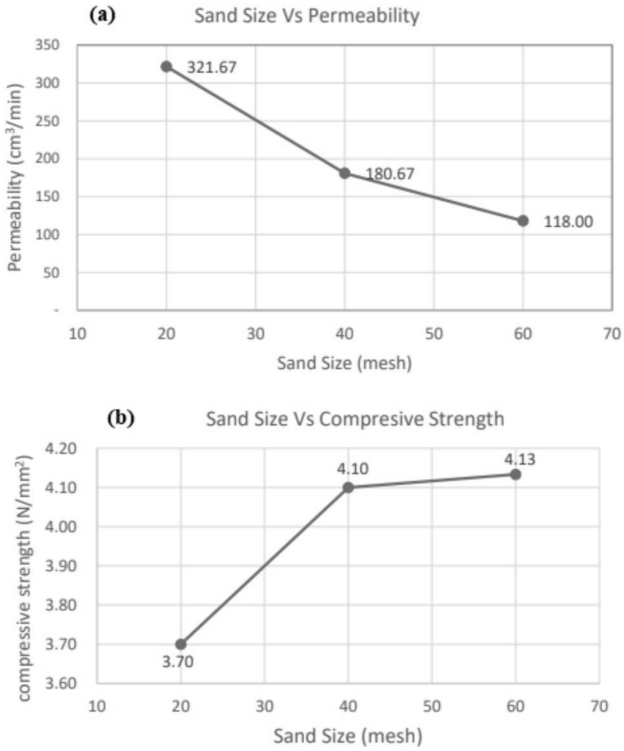

Fig. 3 Influence of grain size on the: **a** permeability and **b** compressive strength of sand molds and cores [74]

enhancing the mechanical properties, especially the compressive strength (Fig. 3b), since molds and cores with high permeability can cause poor surface finish and low strength [60, 75]. Also, sand molds and cores with low strength can undergo erosion while pouring the molten metal; this causes flaws in the casting parts [76–78].

D. Packing density of sand

This feature is another important casting procedure as it influences the accuracy and quality of the cast components. The sand packing density also regarded as packing ratio or bulk density, and this refers to the material volume proportion in which the sand particles occupied, in contrast to the empty spaces or void volume between them [79]. The packing of sand reveals how firmly the sand particles are collectively packed; this impacts the quality, stability, and strength of the final parts. In methodical relationships, the sand packing density can be calculated thus:

$$\text{Sand Packing Density} = \frac{\text{The Sand Mass}}{\text{The Sand Volume}}$$

Some parameters of the packing density that influence the sand are as follows:

i. Compaction: The sand packing density can be changed via compaction. The sand voids are reduced when sands are compacted; this makes the particles to be closely pressed, thus enhancing the packing density. This is important for sand casting engagement, where a greater packing density is commonly chosen to enhance the molds and cores' stability and strength.
ii. Bulk density: In sand context, this parameter is always applied interchangeably. This evaluates the mass of a single sand volume, comprising both the voids and sand particles between them. For sand without moist (dry sand), the bulk density varies from 1.4–1.8 g/cm^{3}.
iii. Void fraction: This is the ratio of the voids volume to the sand particles volume. The void fraction is lesser for excellent-packed sand, resulting in a greater packing density.
iv. Classes of sand: The various classes of sand and its granulation can influence the packing density. For instance, fine sand, has smaller particles with fewer voids between them, leading to a greater packing density, in contrast to coarse sand, which has bigger particles with more voids.

Table 1 highlights the key properties influenced by the packing density of sand in molding processes and their impact on both molds and cores and final castings. These properties include surface finish, which affects the smoothness and quality of the final product; mold and core stability and strength, which ensure the mold and core maintains its integrity during casting; dimensional accuracy, critical for producing parts within specified tolerances; heat transfer efficiency, which determines solidification rates and thermal gradients; and susceptibility to casting defects such as porosity or shrinkage. Understanding the relationship between packing density and these properties is essential for optimizing sand molds and cores and improving overall casting performance.

An optimum packing density is vital for developing superior-quality parts. It makes sure that the molds and cores are correct, strong, and efficient in creating components with negligible errors and good surface finishes. Suitable packing density is attained via cautious control of molding techniques and sand compaction [80–82].

