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Hardness enhancement of Al-Si alloys from sand casting with runner variations

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ABSTRAK

Pengecoran logam adalah salah satu teknik manufaktur tertua dan paling efisien dalam memproduksi komponen logam dengan bentuk yang kompleks. Salah satu tantangan utama dalam proses pengecoran adalah mengendalikan aliran logam cair sehingga dapat mengisi cetakan secara sempurna tanpa menghasilkan cacat. Saluran dalam cetakan pengecoran biasa disebut dengan runner. Runner berfungsi sebagai saluran distribusi logam cair ke dalam rongga cetakan. Pengaturan desain runner yang optimal sangat penting untuk mencegah terjadinya cacat pada produk akhir seperti porositas, cold shut, dan shrinkage. Penelitian ini bertujuan untuk mengidentifikasi pengaruh variasi bentuk runner terhadap kualitas pengecoran Al-Si. Metode yang digunakan dalam penelitian ini adalah metode eksperimen laboratorium. Penelitian dimulai dengan mempersiapkan alat dan bahan, bahan yang digunakan dalam penelitian ini merupakan piston bekas. Suhu peleburan piston dilakukan pada suhu 750°C. Hasil penelitian menunjukkan bahwa hasil produk cor dengan menggunakan runner berbentuk kerucut terpancung (variasi 1) merupakan hasil terbaik. Analisis struktur makro menunjukkan bahwa spesimen pada variasi 1 memiliki cacat cor yang minimum dan penyusutan yang lebih rendah dibandingkan dengan variasi 2. Analisis struktur mikro menunjukkan produk cor menghasilkan beberapa fasa, yaitu fasa Al dan fasa AlSi. Sedangkan angka kekerasan pada spesimen variasi 1 mencapai 98 HR_E.

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ABSTRACT

Metal casting is one of the oldest and most efficient manufacturing techniques in producing metal components with complex shapes. One of the main challenges in the casting process is controlling the flow of molten metal so that it can fill the mold perfectly without producing defects. The channel in the casting mold is usually called a runner. The runner functions as a distribution channel for molten metal into the mold cavity. Optimal runner design settings are very important to prevent defects in the final product such as porosity, cold shut, and shrinkage. This study aims to identify the effect of runner shape variations on the quality of Al-Si casting. The method used in this study is a laboratory experimental method. The study began with preparing the tools and materials, the materials used in this study were used pistons. The piston melting temperature was carried out at 750°C. The results showed that the results of the cast product using a truncated cone-shaped runner (variation 1) were the best results. Macrostructural analysis showed that specimens in variation 1 had minimum casting defects and lower shrinkage compared to variation 2. Microstructural analysis showed that the cast product produced several phases, namely the Al phase and AlSi phase. Meanwhile, the hardness number for specimen variation 1 reached 98 HR_E.

1. Introduction

Metal casting is one of the oldest manufacturing processes used to shape metal materials into various components. One of the commonly used methods is sandcasting or casting with sand moulds [1]. This process involves making a mould from sand that is shaped according to the desired object pattern, then molten metal is poured into the mould, and allowed to cool until it solidifies [2].

Even though manufacturing technology has advanced rapidly, the sand-casting method remains relevant and widely used today [3]. This is because the use of sand casting requires low costs and is efficient for small to medium scale production. Sandcasting offers relatively low mould costs compared to other casting methods such as die casting. Sand moulds can be created and used without the need for expensive equipment, making it an ideal choice for small to medium-scale production, or when specialized or custom products are required. In the process of developing new products, sandcasting allows rapid prototyping without the need for permanent moulds [4]. In addition, this process can also be adapted for mass production with efficient mould modifications. Sandcasting is ideal for producing large, heavy metal components, such as engine blocks, turbine components, or large construction parts. The mould size can be easily adjusted and can be used for large volumes of molten

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metal. One of the advantages of sandcasting is that the sand used in the mould can be recycled and reused after the casting process. This not only reduces production costs, but also makes the process more environmentally friendly [5].

