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CASTING QUALITY ENHANCEMENT USING NEW BINDERS ON SAND CASTING AND HIGH-PRESSURE RHEO-DIE CASTING

Casting quality is a perfection factor for measuring the success of the metal casting. One of efforts to obtain high-quality casting product is identifying the quality of sand moulding used. Identification of the sand-moulding quality is defined by the hardness, shear strength, tensile, and permeability. This article reviews the explanations of the strength of sand moulding with composition variation of binder type: (1) sand moulding, bentonite, fly ash, and water; (2) sand of mount Kelud eruption, bentonite, and water; (3) sand of mount Kelud eruption, Sidoarjo mud, and water; (4) sand of mount Kelud eruption, Portland cement, and water; (5) sand moulding, volcanic ash, and water; (6) green sand, bentonite, fly ash, and water; (7) sand of Malang, bentonite, tapioca flour, and sago flour; (8) sand moulding, bentonite, Portland cement, and water. High-pressure rheo-die casting commonly known in the literature as rheo-high-pressure die casting (rheo-HPDC) is a novel casting technique in producing good-quality cast products. Escalating market demand drives the development of new technology, with which casts with excellent mechanical properties, good microstructure, and minor casting defects can be produced. As an advanced version of HPDC, rheo-HPDC can be regarded as a smart manufacture technique, since it integrates the semi-solid metal technology that considers the proper preparation of slurry. The slurry-making process has been continuously developed, and the latest preparation method is the self-inoculation method. This review article discusses the procedure, mechanism, development, and product quality of sand casting with new binders as well as rheo-HPDC technique.Keywords: diffusion, martensite, austenite, radioisotope, dislocation, stack-ing fault defect.

Keywords: casting quality, moulding sand, binders, rheo-HPDC, smart mechanism, aluminium.

1. Introduction

The ever-increasing amount of engineering process in the field of technology is primarily an effort to optimise the use of natural resources effectively and efficiently for the benefit of human life [1]. Casting is an engineering process in the branch of production engineering, in which Indonesia requires to redouble more serious efforts to improve its product quality, production system, and production cost, hence more internationally competitive cast products. Training programmes are highly suggested by experts in casting, foundry operations in Indonesia, and industrial development [2]. Of all casting techniques, sand casting, as a casting process that utilises sand moulds, is the oldest known in existence. The sand casting process involves designing pattern, making moulding sand, forming a mould cavity, melting metals, pouring molten metal into the mould, breaking up the mould and removing the casting, and cleaning the casting [3].

Sand and metal are two types of mould media commonly used in casting processes. Due to its superior heat dissipation capability, a metal mould can rapidly solidify cast alloys and thereby enhance dendritic cells. Cast components produced in metal moulds typically exhibit higher ductility than in sand moulds [4]. Despite many new advanced technologies for metal casting, sand casting remains the most widely used technique due to its low-cost feedstock, varying sizes and compositions, and reusable moulding sand [5]. In fact, sand casting is by far the oldest and most common manufacturing method [6, 7] for over 70% of all castings [8–10]. The two statements above suggest that good castings can be manufactured through metal casting. This technique is preferred because mass production of castings can be done over a short span of time, hence lower production costs than the sand casting process.

In sand casting, mould making is a critical stage, which must be performed for each casting. The composition of moulding materials affects the bonding strength of the sand. A sand mould is formed by compacting the moulding sand. The types of sand commonly used for moulding are natural sand and artificial sand-clay mixtures [11]. Some determining factors in producing good-quality cast products are raw materials, material composition, moulding sand quality, smelting system, pouring system, and casting finishing process [3].

Several primary requirements of moulding sand are formability, easy to manufacture and capable of holding the mould shape once molten metal is poured into the mould cavity, permeability, determining how much gas in the mould or molten metal is able to pass through during casting, and grain-size distribution, which affects formability and permeability [12]. Moreover, moulding sand should have thermal stability (*i.e.* the ability to withstand heat damage such as cracking and dis-

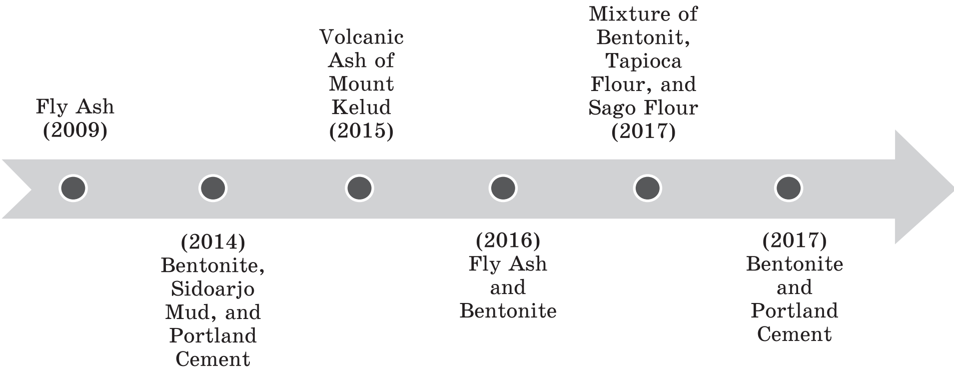

Fig. 1. The sequence of research development of binder compositions for sand moulding to optimise casting quality (2009–2017)

tortion), reusability (*i.e.* the ability to be recycled for future use for environmental and economic significance) [8], and collapsibility (*i.e.* the ability to compress or collapse during casting solidification).

Adding special binders is one way to improve the bonding capacity of moulding sand. Several materials that can be used as binders are water-glass, resin, cement, flour, and others; these binding materials can hold shape and certainly affect the quality of cast products [11]. The most widely used binding material for sand casting is bentonite [13, 14]. Bentonite is preferable because it produces excellent binding strength and becomes plastic when wet and hard when dry [15]. Bentonite is a kind of clay produced from the alteration of volcanic ash, containing primarily montmorillonite. Bentonite consists of plate-silicate minerals and is categorised into a group of minerals called aluminosilicates [16].

A feasible core binder is the key element to optimal sand with high strength and intended performance, and thus, it has a major impact on production technology and casting production costs [17–18]. The development of binding materials over time is illustrated in Fig. 1.

2. Properties of Sand Moulds with Fly Ash

High-quality sand moulds in the casting industry are those composed of sand containing high silica content. Silica is heat-resistant, absorbent, thermally conductive, and sufficiently permeable to allow the escape of gas that forms during casting and, consequently, prevent casting defects [19]. The greatest difficulty in using fly ash in casting is its different composition since it is produced from the burning of coal. Thus, its physical properties and chemical composition are also determined by the criteria of the combustion process [20]. A study on the use of fly ash as a binder in sand mould production.

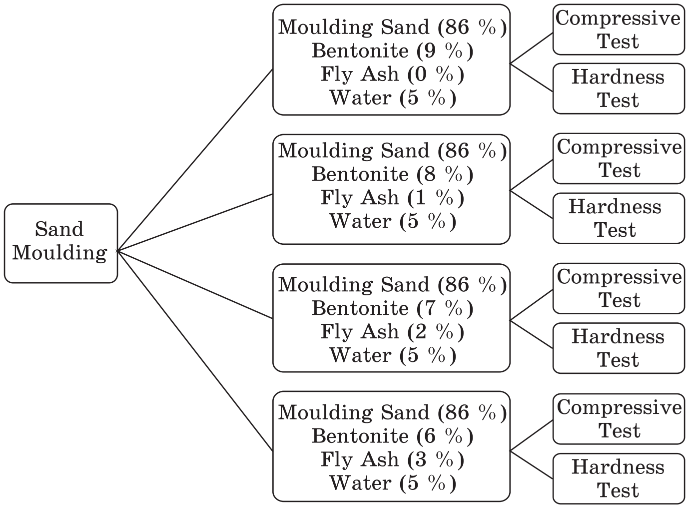

Fig. 2. The study scheme of moulding sand compositions with fly ash [21]

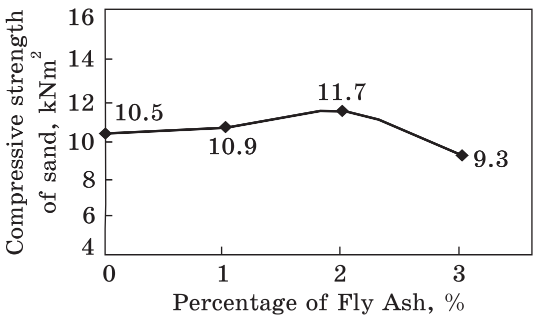

Fig. 3. The compressive strength graph for moulding sand added with fly ash [21]

Figure 2 shows the research scheme to determine the compressive test with a variety of binder compositions. The binder uses bentonite and fly ash. The research found that the addition of fly ash in the moulding sand mixture had an effect on the compressive strength of the sand mould [21].