E. Sand microstructure

The sand microstructure analysis gives insights into its grain morphology, texture, and composition. The sand molds and cores' microstructure can greatly impact the final products' properties and quality. The sand molds and core is usually developed from a mix of sand, binder, and others, and these materials go through some variations during the casting procedure, thus influencing their performance [83, 84]. Some

Table 1 Properties influenced by sand packing density in molding and casting processes

Properties	Low packing density	High packing density
Surface finish	This can cause roughness and surface irregularities of parts, resulting in the detachment of sand grains, which influences the casting surface. This is peculiar with loose sand	A smoother surface finish on the final components can be achieved for a goodly packed mold and core. The highly packed sand minimizes the quantity of sand particles that can be separated and could result in imperfections or rough spots on the cast surface
Dimensional accuracy	Imperfectly packed sand can cause mold and core contraction or expansion, causing dimensional eccentricities and inaccuracies from the desired model or pattern	Highly packed sand ensures that the cavity of the molds and cores creates an accurate shape, producing more exact cast part dimensions. This is very important for components that need accurate tolerances
Mould stability and strength	Low packing density can make molds weak and susceptible to deformation and collapse under the molten metal weight, resulting in casting defects	A densely packed sand ensures higher stability and strength. This reduces the danger of collapse or deformation during the casting procedure, ensuring the mold and core sustains its dimension and shape
Heat transfer	Uneven and rapid cooling rates of parts could be initiated by poorly packed sand, leading to challenges with dimensional stability or mechanical properties of the final parts	The packing density can influence the molds' thermal conductivity. A densely packed sand possesses less thermal conductivity, which could impact cooling rates and molten metal solidification
Casting defects	Poor molds and cores integrity because of loose sand can lead to defects like uneven filling, stuck air pockets, and other casting anomalies	Efficiently packed sand declines the prospect of defects, like cold shuts, misruns, and sand inclusions, because the molds and cores are not expected to deform or permit gaps

Table 2 Some factors of the microstructure influencing certain properties

Some factors of microstructure	Properties	
Binder properties	Quantity and type: The thermal and strength solidity of the molds and cores could be influenced by the binder quantity and type. Hence, an efficient binder type and amount should be carefully chosen so as to ensure good interaction with sand grains and sufficient to bear the temperature of the molten metal	Binder distribution: For consistency in the molds and core properties, the uniform binder dispersal throughout the sand mixture is very paramount
Porosity	Microstructural porosity: Porosity presence in molds and cores always impacts their strength and permeability. Regularized porosity can aid the gas discharge of molten metal in the molds and cores. However, disproportionate porosity could lead to surface defects and structural faults in the casting	
Chemical interactions	Interactions with molten metal: The binder and sand's chemical composition react with the molten metal. For example, some faults like mold erosion or metal penetration could be caused if the metal interacts with sand. The comprehension of these relationships can assist in choosing the accurate sand mixture	
Thermal stability	Heat resistance: Inappropriate thermal stability can result in mold depletion, like cracking or sand fusion, thus influencing the final product	
Grain texture and shape	Surface texture: Better surface finish of cast products can be attributed to the application of smoother grains	Angular and round grains: The application of angular grains can affect the strength of molds and cores, because of their interlocking shape, although at the compromise of permeability. There is improved uniformity and flowability when rounded grains are applied, producing more consistency in the mold and core development

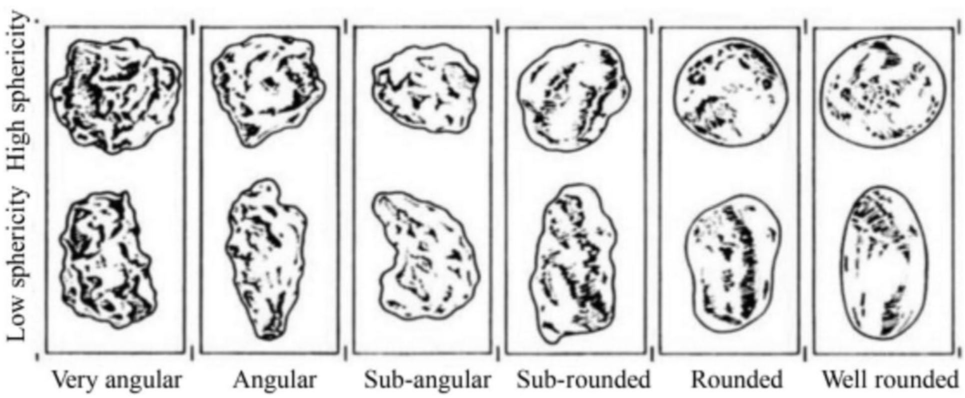

Fig. 4 Categories of grain shapes [90]