In the casting industry, one of the metal materials that is often used is Aluminium-silicon (AlSi) alloy [4]. AlSi alloys are used in a variety of industries, such as automotive, aerospace, and machinery manufacturing, due to their combination of strength, corrosion resistance, and excellent casting properties [6]. Metal alloys with special properties, such as AlSi alloys, are often better processed using sandcasting methods because of the sand mould's ability to withstand high temperatures and adapt to the flow characteristics of the molten metal. AlSi alloy has superior properties such as being lightweight, corrosion resistant, and able to conduct heat well, so it is widely applied in automotive components, household appliances, and industrial machines. The combination of aluminium and silicon in this alloy provides good strength and optimal flow properties for the casting process [7].

Sandcasting with AlSi has several advantages, including relatively low mould costs, the ability of sand moulds to withstand high temperatures of molten metal, and flexibility in casting various complex geometric shapes. However, this process also has challenges such as strict mould quality control to avoid defects in the casting results, such as porosity, cracks, and shrinkage [8]. Therefore, a thorough study of the casting process parameters, including sand type, AlSi composition, casting temperature, and cooling method, is essential to ensure optimal product results. In the sand-casting process, the runner is part of the mould channel system that functions to direct the flow of molten metal from the inlet (sprue) to the mould cavity.

The sand mould used in sandcasting consists of drag and cope, while the channels in the casting consist of runner, in gate, and riser [9]. The use of runners is very important because it plays several key roles in ensuring high-quality casting results and reducing the risk of defects in the product. Therefore, this study aims to compare the results of sand casting with the runner variations [10], [11].

2. Experimental procedure

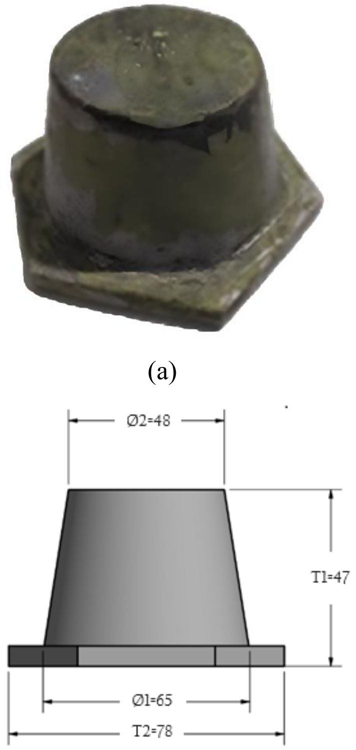
2.1. Material and specimen

The material used in this study is AlSi alloy. The AlSi alloy used in this study is a used piston. The chemical composition of AlSi alloys varies depending on the type and application, but in general, the following are the main components in AlSi alloys that shown in table 1.

Table 1. Chemical composition of AlSi alloy [12]

Material	Weight of elements (%)				
	Al	Si	Mg	Cu	Fe
AlSi Alloy	70-90	5-25	0.5-1.5	0.1-5	<1

The research specimens were formed using an ashtray pattern. The specimens were prepared through a sandcasting process that began with the creation of a casting mold using sand. The sand mold was made from silica sand using a flask consisting of two parts, namely drag and cope. The following are the specimen shapes and dimensions used in this study.



(a) (b)

Fig. 1. Shape of specimen, (a) pattern, (b) dimension of specimen (all units in mm)

The specimen was formed using an ashtray pattern, with a small diameter of 48 mm, and a large diameter of 65 mm, a height of 47 mm, and the top of the ashtray was hexagon-shaped with a diameter of 78 mm.

2.2. Sandcasting process

Sand casting is a metal casting method that uses sand moulds as a container for pouring molten metal. This process is one of the oldest and most common methods in the casting industry because it is relatively inexpensive, flexible, and can be used to create various shapes and sizes of metal components [5]. The sandcasting process diagram is shown in Fig. 1.