Figure 3 shows among the other three compositions, the fourth moulding sand composition had the lowest compressive strength. The addition of 2% fly ash in the moulding sand mixture increased the compressive strength by 11.4% compared to the one without fly ash; it was due to the occurrence of a complete pozzolanic reaction [21]. The pozzolanic reaction is a reaction between calcium and silicates or aluminates to form cementing agents ($CaSiO_2H_2O$ and $CaAl_2O_3H_2O$), as shown below:

$$CaO + H_2O \to Ca(OH)_2;$$
$$Ca(OH)_2 \to Ca^{2+} + 2(OH)^-;$$
$$Ca^{2+} + 2(OH)^- + SiO_2 \to CaSiO_2H_2O;$$
$$Ca^{2+} + 2(OH)^- + Al_2O_3 \to CaAl_2O_3H_2O.$$

The addition of 2% fly ash to the mould composition increased the hardness of the sand mould by 82.6%. A pozzolanic reaction occurred completely in the specimen, in which the cementing agents hardened and bound sand grains. The strong bond shortened the distances between grains so that the sand mould got solid.

3. Properties of Sand Moulds with Bentonite, Sidoarjo Mud, Portland Cement

The study of combining bentonite, Sidoarjo mud, and Portland cement as a binding agent for sand moulding is described as follows.

Figure 4 shows the research procedure for optimising casting quality through the addition of different binders, *i.e.* bentonite, Sidoarjo mud, and Portland cement. Compressive, shear, and tensile tests were carried out on sand moulds both in dry and wet conditions. These researches found that the addition of bentonite in moulding sand mixture with dry condition had an effect on the compressive strength and shear strength of the sand mould, while the addition of Sidoarjo mud had an effect on the tensile strength [22].

As shown in Fig. 5, the mixture of moulding sand and bentonite in dry condition had the highest compressive strength, followed by the moulding sand-Sidoarjo mud mixture, while the moulding sand added with Portland cement in wet state had the lowest compressive strength [22].

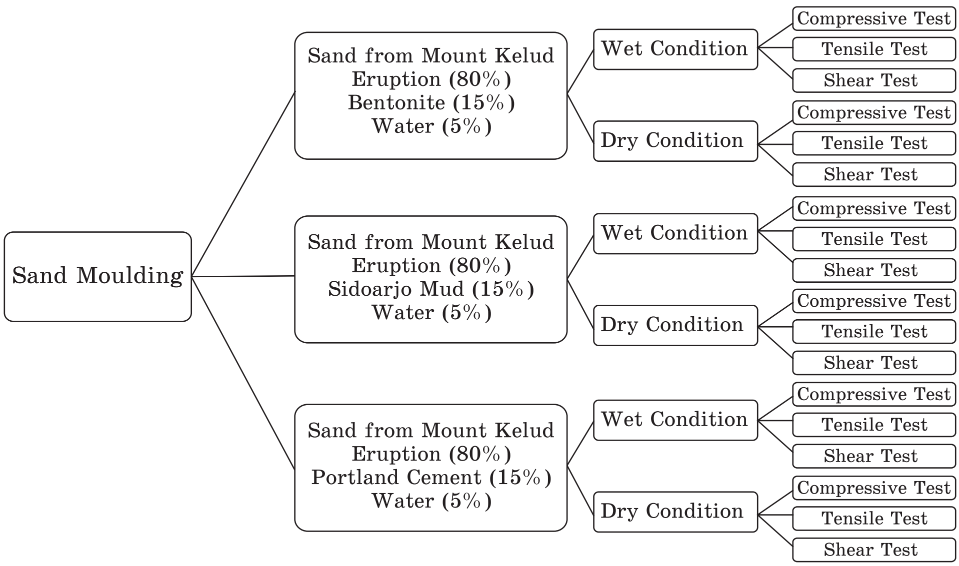

Fig. 4. The study scheme of moulding sand compositions with bentonite, Sidoarjo mud, and Portland cement [22]

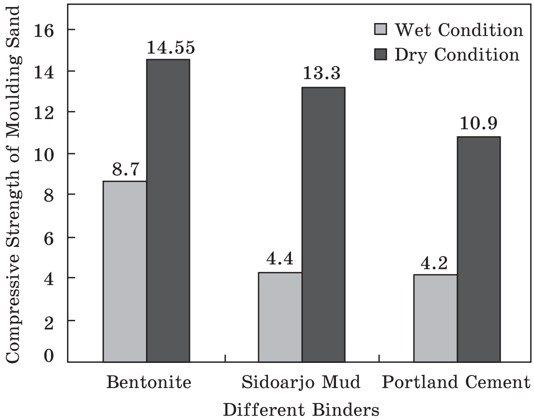

Fig. 5. Compressive strength (N/cm^2) comparison of moulding sand specimens mixed with bentonite, Sidoarjo mud, and Portland cement [22]

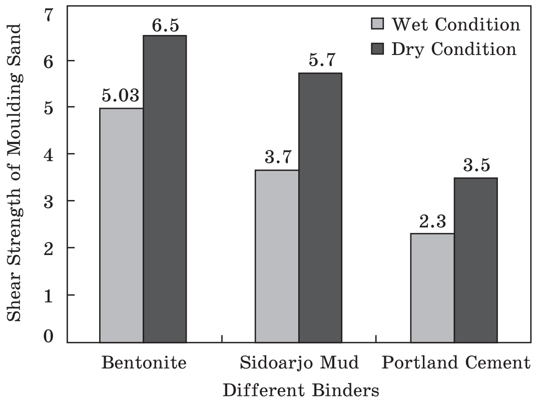

Fig. 6. Shear strength (N/cm^2) comparison of moulding sand specimens mixed with bentonite, Sidoarjo mud, and Portland cement [22]

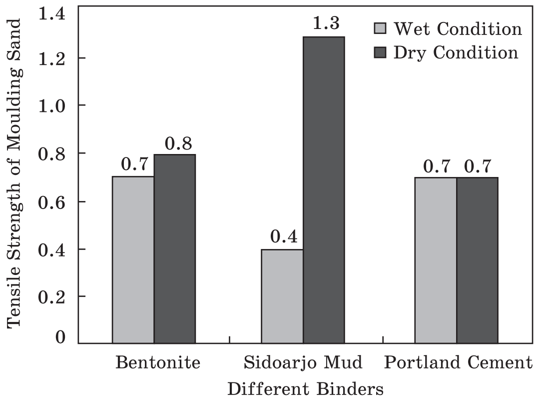

Fig. 7. Tensile strength (N/cm^2) comparison of moulding sand specimens mixed with bentonite, Sidoarjo mud, and Portland cement [22]

According to Fig. 6, the mixture of moulding sand and bentonite in dry condition had the highest shear strength compared to those with the other binders under study (Sidoarjo mud and Portland cement), while the moulding sand-Portland cement mixture in wet condition had the lowest shear strength [22].

As shown in Fig. 7, the results of the tensile testing showed that the mixture of moulding sand and Sidoarjo mud used in dry condition had the highest tensile strength, followed by that with bentonite in dry condition and the lowest tensile strength was found in the moulding sand mixed with the Sidoarjo mud in wet condition [22].

Under wet condition, the moulding sand added with 15% bentonite had the highest compressive strength of 8.7 N/cm^2. The mixture with the highest shear strength was that with moulding sand and 15% bentonite (5.03 N/cm^2). The highest tensile strength of 0.7 N/cm^2 belonged to the mixture of moulding sand, 15% bentonite, and 15% Portland cement. In wet condition, the highest compressive strength of 14.55 N/cm^2 belonged to the mixture of moulding sand and 15% bentonite. The highest shear strength was 6.5 N/cm^2 and found in moulding sand containing 15% bentonite. The highest tensile strength of 1.3 N/cm^2 belonged to the moulding sand mixed with 15% Sidoarjo mud.