microstructure features that affect sand casting molds and cores include binder properties, thermal stability, chemical interactions, porosity, grain shape, and texture, as stated in Table 2.

F. Grain shape of sand

The sand angularity, also regarded as grain morphology, reveals the grain shape of the sand, this can be observed via scanning electron microscope (SEM) examination. The grain shape differs from angular to round. This influences the sand's permeability, chemical resistivity, and refractoriness [5, 85].

The angular grains which are characterized by sharp edges influence the refractoriness since the grains easily stick to one another, while the rounded grains give smallest contact with one another when they are rammed, thus leaving out some spaces or gaps between the grains, ensuring increasing permeability [86]. The rounded sand grains for molds development give excellent handling properties with higher compacted molds and cores, thus causing veining defects. The molding sand strength relies on the surface area obtainable for bounding. As previously stated, there is minimum contact between the rounded grains; this consequently gives good room for strength enhancement by sand additives [68, 87]. The desired grain size is round to angular, ensuring good permeability, strength, lesser veining flaws, and minimum binder additions [88, 89]. The various categories of grain shapes are revealed in Fig. 4.

The major classes of grain shape needed for foundry sand are angular, rounded, and sub-angular. Angular grains possess higher bonding strength because of their interlocking, although they have poor permeability and flowability in contrast to rounded grains. Rounded grains have a good surface finish and flowability but relatively poor strength. Sub-angular grains possess lower permeability and strength in contrast to rounded grains, although they have better permeability and lesser strength in relation to angular grains [91, 92].

Angular grains are largely found in chromite sand because they are obtained from crushed ore. Sand grains angularity can be evaluated via the fine aggregate analysis technique (FAA). A rough surface and angular grain texture can be determined when a high void percentage is achieved. The uncompacted void percentage of sub-angular grains ranges from 38 to 45%, and sub-rounded grains range from 35 to 38% and very rounded grains range from 32 to 33% [93–95]. Research by Zhao et al. [96] emphasized the impact of sand grain shape on casting quality, highlighting that more rounded grains improve sand flow but compromise mold strength, while angular grains promote stronger molds, though they can lead to rougher surfaces. Their findings provide a detailed understanding of how grain shape correlates with casting defects and overall product quality.

G. Flowability

The flowability of sand evaluates its capacity to flow freely, and this is measured by the repose angle. The repose angle is referred to as the angle that the contact plane between two objects makes with the horizontal; this occurs when the upper object is at the sliding phase [97, 98].

In rapid sand casting, the obtainable optimum repose angle is a 45°. The obtainable range is divided into various classes. The flowability with a repose angle between 25° and 30° are referred as being excellent, 31° and 35° is regarded as good, and 36° and 40° as fair [57, 99, 100].

Flowability has an important role in the uniform deposition of layers during printing; it also ensures the least differences in the mechanical movement during each layer recoating. Poor flowability can cause non-uniform strength development when printing, hence causing poor core or mold features. In rapid sand casting, sand coating is a vital process [64, 101]. The sand grains need to be premixed with a catalyst or curing agent. The percentage of catalysts included in sand influences the molding sand flowability and vitally the casting quality. Sand flowability is evaluated by evaluating the sand repose angle. The sand angularity influences sand flowability. Rounded sand grains will have greater flowability than sand having angular grains [4, 102].

H. Sand chemical composition

For casting, the sand chemical composition analysis entails defining the features and constituents of sand to make it fit for application in casting processes. The following parameters of sand chemical composition analysis are essential to determine the effective use of sand in molds and core production [64, 103–105].