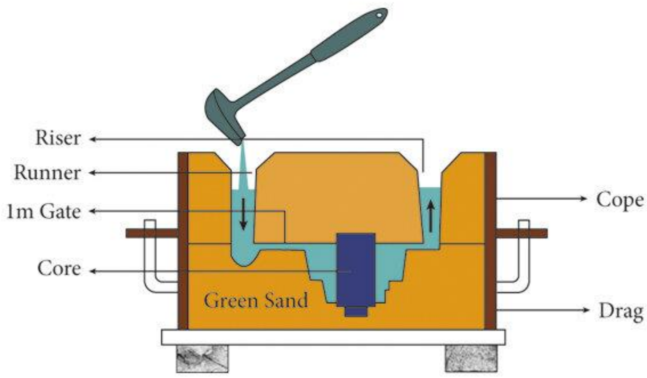


Fig. 2. Sandcasting scheme [9]

The casting process in this study can be described through Fig.3. Fig.3. shows the sandcasting process. The sand mold is made using a variety of runner shapes. The first variation uses a truncated cone-shaped runner, while the second variation uses a semicircular runner. Molding sand consists of small mineral grains or particles and crushed stone. Although the grains can be any mineral composition, the main component of sand is usually quartz, which consists of silicic acid (silica). The making sand mold process needs 15 kg of silica sand with a SiO_2 content of 80% and a bentonite content of 20%. The water mixture we use is 4% of the total weight of the sand.

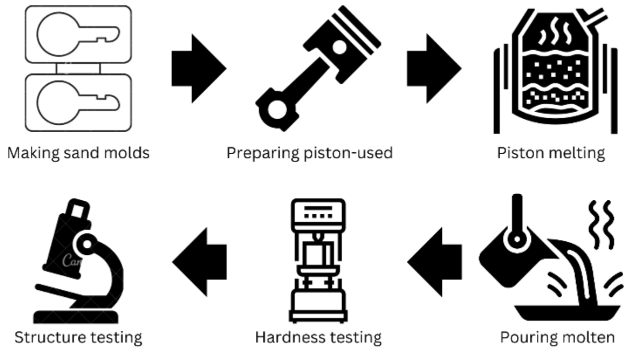


Fig. 3. Sandcasting process

The sand mold is made using a flask. A flask is a frame or box that holds the sand in place when making a mold. The top is called a cope, and the bottom is called a drag. Usually made of wood or metal, it can be round or hexagonal. The square flask measures 20 x 25 x 15 cm and has a volume of 7,500 cm^3. Then prepare silica sand and bentonite with a water content of 4% or 600 ml. The pattern is made by placing the pattern between the drag and cope, which is a solid sand that has been given a runner and raiser on the cope and additional carbon powder.

After the mold is ready, the metal is heated. Heating using a melting furnace, which is a tool used to melt and melt aluminum material in the melting process (casting) or to heat the material in the heat treatment process. The melting furnace used in this study is a type of crucible furnace. The crucible furnace is a cylindrical furnace that is only used to melt cast iron with a capacity of 11 kg. The metal is heated to a temperature of 750ºC and held for 60 minutes to melt the metal. The fuel of this furnace is LPG gas fuel. The content of LPG gas is propane, a three-carbon alkane with the chemical formula C_3H_5 which is in the form of gas under normal conditions.

2.3. Characterization sample

The casting specimens were tested using several types of characterization. Several types of characterization performed on casting specimens are as follows:

1. Hardness test
   Metal hardness testing is one method to determine the resistance of a material to permanent deformation or penetration. In the metal industry, hardness testing is used to measure the strength, wear resistance, and quality of manufacturing processes, including casting and hot working. This study used the Rockwell hardness test method, using the E scale with a major load of 100 kg. The indenter used was a 1/8" steel ball [13].
2. Microstructure test
   Microstructure testing of aluminum casting specimens is an analytical technique used to examine the distribution, size, shape, and composition of microstructural elements in aluminum alloys. This test is essential for assessing casting quality, detecting defects, and understanding how the manufacturing process affects material properties [14]. This test aims to examine the distribution of phases formed during the casting process. Microstructure testing was carried out by preparing the specimen, starting with specimen cutting, polishing, and etching using Keller's Reagent solution. Microstructure observation was carried out at 200x magnification [15].
3. Macrostructure test
   Macrostructure testing on aluminum-silicon (AlSi) alloys from casting aims to examine the internal conditions and macroscopic quality of the material. Unlike microstructure testing which uses high magnification, macrostructure testing uses low magnification or even direct observation to identify material characteristics such as phase distribution, grain size, porosity, cracks, and other casting defects. Macrostructure testing begins with specimen cutting, grinding, and polishing as well as macro etching using NaOH. After the specimen is etched, observations are made either directly with the naked eye, or using a stereo microscope with low magnification (5x to 50x) [16].