4. Properties of Sand Moulds with Mount Kelud's Volcanic Ash

Mount Kelud erupted in 2014. The sound of the blast was so powerful that it was heard across the city of Yogyakarta (200 km away) and even Purbalingga (300 km away) [23]. During this eruption, mount Kelud ejected many kinds of volcanic material such as volcanic ash. Volcanic ash or volcanic sand contains major elements (aluminium, silica, potassium, and iron), minor elements (iodine, magnesium, manganese, atrium, phosphor, sulphur, and titanium), and trace levels (aurum, asbestos, barium, cobalt, chrome, copper, nickel, plumbum, sulphur, stibium, stannum, strontium, vanadium, zirconium, and zinc). Five elements

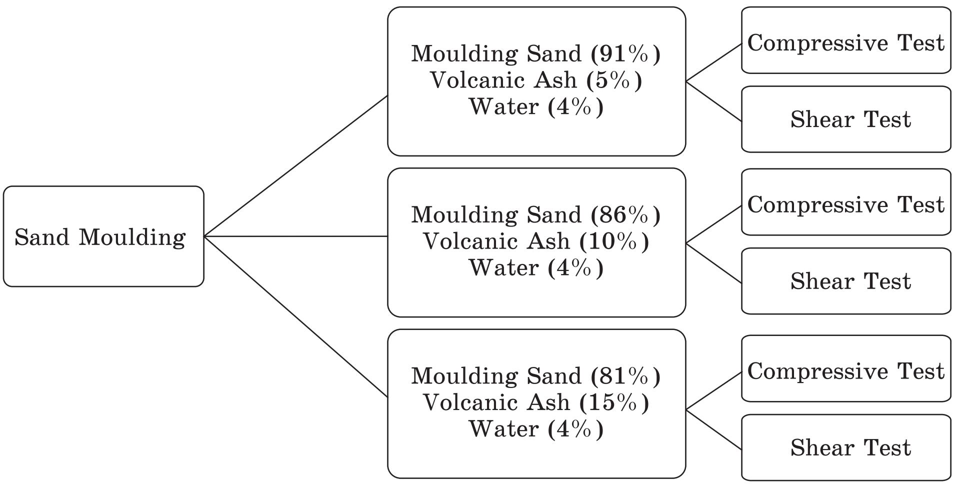

Fig. 8. The study scheme of moulding sand compositions with volcanic ash [25]

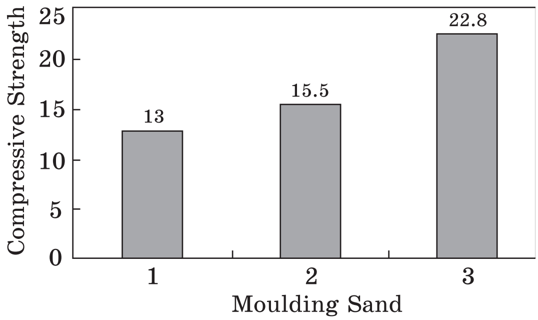

Fig. 9. Compressive strength (N/cm²) comparison of moulding sand specimens with 5%, 10% and 15% volcanic ash [25]

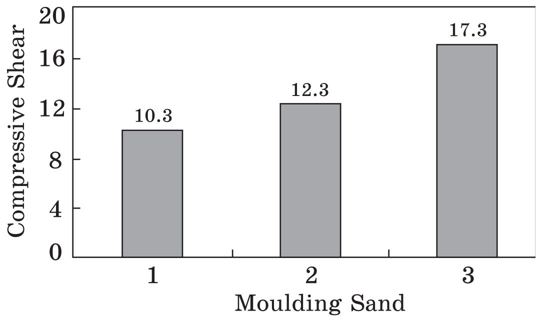

Fig. 10. Compressive shear (N/cm²) comparison of moulding sand specimens with 5%, 10%, and 15% volcanic ash [25]

with the highest concentrations in volcanic ash are silicon dioxide (55%), aluminium oxide (18%), iron oxide (18%), calcium oxide (8%), and magnesium oxide (2.5%) [24].

Despite the disaster it creates, volcanic ash also brings benefits to the agricultural and casting industry [25]. One of the research on the use of volcanic ash as a binder in sand mould production.

Figure 8 shows the research procedure in which the samples of moulding sand were added with varying amounts of volcanic ash as a binder, *i.e.* 5% (moulding sand I), 10% (moulding sand II), and 15% (moulding sand III). Each mixture was tested for its compressive and shear strengths. The results of the tests are represented in Figs. 9 and 10.

As shown in Fig. 9, the moulding sand III containing 81% moulding sand, 15% volcanic ash, and 4% water had the highest compressive strength. The lowest compressive strength belonged to the moulding sand I composed of 91% moulding sand, 5% volcanic ash, and 4% water.

Figure 10 represents the results of shear testing which are not far different from the compressive test results. The moulding sand III, which consisted of 81% moulding sand, 15% volcanic ash, and 4% water, had the highest shear strength, whereas the moulding sand I containing 91% moulding sand, 5% volcanic ash, and 4% water had the lowest. Thus, it can be seen that the increasing amount of volcanic ash resulting the increasing value of compressive strength and shear strength [25].

5. Properties of Sand Moulds with a Mixture of Fly Ash and Bentonite

The following research involved a mixture of fly ash and bentonite as a binder in sand mould production.

As shown in Fig. 2 and 11, the two research schemes are similar. In this research, the amount of fly ash was increased to 2%, 4%, and 6% [26]. This research aimed to investigate the compressive strength and permeability of the mixtures. The results of the tests are as follows.

As presented in Fig. 12, the moulding sand with 6% fly ash had the greatest permeability, while the lowest belonged to the one with 4% fly ash. As shown in Fig. 13, the highest compressive strength was found in the mixture with 2% fly ash, while the lowest belonged to that with 6% fly ash. Based on Fig. 12 and 13, the mixture with 2% of fly ash has the best permeability and compressive strength [26].

6. Properties of Sand Mould with a Mixture of Bentonite, Tapioca Flour, and Sago Flour

The following research studied bentonite, Sidoarjo mud, and Portland cement as binding materials in the production of sand moulds.

One can see in Fig. 14 three types of binders used to make sand moulds, *i.e.* bentonite, tapioca flour, and sago flour. The research examined each binding material and a mixture of the three. Compressive, tensile and shear tests were performed on each moulding sand specimen both in wet and dry conditions. This research found that the addition of tapioca flour in moulding sand mixture with dry condition had an effect

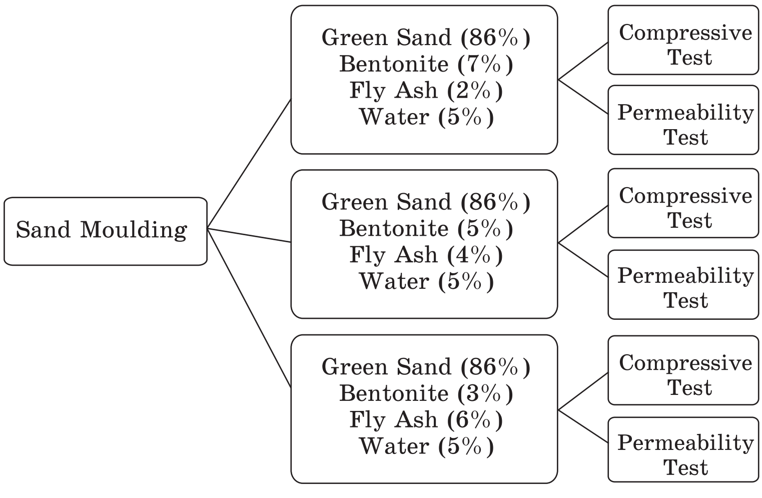

Fig. 11. The study scheme of moulding sand compositions with fly ash [26]

on the shear strength and tensile strength of sand mould, while the addition of sago flour in moulding sand mixture with dry condition had an effect on the compressive strength [27]. The findings of the research scheme are shown in Table 1.