1. pH level: The sand acidity or alkalinity can impact its reactions with other materials and the final casting parts.
2. Iron oxide: Iron oxides presence in sand can affect its reactivity with sand. Higher quantity of oxides can influence the cast surface quality.
3. Silica content: The major composition of some sand molds and cores is often evaluated as silicon dioxide. Higher quantity of silica is chosen for a mold capacity and stability to bear elevated temperatures.
4. Binder systems: These are materials that cohesively bond sand grains to form molds and cores, ensuring structural stability and strength to endure thermal and mechanical stresses during the casting process. Binder systems are evaluated by analyzing their compatibility with sand chemical properties, including surface chemistry, thermal behavior, bond strength, and gas evolution, to optimize molds and cores performance and casting quality
5. Ignition loss: This evaluates the quantity of materials that escape at elevated temperatures. This measurement can reveal the existence of volatile or organic materials.

Comprehending these above properties aids in the sand molds and cores and the final parts' quality control, reproducibility and consistency, cost management, contaminants management, process efficiency, thermal and strength stability.

Showman et al. [106] demonstrated how incessant molds and core shrinkage was accrued over the curing time, causing a dimensional variation in the chemically bonded molds. This defect was accredited to the resin bridge shortening. Khandelwal and Ravi [107] similarly detected the shrinkage in cores; the cores was developed via alkyd urethane binder mechanism and connected to the solvent evaporation. The core hardness and shrinkage were discovered to be influenced by the resin percentage, excluding the catalyst amount. Lowe and Showman [108] conducted a comprehensive study in which they applied various categories of sand combined with different binder systems and processing conditions to evaluate their impact on casting properties. Their work examined how variations in sand grain shape, binder types, and molding techniques influence factors like mold strength, permeability, and surface finish. Additionally, they explored the interactions between these elements and how they collectively affect the quality and precision of the final casting, particularly regarding common defects such as gas porosity and rough surface finishes.

Guo et al. [109] explored the mechanical properties of furan resin sand molds, observing that sand mold strength increases with higher resin content when the curing agent content remains constant. However, as resin content rises, thin, plate-like sand molds exhibit more pronounced warping deformation, leading to dimensional inaccuracies in the directions in which they were printed [110]. Conversely, with a fixed resin content, mold strength initially improves with increased curing agent content but eventually declines as the curing agent concentration becomes excessive. At higher resin and curing agent levels, sand particles aggregate unevenly, which can cause localized cracking in the sand molds and cores and subsequent casting defects. In enhancing the precision of sand molds and cores, compacting the sand layers and minimizing porosity and the hydraulic radius are observed to be crucial. Nevertheless, excessive resin binder in the sand molds and cores may elevate gas generation during casting, leading to defects like porosity in the metal castings.

3.1 The potential industrial impact of addressing these sand properties

Improving sand properties in manufacturing processes, particularly in rapid sand casting, can have a transformative impact on industrial operations. Enhancing sand characteristics like grain shape, size distribution, and chemical stability directly reduces defect rates, such as porosity and shrinkage. This ensures more consistent product quality and minimizes waste, leading to substantial cost savings and improved customer satisfaction [111, 112].

Optimized sand properties also decrease production costs by extending molds and cores durability and enabling reuse. This reduces raw material consumption and lowers labor costs associated with molds and cores preparation. Additionally, better flowability and thermal conductivity of sand accelerate molds and cores preparation, and solidification processes, thereby shortening production cycles and enabling manufacturers to respond swiftly to market demands [94].

Enhanced sand properties yield higher-quality components with superior surface finishes and dimensional accuracy. This is especially crucial in industries like aerospace and automotive, where precision and reliability are paramount. Furthermore, innovations in reusable and eco-friendly sand materials address environmental concerns, reducing waste and disposal costs while promoting sustainability [111].

Real-world benefits include more efficient production in the automotive sector, with lighter and stronger components for fuel-efficient vehicles, and precision in aerospace parts that comply with strict safety standards. Overall, advancements in sand optimization not only reduce lead times and costs but also position manufacturers to meet evolving industrial and environmental demands effectively [112].