3. Results and discussion

The following are the results of sand-casting products. Fig. 4 shows the casting specimens with various runner applications. Fig. 4a is sandcasting specimens with runner variation 1, while Fig. 4b is sandcasting specimens with runner variation 2. The first variation is a specimen that uses a runner with a truncated cone shape, while the second variation is a specimen that uses a runner with a semicircular shape. Visually, the second specimen has more casting defects. The following is the specimen shrinkage data.

Based on Table 2, it is known that the specimens in variation 1 experienced slight shrinkage compared to the specimens in variation 2. The specimens in variation 1 experienced shrinkage of 1.65%, while the specimens in variation 2 experienced shrinkage of 4.23%. Shrinkage in casting is caused by the change in volume of the molten metal as it cools and transitions from the liquid phase to the solid phase. This shrinkage occurs because metals, experience a reduction in volume as the temperature drops [2]. There are several factors that can cause shrinkage in the casting process, which are phase change, uneven cooling, material composition, and mold design [17].

Runners in the casting system serve to flow molten metal from the pouring cup into the mold. The shape and design of the runner have a major influence on the distribution of molten metal, flow rate, and ultimately on the formation of defects such as shrinkage [11]. A good runner shape will ensure even distribution of molten metal throughout the mold. If the runner is not designed properly, for example, too narrow, too short, or has asymmetrical branches, the molten metal may not reach some areas quickly and effectively, causing uneven cooling. Areas that cool more slowly are prone to shrinkage because there is not enough molten metal supply to fill the space that shrinks during solidification [2].

(a)

(b)

Fig. 4. Specimen (a) casting product (variation 1), (b) casting product (variation 2)

Table 2. Shrinkage of cast products

Parameter	Pattern	Var. 1	Shrinkage (%)	Var. 2	Shrinkage (%)
Ø1 (mm)	65	64	1.5	60.5	6.9
Ø2 (mm)	48	47.5	1	46	4.1
T1 (mm)	47	46	2.1	46	2.1
T2 (mm)	78	77	2	75	3.8
Average (%)			1.65		4.23

The flow rate generated by the runner greatly influences the formation of shrinkage. If the flow is too slow, certain parts of the mold may start to freeze before the molten metal has fully flowed. This causes a shortage of molten metal in areas that are slower to freeze, resulting in shrinkage. On the other hand, too fast a flow can cause turbulence, which traps air and increases the risk of voids [18]. The runner that designed with improper cross-sectional variations, the flow of molten metal can become too slow or too fast, causing shrinkage at critical points. Runner shape variations in casting have a direct impact on the risk of shrinkage. A good runner design must consider even distribution of molten metal, appropriate flow rate, and optimal pressure and cooling settings. With the right runner shape, the risk of shrinkage can be minimized, resulting in better quality castings [10], [19].

3.1 Analysis of AlSi macrostructure

Macro characterization of AlSi alloy castings is essential for evaluating the quality of final products in the casting industry. Macro characterization involves the analysis of structures that can be observed with the naked eye or using low-magnification tools [20]. Below are presented the results of testing the Al Si macrostructure resulting from the sand-casting product that taken from several points.

(a)

(b)

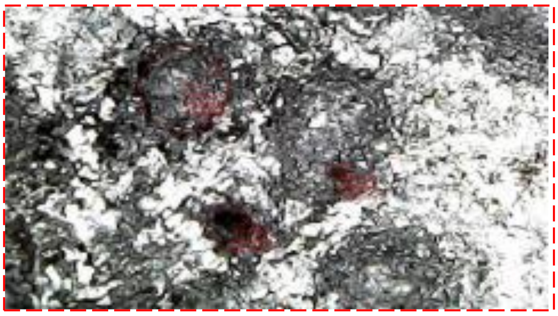
(c)

Fig. 5. Specimen with variation 1 (a) first point, (b) second point, (c) third point.