The moulding sand added with sago flour as a binder and used in dry condition had the highest compressive strength, as shown in Table

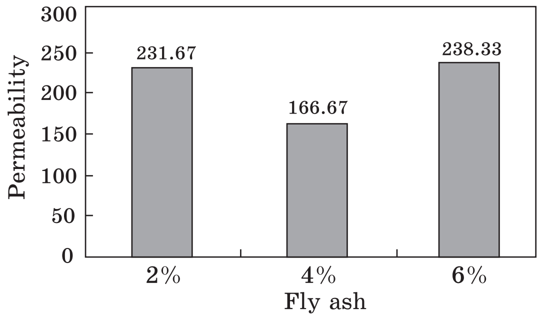

Fig. 12. Permeability (cm^3/min) comparison of moulding sand specimens with 2%, 4%, and 6% fly ash [26]

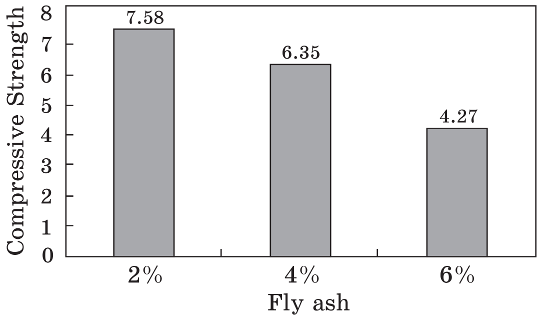

Fig. 13. Compressive strength (N/cm^2) comparison of moulding sand specimens with 2%, 4%, and 6% fly ash [26]

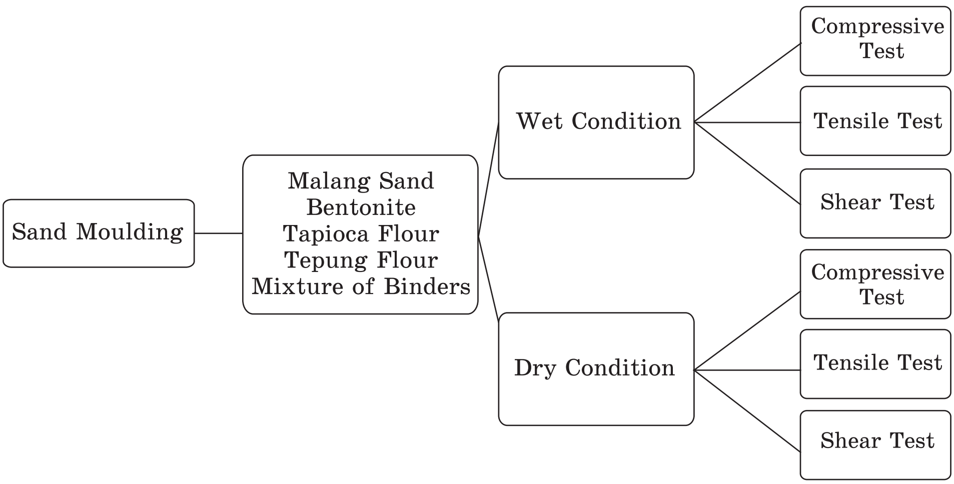

Fig. 14. The study scheme of moulding sand compositions with bentonite, tapioca flour, and sago flour [27]

Table 1. **Comparison of wet and dry compressive strengths [27]**

Binder	Wet compressive strengths, N/cm^2	Dry compressive strengths, N/cm^2
Bentonite (B)	11.83	12.16
Tapioca Flour (TF)	5.06	25.16
Sago Flour (SF)	4.9	28.6
B (5%) + SF (5%) + TF (5%)	6.3	6.51
B (5%) + SF (2.5%) + TF (2.5%)	6.7	7.51
B (2%) + SF (4%) + TF (4%)	5.5	9.71

Table 2. **Comparison of wet and dry shear strengths [27]**

Binder	Wet shear strengths, N/cm^2	Dry shear strengths, N/cm^2
Bentonite (B)	3.16	5.86
Tapioca Flour (TF)	2.13	18.16
Sago Flour (SF)	2.18	6.9
B (5%) + SF (5%)	2.53	3.1
B (5%) + TF (5%)	2.36	7.83
B (5%) + SF (2.5%) + TF (2.5%)	1.9	6.78

Table 3. **Comparison of wet and dry tensile strengths [27]**

Binder	Wet tensile strengths, N/cm^2	Dry tensile strengths, N/cm^2
Bentonite (B)	0.7	0.75
Tapioca Flour (TF)	0.85	1.73
Sago Flour (SF)	0.52	0.53
B (5%) + SF (5%)	0.48	0.6
B (5%) + TF (5%)	0.45	0.65
B (2%) + SF (2.5%) + TF (2.5%)	0.58	1.03
B (2%) + SF (4%) + TF (4%)	0.35	1

1. However, the moulding sand added with sago flour in wet conditions had the lowest compressive strength.

As shown in Table 2, the highest shear strength was found in the moulding sand, which was in dry condition and added with tapioca flour. On the other hand, the lowest shear strength belonged to the moulding sand, which was in wet state and mixed with several binding materials (5% bentonite, 2.5% sago flour, and 2.5% tapioca flour).

In dry state, the moulding sand mixed with tapioca flour had the highest tensile strength, as shown in Table 3. The lowest tensile strength belonged to the moulding sand containing 2% bentonite, 4% sago flour, and 4% tapioca flour in wet condition.

Table 4. **Comparison of tensile, shear, and compressive strengths of moulding sand with bentonite (B)–Portland cement (PC) binder [28]**

Type of testing	B (5%) + + PC (5%)	B (4%) + + PC (6%)	B (6%) + + PC (4%)	B (7%) + + PC (3%)
Compressive strength, N/cm^2	7.20	7.03	8.13	7.93
Shear strength, N/cm^2	2.60	2.70	2.63	2.86
Tensile strength, N/cm^2	0.51	0.51	0.51	0.46

Therefore, the best conditions for sand moulding to obtain compressive strengths, shear strengths, and tensile strengths are in dry conditions [27].

7. Properties of Sand Mould with a Mixture of Bentonite and Portland Cement

The study procedure for producing moulding sand binders formulated with bentonite and Portland cement is demonstrated in Fig. 15, where one can see two types of binding materials used in the research, *i.e.* bentonite and Portland cement. Compressive, shear, and tensile tests were performed on the moulding sand specimens. The results of the tests are shown in Table 4. These researches found that the addition of a mixture of bentonite and Portland cement in moulding sand mixture had an effect on compressive strength, shear strength and tensile strength [28].

As presented in Table 4, the moulding sand composed of 6% of bentonite and 4% of Portland cement had the highest compressive strength,

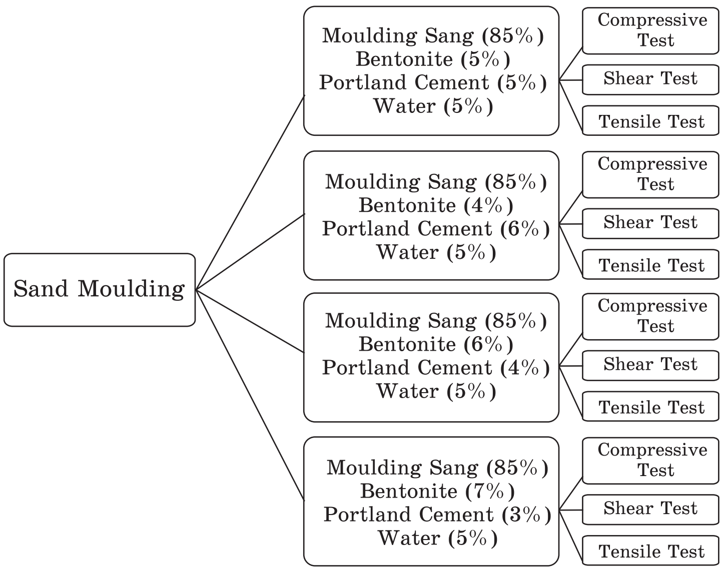

Fig. 15. The study scheme for moulding sand compositions with bentonite Portland cement binder [28]

while that mixed with 4% of bentonite and 6% of Portland cement had the lowest. The shear test results showed that the highest shear strength belonged to the moulding sand added with 7% of bentonite and 3% of Portland cement, whereas the lowest was found in the mixture with 5% of bentonite and 5% of Portland cement. Regarding tensile strength, the moulding sand containing three different concentrations of binding materials (5% bentonite and 5% Portland cement, 4% bentonite and 6% Portland cement, and 6% bentonite and 4% Portland cement) had the same highest tensile strength, leaving the mixture composed of 7% bentonite and 3% Portland cement with the lowest tensile strength [28].

8. New Optimal Binder Compositions for Sand Moulding

Based on reports of previous studies, bentonite is an ideal binding agent for sand moulding despite its higher price compared to other types of binders [21]. The findings of past research on binder compositions are summarised as follows.