3.2 Examining the applicability of traditional sand standards for rapid sand casting techniques in additive manufacturing

- Conventional standard with rapid sand casting-AM in the context of grain size and distribution: The AFS (American Foundry Society) sets guidelines for grain size distribution to balance permeability and molds and cores strength, essential factors for successful sand casting. These typical ranges are designed for general sand casting applications to ensure that molds and cores have adequate strength to withstand the pouring of molten metal, while also allowing for sufficient airflow to prevent defects. Proper grain size distribution is crucial to achieving consistent casting quality by optimizing both the molds and core's structural integrity and its ability to release gases during the casting process [57]. Rapid sand casting through additive manufacturing (AM) requires precise control over grain size to achieve optimal layer resolution and surface finish. Conventional standards typically do not provide the level of detail needed for such fine control, often leading to suboptimal outcomes when applied to additive processes. The lack of specific guidelines for finer grain sizes in traditional sand casting may result in compromised mold and core strength and surface quality, which can be detrimental to the overall performance of rapid sand casting applications. Therefore, there is a need to adapt or develop new standards that account for the unique demands of AM-based rapid sand casting techniques. The research conducted by the author has demonstrated how packing density influences casting defects, an area that is insufficiently addressed in conventional standards for AM molds and cores. While traditional standards acknowledge packing density, they often fail to provide the detailed guidance necessary for optimizing this property in AM processes, which can lead to increased casting defects. This underscores the need for more comprehensive standards that specifically address packing density for AM molds and cores to ensure higher-quality casting outcomes.
- Conventional standard with rapid sand casting-AM in the context of Binder-sand interaction: The AFS provides binder compatibility guidelines for conventional casting procedures, focusing on the effects of gas evolution during metal casting and its impact on mold and core

strength. These guidelines help ensure that the binder materials used in sand molds are compatible with the casting process, minimizing gas-related defects and enhancing the structural integrity of the mold and core during casting [113]. However, for rapid sand casting through additive manufacturing, the unique dynamics of binder-sand interaction and gas formation require more precise and tailored guidelines. Since AM always needs various binder systems like liquid resins for 3D printing and could necessitate additional specifications for layer adhesion, curing times and minimum gas evolution. The work carried out [114] showed how binder composition hugely affects the accuracy and deformation in 3D-printed sand molds and cores, a property partly regarded in conventional standards [115].

- Conventional standard with rapid sand casting-AM in the context of Binder-sand interaction: In conventional casting, current standards emphasize the importance of thermal stability and refractoriness in sand mold and cores used for high-temperature casting. These properties ensure that mold and cores can withstand the intense heat of molten metal without degrading or distorting, preserving mold and core integrity and preventing defects in the final product. However, such standards may not fully address the specific requirements of rapid sand casting through additive manufacturing (RSC AM), where thermal behavior and mold and core stability might be affected by more intricate processes and finer material controls. The layer-by-layer development in RSC-AM needs enhanced thermal conductivity and minimized heat distortion, which may not fully be covered in the present guidelines. Research, including studies by Chelladurai et al. [116], highlights the necessity for more detailed data on thermal effects to prevent casting defects such as hot tears and uneven shrinkage. These findings suggest that current knowledge may not fully address the complexities of thermal behavior in sand mold and cores, particularly in advanced casting techniques like rapid sand casting. Further research is required to refine thermal stability guidelines for improved defect control in these processes.
- Conventional standard with rapid sand casting-AM in the context of environmental impact and reusability: Traditional casting processes typically place less emphasis on environmental impact and material reusability, with discarded sand being the common practice after use. This contrasts with more modern methods, which prioritize sustainability and material recycling. Rapid sand casting using additive manufacturing (AM) could benefit from guidelines on sand reusability, ensuring reliable performance over multiple cycles, an area not adequately addressed by current standards. Ongoing research and development projects focusing on sand materials and biodegradable binders suggest potential for the creation of new standards in the field [52].

4 Futuristic approaches on how the sand properties can be improved to fit upcoming industrial demands

Continuous demands from industries, especially in manufacturing and high-tech sectors, have necessitated advancements in sand properties to meet modern casting requirements. The random selection of sand, without a careful evaluation of its properties and compatibility with other materials for mold and core making, can lead to failures in both the molds and the resulting cast parts.