Based on Table 5, the highest compressive strength can be seen in the binder with composition of silica sand (81%), volcanic ash (15%) and water (4%) with a value of 22.8 N/cm^2, while the lowest compressive strength is in accordance with silica sand (86%), bentonite (6%), fly ash (3%) and water (5%) with a value of 0.93 N/cm^2. The highest shear strength was in the binder with composition of silica sand (81%), volcanic ash (15%) and water (4%) at 17.3 N/cm^2, while the lowest

Table 5. **Mechanical properties sand moulding based on binder variation**

Year	Composition	Compressive strength, N/cm^2	Shear strength, N/cm^2	Tensile strength, N/cm^2	Permeability, cm^3/min	Ref.
2009	Silica sand (86%) Bentonite (9%) Fly ash (0%) Water (5%)	1.05	–	–	–	[21]
	Silica sand (86%) Bentonite (8%) Fly ash (1%) Water (5%)	1.09	–	–	–	
	Silica sand (86%) Bentonite (7%) Fly ash (2%) Water (5%)	1.17	–	–	–	
	Silica sand (86%) Bentonite (6%) Fly ash (3%) Water (5%)	0.93	–	–	–	

The End of Table 5

Year	Composition	Compressive strength, N/cm^2	Shear strength, N/cm^2	Tensile strength, N/cm^2	Permea-bility, cm^3/min	Ref.
2014	Kelud mountain eruption sand (80%) Bentonite (15%) Water (5%) WET	8.7	5.03	0.7	—	[22]
	Kelud mountain eruption sand (80%) Sidoarjo mud (15%) Water (5%) WET	4.4	3.7	0.4	—	
	Kelud mountain eruption sand (80%) Portland cement (15%) Water (5%) WET	4.2	2.3	0.7	—	
	Kelud mountain eruption sand (80%) Bentonite (15%) Water (5%) DRY	14.55	6.5	0.8	—	
	Kelud mountain eruption sand (80%) Sidoarjo Mud (15%) Water (5%) DRY	13.3	5.7	1.3	—	
	Kelud mountain eruption sand (80%) Portland cement (15%) Water (5%) DRY	10.9	3.5	0.7	—	
2015	Silica sand (91%) Volcanic ash (5%) Water (4%)	13	10.3	—	—	[25]
	Silica sand (86%) Volcanic ash (10%) Water (4%)	15.5	12.3	—	—	
	Silica sand (81%) Volcanic ash (15%) Water (4%) Silica sand (81%) Volcanic ash (15%) Water (4%)	22.8	17.3	—	—	
2016	Green sand (86%) Bentonite (7%) Fly ash (2%) Water (5%)	7.58	—	—	231.67	
	Green sand (86%) Bentonite (5%) Fly ash (4%) Water (5%)	6.35	—	—	166.67	
	Green sand (86%) Bentonite (3%) Fly ash (6%) Water (5%)	4.27	—	—	238.33	

shear strength was in mountain eruption sand (80%), Portland cement (15%), water (5%) in wet conditions with a value of 2.3 N/cm^2. The highest tensile strength in binder with composition of Kelud mountain eruption sand (80%), Sidoarjo mud (15%), water (5%) in dry conditions with a value of 1.3 N/cm^2, while the lowest tensile strength in sand from Kelud eruption (80%), Sidoarjo (15%) and water (5%) in wet conditions with a value of 0.4 N/cm^2. The highest permeability is the binder with composition of green sand (86%), bentonite (3%), fly ash (6%) and water (5%) with a value of 238.33 cm^3/minute, while permeability is lower in green sand (86%), bentonite (5%), fly ash (4%) and water (5%) with a value of 166.67 cm^3/minute.

The types of sand used in producing sand moulds can vary and are dependent on the location of the source. The quality of the sand greatly affects the quality of casting. High-quality castings can be realized if the sand has the following five characteristics. (i) Strength, *i.e.* the ability of the sand to sustain its shape once formed. (ii) Permeability, *i.e.* the ability of gas to escape through the sand; higher permeability is capable of reducing porosity in castings. (iii) Thermal stability, *i.e.* the ability of the sand to withstand heat damage such as cracking and distortion. (iv) Collapsibility, *i.e.* the ability of the sand to compress or collapse during solidification. Finally (v) reusability, *i.e.* the ability of the sand to be recycled for subsequent use for environmental and economic significance.

The results of the above studies suggest that previous tests on sand moulds with various types of binders aimed to investigate the strength of each composition, revealing the compressive strength, hardness, shear strength, and tensile strength. The past studies were carried out with the aim of improving one aspect of casting quality optimisation, *i.e.* strength. Reviewing the research literature on sand moulding, we found that the moulding sand containing tapioca flour as a binder and used in dry condition had the highest overall strength, namely, compressive strength of 25.16 (N/cm^2), shear strength of 18.16 (N/cm^2), and shear strength of 1.73 (N/cm^2).

Metal casting involves two separate activities. The first one is the production of patterns and moulds, whereas the second is the casting process including melting metal, controlling its composition and impurities, and pouring the molten metal into a mould, cleaning the casting, giving heat treatment, and inspecting the casting for defects [29]. Metal moulds are permanent and reusable, unlike those made out of sand. In sand casting, the mould making is a critical stage, which must be performed for each casting. A sand mould is formed by compacting the moulding sand. The types of sand commonly used for moulding are natural sand and artificial sand–clay mixtures [11]. Metals are among the most important and most extensively used materials in different

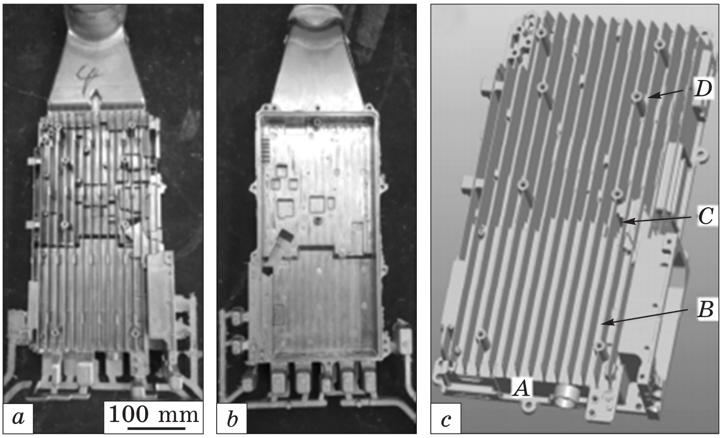

Fig. 16. Thin wall heat dissipation shells (*a*, *b*, and *c* — front, back, and perspective view, respectively), which are produced by air cooled stirring rod (ACSR) process combined with high-pressure die casting machine [51]. Here, *A*, *B*, *C*, and *D* — regions from which the samples were prepared [51] to study their microstructure and mechanical properties

engineering fields, particularly in the casting industry. Of all non-ferrous metals, aluminium has become of great importance in engineering [1], which is widely used for casting [30]. Aluminium alloys have also been used in the manufacture of components for automotive applications, such as piston, engine block, cylinder head, valve, and others [31, 32]. Since its pure form is not as good as other metals, aluminium is often alloyed with other elements such as copper, magnesium, silicon, manganese and zinc to improve its castability, corrosion-resistance, machinability, and weldability properties [33]. Combining aluminium as the predominant metal with other elements results in aluminium alloys [31, 34–36]. The use of aluminium in the automotive industry has escalated in the past few decades and served as a frequent substitute for iron and steel because aluminium contributes in the reduction of structural mass and exhaust emissions [37, 38]. Aluminium alloys have excellent properties including lightweight, good castability, and high thermal conductivity, hence wide applications in field of computer, communications, electronics and automotive [39–43]. ADC12, a type of Al–Si alloys, even exhibits additional properties, *i.e.* high productivity, low shrinkage rate, corrosion resistance [44, 45], and high durability [46].

Revealing the remarkable properties of aluminium alloys leads to an increase in its demand, reaching 29 million tons per year consisting of 22 million tons of new aluminium and 7 tons of recycled one [47]. There is no substantial difference in quality between pure and recycled aluminium alloys, and thus they have become the most frequently used materials after steel [48, 49]. The aluminium consumption in Indonesia reaches between 200.000–300.000 tonnes per year with a price of US$ 1.951,50 per ton [50].

The growing demand for high quality casts made with stricter tolerances, as in Fig. 16, is more difficult to meet if using sand casting [51]. As a result, some companies are beginning to develop and use sophisticated casting machines equipped with automatic control systems. As discussed in depth in the American Metalcasting Consortium (AMC), the high-pressure die casting (HPDC) technique involves smart machines, manufacturing, testing, and control [52]. The HPDC is continuously being developed to make the best use of it.

HPDC technique is one of the metal casting techniques utilising permanent moulds into which molten metal is poured under very high pressure. This technique is employed commonly in the manufacture of alloy parts [53–55]. The HPDC technique offers several advantages such as cast products with thin walls, near-net shapes, and stable and precise dimensions, fast cooling rates, high productivity levels [56, 57], and efficient production which leads to low manufacturing costs [55, 58, 59].

Notwithstanding the above beneficial aspects, high-pressure die-casting has its drawbacks. Its final products often suffer from internal defects [60, 61], one of which is gas porosity due to air or gas entrapped during the mould filling done under high speeds which adversely affects the mechanical properties of the material [55, 62].

9. Overview of Rheo-Die Casting

Adding a touch of new technology is one of the ways to remedy the shortcomings of high-pressure die casting technique. Since this casting technique applies the smart machine, manufacturing, testing, and control, the addition of a new device to the system is considered a favourable solution. As a result, rheo-HPDC has been pioneered as a developed version of high-pressure die casting technique, integrating HPDC with semi-solid processing [63–65]. Over the past few years, this technology has produced high-quality components with a good microstructure [53, 66–68]. Rheo-HPDC has attracted increasing attention and been continuously developed [69, 70] due to the effectiveness of this smart manufacturing process to offer improved mechanical properties [63] and produce a more refined microstructure, hence better aluminium alloy properties and reduction of shrinkage [71]. Also, the products of rheo-HPDC exhibit lower porosity than the conventional HPDC techniques [72, 70]. Based on their mechanical properties, the results of rheo-HPDC have superior properties than those manufactured by HPDC [66].

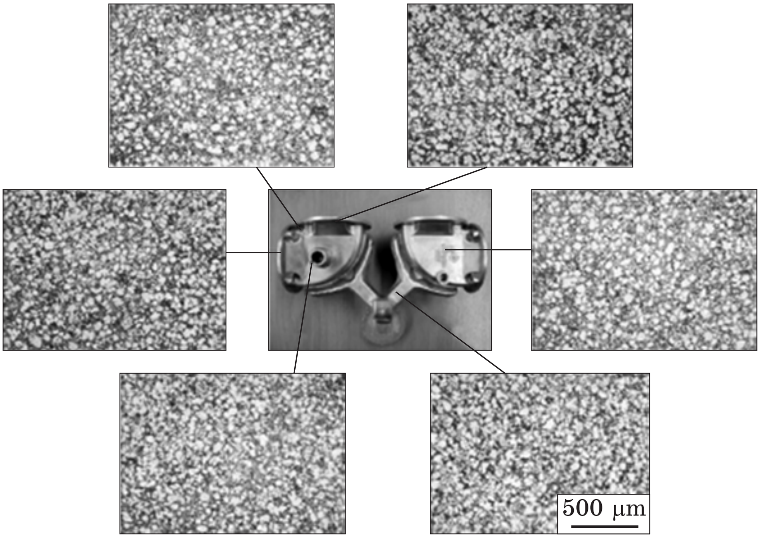

Fig. 17. Microstructure for the rheo-die cast AZ91D magnesium alloy component at various positions [74]

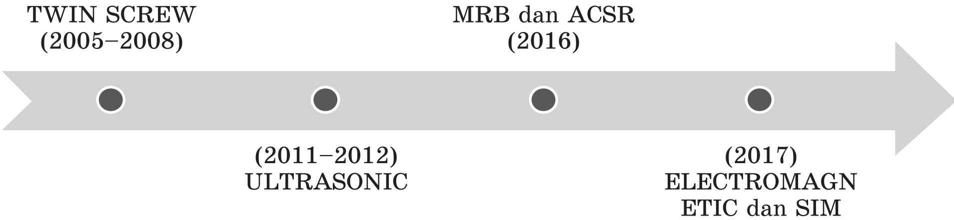

Fig. 18. Development of casting process optimization through high-pressure rheo-die casting from 2005–2017

As one can see in Fig. 17, the microstructure AZ91D alloy component at different locations is homogeneous after the rheo-die casting (RDC) procedure. Based on the microstructure, it can also be seen that RDC can increase strength and ductility compared to products from HPDC [74].

10. Mechanism of Rheo-Die Casting

Rheo-die casting is a version of semi-solid metal (SSM) technology [75] that has become the focus of research work in recent years [69, 73, 74] due to its high production volume [74] and been developed continuously to meet scientific and industrial demands [70]. Rheo (or rheology) is closely related to viscosity and includes slurry mixing to be poured into a container or mould under high pressures. In other words, rheo-processing requires a liquid metal alloy, which is then cooled to obtain a liquid–

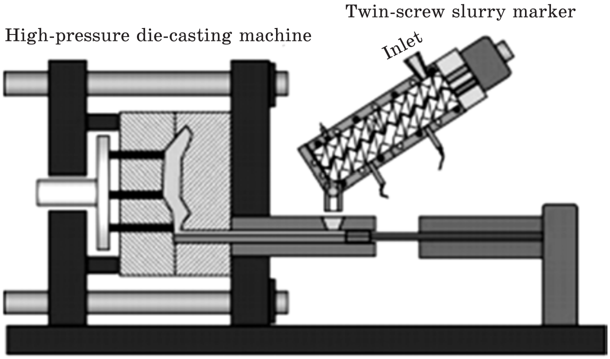

Fig. 19. The rheo-die casting process with twin screw to make slurry [74]

solid alloy (slurry) and cast in a permanent mould through HPDC [61, 78]. With the above procedure, this highly innovative technique is able to cast precise components with a high complexity, improved mechanical properties [73–75, 79], and fine grain size [80].

In fact, slurry serves a very significant role in producing high-quality castings, and thus proper preparation is necessary before rheo-HPDC [81–83]. The core of rheo-die casting process consists of, first, the preparation of slurry which is then processed in the HPDC machine and, second, the forming process through rheo-HPDC [64]. In other words, the molten metal will undergo both primary and secondary solidification [84]. SSM casting is, indeed, a novel metal casting technique that involves rheological properties to process components [63, 85].

11. Development of Rheo-Die Casting

Judging from its viscosity level, slurry has a higher viscosity than molten or liquid metal. This leads to the less entrapped gas contained in the materials and hence a final product with no porosity defects [86–88]. Rheo-die casting is, in fact, smart manufacture that fulfils the needs the industry since it frequently utilises aluminium alloys in the process [69]. The development of slurry processing through this smart machine, manufacturing, testing and control from 2005 to 2017 is illustrated in Fig. 18.

11.1. Rheo-Die Casting with a Twin-Screw Slurry Maker

Making slurry using a twin-screw system is one of the alternatives to produce high-quality cast products; this method had been studied until 2008. Figure 19 exhibits the use of the twin-screw slurry maker in rheo-die casting.

As shown in Fig. 19, the RDC process with twin screw consists of two main components, the twin-screw slurry maker and the HPDC ma-

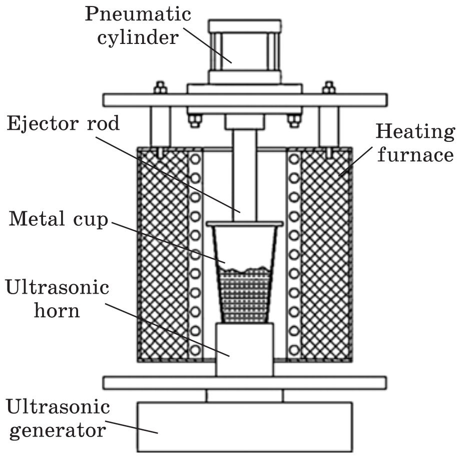

Fig. 20. Components of indirect ultrasonic vibration [69]: schematic illustration

chine. The screw slurry has a pair of screws that rotate inside the cylinder. The function of this component is to convert molten metal into high-quality semi-solid slurry. The next component is the standard HPDC machine. The function of this HPDC machine is to achieve the formation of final product. The products produced from the RDC process with twin screw are having low porosity (0.1–0.3%), smooth and uniform microstructures on all surfaces, and better ductility than HPDC [74].

11.2. Rheo-Die Casting with an Ultrasonic Slurry Maker

The preparation of slurry using the twin-screw system, judged from its cast products, was considered to have significant shortcomings. Owing to this, in 2011, many researchers started to switch their focus to the slurry-making process using the indirect ultrasonic vibration system. Figure 20 illustrates the equipment of ultrasonic vibration.