Current sand properties exhibit critical limitations that significantly impact casting quality and process efficiency. For example, the inherent trade-off between angular and rounded sand grains poses challenges in achieving a balance between mold strength and surface finish, often leading to inconsistent outcomes. Additionally, variability in thermal properties, such as conductivity and heat capacity, can disrupt uniform cooling rates, resulting in defects like hot tears, shrinkage, and uneven solidification. Furthermore, chemical reactions between sand and binders during the casting process can produce gases, contributing to porosity and structural defects in the final products. Addressing these issues is essential to improving the reliability and efficiency of sand-casting processes.

Uneven packing density exacerbates issues like localized porosity, reducing mold and core stability, dimensional accuracy, and overall product reliability. Furthermore, the reliance on non-recyclable sand increases environmental waste and operational costs, with limited research addressing the development of sustainable and reusable materials.

Key gaps in research include the scarcity of empirical data linking specific sand properties, like grain microstructure, to defect formation and casting outcomes. Advanced characterization techniques to monitor dynamic changes, such as thermal expansion during casting, are underdeveloped. Studies on binder-sand interactions at high temperatures and the integration of digital simulation tools remain insufficient, often resulting in reliance on trial-and-error methods.

Future advancements in rapid sand casting could include the development of hybrid sands incorporating engineered additives for optimized thermal and mechanical properties. Leveraging data-driven approaches, such as AI and machine learning, can significantly enhance predictability in sand casting processes by correlating sand characteristics with defect patterns. By utilizing historical simulations and real-time data, these technologies can forecast sand behavior under varying conditions, enabling the development of optimized sand compositions and techniques. This approach ensures precise sand selection and efficient mold and core development, ultimately leading to improved casting quality and process reliability. Sustainable innovations, like biodegradable binders and fully recyclable sand, could reduce the environmental impact, while real-time monitoring tools could enable on-the-fly adjustments during the casting process, ensuring higher product quality and process efficiency. Addressing these issues holistically will be instrumental in pushing the boundaries of rapid sand casting technology.

Incorporating nanotechnology into sand treatment holds another significant potential for improving casting processes. Introducing nanoparticles into sand can enhance its thermal resistance, durability, and strength, making it more suitable for high-performance applications. Additionally, nanoparticles can be employed to modify the surface characteristics of sand grains, reducing flaws and improving the bonding within molds and cores. These advancements can lead to higher-quality castings with fewer defects and improved dimensional accuracy.

Also, employing smart sand composites and tailored sand mixtures can be significant in mold and core making. Developing composite materials that associate sand with polymers or some materials so that smart sand can be developed thus making the sand change its characteristics in response to environmental circumstances such as pressure, temperature, and time. Furthermore, custom sand blending with certain sand sizes, properties, and additives can improve the parts' performance.

These recommendations are based on emerging technologies, such as artificial intelligence, machine learning, and other components of Industry 4.0, which are the driving advancements in various manufacturing techniques. Additionally, the growing use of materials in high-tech applications, including aerospace, biomedical, and automotive sectors, has inspired these suggestions for rapid sand casting. This method shows potential for substitutional use in these fields, as it competes with other techniques by offering benefits in terms of cost, customization, and adaptability for producing complex parts. The integration of these advanced technologies and materials into rapid sand casting could make it more competitive in high-tech industries compared to traditional casting methods.

5 Conclusion

This review has comprehensively explored the critical properties of sand, including bulk density, microstructure, shape and size distribution, packing density, surface characteristics, grain shape, and chemical composition. These properties play a pivotal role in the creation of molds and cores, particularly in rapid sand casting, and directly influence the quality and integrity of the resulting cast parts. These properties were thoroughly examined, with extensive elaboration on various studies conducted for some of them. The influence of these sand properties on molds and core characteristics such as permeability, stability, strength, surface finish, dimensional accuracy, and refractoriness was critically discussed, emphasizing their consequential impact on the quality of cast parts.

Additionally, the increasing demands from industries for advanced manufacturing of parts using sand molds and cores necessitate the integration of innovative materials and techniques. Future advancements may include sand treatments leveraging nanotechnology, the development of smart sand composites, and tailored sand mixtures. Moreover, digital simulation tools are anticipated to enhance the precision and predictability of molds and core performance. These advancements will ensure that future industrial requirements are met, positioning sand as an indispensable material in the evolving landscape of parts production.

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Declarations

Competing interests The authors declare no competing interests.

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