Based on Fig. 20, it can be seen that the component of indirect ultrasonic vibration consists of an ultrasonic generator, ultrasonic horn, metal cup, ejector rod, pneumatic cylinder and heating furnace. The horn that is on the outside of the metal cup has the duty to vibrate the molten metal. The vibration is produced from an ultrasonic generator that has a power of 2.6 kW with a vibration frequency of 20 kHz. The products produced have a smooth microstructure and better tensile strength as compared to conventional die casting [69].

11.3. Rheo-Die Casting with an MRB Slurry Maker

In an effort to improve the quality of casts through rheo-HPDC, researchers have developed many innovations, one of which is a mechanical rotational barrel (MRB), which has been introduced in 2016.

Based on Fig. 21, it can be understand that the preparation of semi-solid slurry through a MRB system is to use a stainless steel barrel with a length of 500 mm, a diameter of 150 mm and a tilt angle of 45°. Liquid becomes high-quality semi-solid slurry. This is due to the presence of high shear and turbulence through solidification [75].

11.4. Rheo-Die Casting with an ACSR Slurry Maker

Researchers also introduced a new invention called an air-cooled stirring rod (ACSR) in 2016. Figure 22 shows the preparation of slurry for rheo-HPDC using the ACSR.

Based on Fig. 22, one can see that the ACSR consists of an air compressor, airway, stirring rod, crucible and thermocouple. Preparation of semi-solid slurry is by continuously flowing air into the stirring rod. An air release valve controls the airflow. Thus, the liquid metal can turn into semi-solid slurry. Products produced from this method can increase tensile strength, yield strength, hardness and thermal conductivity [51].

11.5. Rheo-Die Casting with SIM

The latest innovation among all slurry-making processes above is the self-inoculation method (SIM) (see Fig. 23).

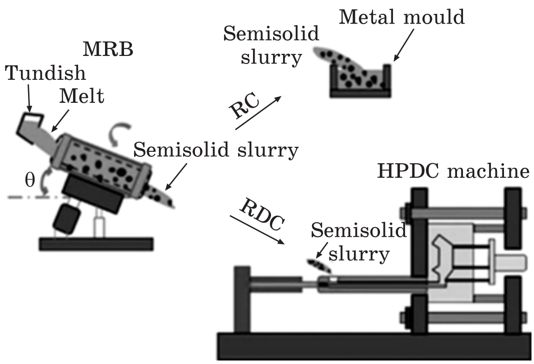

Fig. 21. Rheo-casting (RC) and rheo-die-casting (RDC) with mechanical rotational barrel (MRB) system to make semisolid slurry [78]

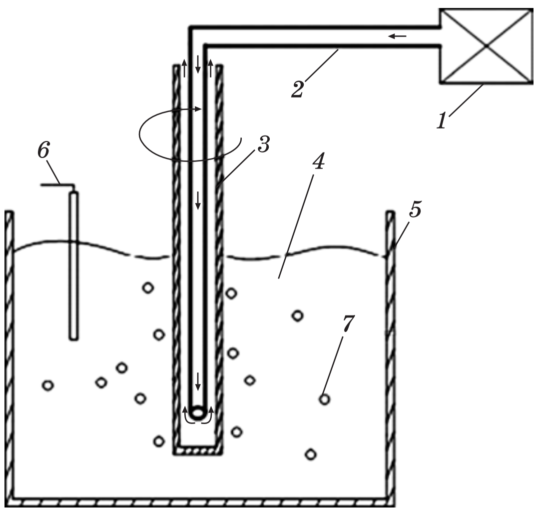

Fig. 22. Components of the air cooled stirring rod (ACSR), where *1* — air compressor, *2* — airway, *3* — stirring rod, *4* — melt, *5* — crucible, *6* — thermocouple, *7* — primary α-Al particle) [51]

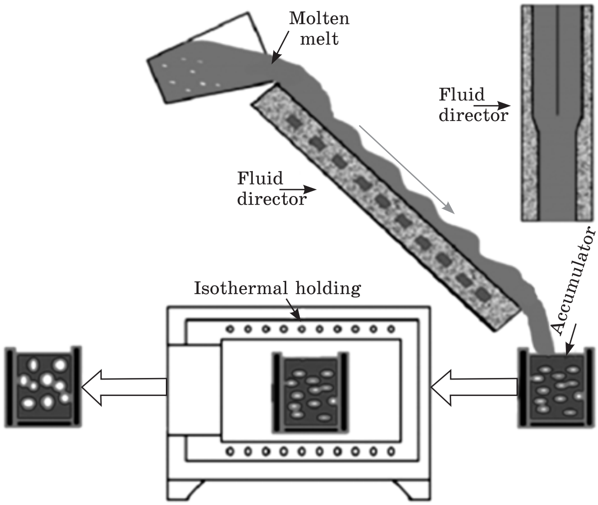

Fig. 23. The RDC process combined with self-inoculation method (SIM) [84]

We can see in Fig. 23, that the RDC process with SIM uses a fluid director to prepare semi-solid slurry. There is a specification of fluid director having a length of 500 mm and a tilt angle of 45°. The addition of self-inoculants (5% of alloy mass) is carried out when the molten metal is then stirred quickly. The last step of this method is to provide treatment in the form of isothermal holding. The results obtained from this method are the eutectic growth rate in RDC is 4 times faster than HPDC [84].

12. Discussion

This section examines the advantages of rheo-HPDC viewed from several aspects of its cast products including mechanical properties, porosity, and microstructure.

12.1. Mechanical Properties

The mechanical properties to be discussed are the tensile strength, hardness, and some others; the properties of casts produced by rheo-HPDC are compared with those of the products of the conventional HPDC technique.

Table 6. **Comparison of mechanical properties, density and thermal conductivity of samples produced by HPDC and ACSR rheo-HPDC [51]. Here, UTS — ultimate tensile strength, YS — yield strength**

Process	Air flow, Ls^{-1}	Mechanical Properties				Density, $g \cdot cm^{-3}$	Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
		UTS, MPa	YS, MPa	Elongation, %	Hardness, HV		
HPDC		217	108	2.6	88	2.618	139
ACSR rheo-HPDC	0	231	112	3.2	92	2.635	143
	1	239	113	3.7	94	2.645	145
	3	255	119	4.6	97	2.660	151
	5	261	124	4.9	99	2.664	153

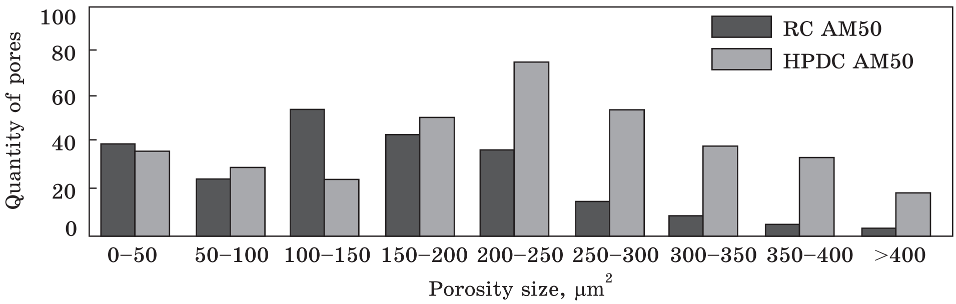

Fig. 24. Comparison of porosity levels for Mg–Al (AM50) alloy produced by rheo-casting (RC) and high pressure die casting (HPDC) [75]

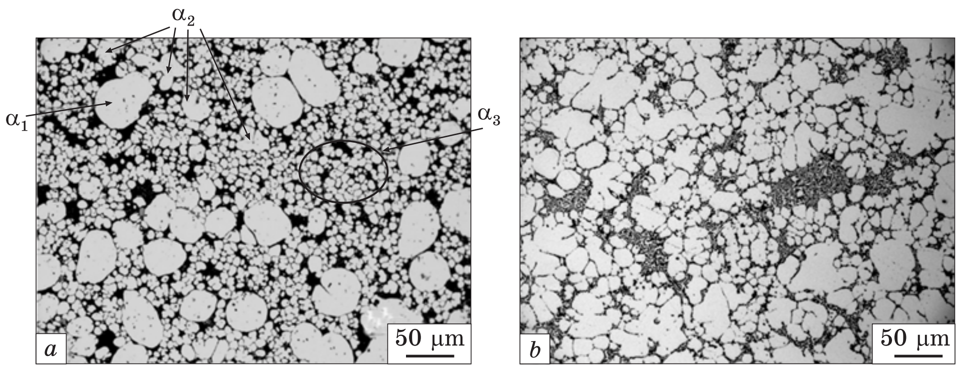

Fig. 25. Typical microstructure of the as-cast Al–Si–Mg (A357) alloy, which is prepared through the RDC (*a*) and HPDC (*b*) methods [70]. In the figure left (*a*), α_1–α_3 denote primary α-Al globules (α_1), dendritic fragments (α_2), and equiaxed particles (α_3) [70]

According to Table 6, the rheo-HPDC could improve the mechanical properties of a material. The ultimate tensile strength of specimen cast using the conventional HPDC was 217 MPa, while that of products cast by rheo-HPDC was up to 261 MPa. Moreover, the rheo-HPDC produced casts with a higher yield strength (124 MPa at highest), compared to the product of the conventional HPDC which only reached 108 MPa. Based on its elongation, the cast of the conventional HPDC only reached 2.6%, whereas those produced by rheo-HPDC had higher elongation value, *i.e.* up to 4.9%. The cast density of the conventional HPDC and rheo-HPDC was 2.618 g/cm^3 and 2.664 g/cm^3, respectively. The hardness achieved by the conventional HPDC was 88 HV and by rheo-HPDC was 99 HV. Lastly, the thermal conductivity of the result of the conventional was 139 $W \cdot m^{-1} \cdot K^{-1}$, while that of the products of rheo-HPDC was up to 153 $W \cdot m^{-1} \cdot K^{-1}$.

12.2. Porosity

Porosity is a form of defect that may reduce the mechanical properties or performance of a material, and thus, it should be prevented. Figure 24 illustrates the comparison of porosity levels in casts produced by the conventional HPDC and rheo-HPDC [75].

Figure 24 suggests that the rheo-HPDC leads to a reduced porosity. The thing that needs to be highlighted here is the size of porosity, smaller pores (0–150) appeared more in the products of rheo-HPDC, while pores bigger than 150 appeared more in the casts of HPDC [75].

12.3. Microstructure

In addition to mechanical properties, microstructure is another aspect should be analysed to investigate the advantages of a material. Based on the mechanical properties, the products of rheo-HPDC have better properties than the conventional HPDC. Figure 25 shows the microstructure of rheo-HPDC and conventional HPDC.

The image of microstructure in Fig. 25, *a* is much better and clearer than the image in Fig. 25, *b*. The clearly visible grain boundaries and the homogeneity of the spherical microstructure support the superior mechanical properties of casts produced by rheo-HPDC [70].

13. Conclusions

The use of bentonite as a binding agent in moulding sand can be replaced by tapioca flour if viewed from the resulting strength. Tapioca starch, as a binder, is potentially preferable, since it can produce higher strength in sand moulds when in dry condition than bentonite.

As a recommendation for further research, this study suggests the more comprehensive studies on the use of tapioca flour as a new type of binder in the metal casting industry. Future researchers should take a closer look at other sand characteristics for optimising casting quality. We can offer research recommendations that appear below.

1. To test the permeability level of moulding sand with tapioca flour as the binder.

2. To test the thermal stability level of moulding sand with tapioca flour as the binder.

3. To test the collapsibility level of moulding sand with tapioca flour as the binder.

4. To test the reusability level of moulding sand with tapioca flour as the binder.

Rheo-HPDC is a smart manufacture technique in metal casting. One of the crucial aspects of the casting process is the proper preparation of slurry. Based on the development of its equipment, rheo-HPDC involving the self-inoculation method is the latest system and able to improve the quality of the cast products. Compared to the conventional HPDC, the rheo-HPDC resulted in improved mechanical properties such as ultimate tensile strength, yield strength, elongation, hardness, density, and thermal conductivity.

In addition, rheo-HPDC could lead to a homogeneous and uniform microstructure, and reduce porosity. In conclusion, this technique has high productivity and is reliable to produce excellent casts with great precision.

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ПОЛІПШЕННЯ ЯКОСТИ ЛИТТЯ З ВИКОРИСТАННЯМ НОВИХ ЗВ'ЯЗУВАЛЬНИХ ПРИ ЛИТТІ У ПІЩАНУ ФОРМУ ТА КОКІЛЬНОМУ ЛИТТІ ЗА ВИСОКОГО ТИСКУ

Якість литва є чинником досконалости для міряння успішности лиття металу. Однією зі спроб одержати високоякісний ливарний продукт є визначення якости використовуваної формовки у піскувато-глинистої суміші. Ідентифікація якости формування піскувато-глинистої суміші визначається такими характеристиками як твердість, міцність на зсув, розтяг та проникність. У цій статті розглядаються пояснення міцности формовки з піску з композиційною зміною типу зв'язувального: (1) формування з піску, бентоніту, золи виносу та води; (2) пісок виверження гори Келуд, бентоніт і вода; (3) пісок виверження гори Келуд, бруд Сідоарджо та вода; (4) пісок виверження гори Келуд, портландцемент і вода; (5) пісок, вулканічний попіл і вода; (6) зелений пісок, бентоніт, летюча зола та вода; (7) пісок із Маланґу, бентоніт, пудри з тапіоки та саґо; (8) пісок для формовки, бентоніт, портландцемент і вода. Кокільне лиття за високого тиску (зазвичай відоме в англійській літературі як rheo-HPDC) є новим методом лиття у виробництві якісних ливарних виробів. Зростаючий попит на ринку стимулює розробку нової технології, за допомогою якої можна виробляти виливки з чудовими механічними властивостями, хорошою мікроструктурою та незначними дефектами литва. Метод кокільного лиття під високим тиском, що є вдосконаленим способом виливання в кокіль, можна розглядати як розумну технологію виготовляння, оскільки вона узагальнює технологію напівтвердого металу, яка враховує правильне приготування суспензії. Процес приготування гноївки постійно вдосконалюється, і новітнім методом готування є метод самозабруднення. У даній оглядовій статті обговорюються процедура, механізм, розроблення та якість продукції лиття в піскову форму з використанням нових зв'язувальних, а також методи лиття у кокіль за високого тиску.

Ключові слова: якість відливання, формувальний пісок, зв'язувальні, кокільне лиття за високого тиску (rheo-HPDC), інтелектний механізм, алюміній.

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ПОВЫШЕНИЕ КАЧЕСТВА ЛИТЬЯ С ИСПОЛЬЗОВАНИЕМ НОВЫХ СВЯЗУЮЩИХ ПРИ ЛИТЬЕ В ПЕСЧАНУЮ ФОРМУ И КОКИЛЬНОМ ЛИТЬЕ ПОД ВЫСОКИМ ДАВЛЕНИЕМ

Качество литья является фактором совершенства для измерения успешности литья металла. Одной из попыток получить высококачественный литейный продукт является определение качества используемой формовки в песчано-глинистой смеси. Идентификация качества формовки песчано-глинистой смеси определяется такими характеристиками как твёрдость, прочность на сдвиг, растяжение и проницаемость. В этой статье рассматриваются объяснения прочности формовки из песка с композиционным изменением типа связующего: (1) формование из песка, бентонит, зола уноса и вода; (2) песок извержения горы Келуд, бентонит и вода; (3) песок извержения горы Келуд, грязь Сидоарджо и вода; (4) песок извержения горы Келуд, портландцемент и вода; (5) песок, вулканический пепел и вода; (6) зелёный песок, бентонит, летучая зола и вода; (7) песок из Маланга, бентонит, пудры из тапиоки и саго; (8) песок для формования, бентонит, портландцемент и вода. Кокильное литьё под высоким давлением (часто известное в английской литературе как rheo-HPDC) является новым методом литья в производстве качественных литейных изделий. Растущий спрос на рынке стимулирует разработку новой технологии, с помощью которой можно производить отливки с превосходными механическими свойствами, хорошей микроструктурой и незначительными дефектами литья. Являющийся усовершенствованным способом литься в кокиль метод кокильного литья под высоким давлением можно рассматривать как разумную технологию изготовления, поскольку она обобщает технологию полутвёрдого металла, которая учитывает правильное приготовление суспензии. Процесс приготовления навозной жижи постоянно совершенствуется, и новейшим методом подготовки является метод самозагрязнения. В данной обзорной статье обсуждаются процедура, механизм, разработка и качество продукции литья в песчаную форму с использованием новых связующих, а также метода литья в кокиль под высоким давлением.

Ключевые слова: качество отливки, формовочный песок, связующие, кокильное литьё под высоким давлением (rheo-HPDC), интеллектный механизм, алюминий.