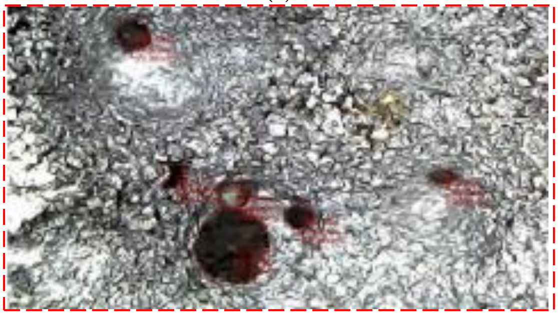
Fig. 5. is the result of macrostructure testing on specimen variation 1. Based on the observation results, a rough surface was found on several sides of the cast product. The surface of the AlSi casting results can be examined to determine the quality of the resulting surface. High surface roughness indicates defects in the mold or imperfections in the casting process, such as molding sand sticking or irregularities in the flow of molten metal.

Figure 6 shows the results of macro testing on specimen variation 2. Based on the observation results, it was found that there were several pores in one part of the cast product. Porousness is a defect that often occurs in metal castings, including AlSi. Macro porosity can be seen as holes or gaps on the metal surface. Porousness can be caused by shrinkage during solidification or by gas trapped in the molten metal. High porosity reduces the strength and fatigue resistance of the material.

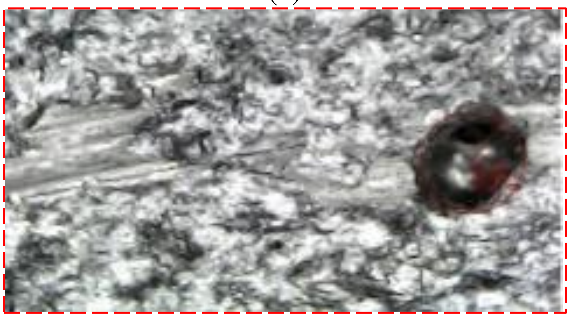
Runner shape variations in the casting system directly affect the macrostructure characterization of the casting results. Macrostructure includes aspects such as grain size, phase distribution, porosity, and casting defects such as shrinkage or cracks. The optimal runner shape will ensure an even distribution of the molten metal throughout the mold cavity. This is very important because uneven distribution of the molten metal can cause non-uniform cooling, which then affects the grain size and shape in the macrostructure [21].



(a)



(b)



(c)

Fig. 6. Specimen with variation 2 (a) first point, (b) second point, (c) third point.

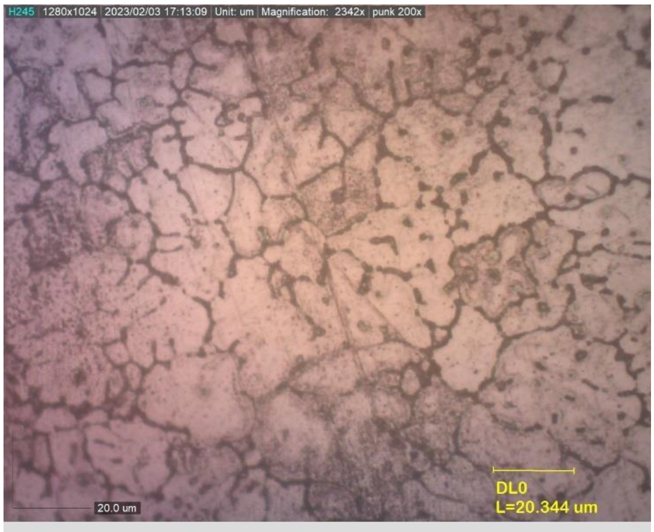
A good runner shape (e.g. convergent or laminar flow) ensures a more consistent flow of molten metal and an even distribution. This promotes the formation of a more uniform grain structure. A bad runner shape (too narrow, unevenly branched, or with sharp bends) can result in areas being under-supplied with molten metal, creating large variations in cooling. This can lead to the formation of a non-uniform grain structure, with fine-grained areas where solidification occurs quickly and large grains where cooling is slower [22].

Variations in the distribution of molten metal flow produced by the runner shape will affect the cooling pattern, which in turn affects the grain structure. Large grains tend to form in areas of slow metal flow or delayed solidification, while small grains usually form in areas of rapid cooling [23]. As discussed earlier, shrinkage can occur if the molten metal supply is inadequate during solidification. Bad runner shape can result in suboptimal molten metal supply, especially to parts of the mold further away from the center of metal flow. This leads to the formation of macro porosity and shrinkage in these areas [24].

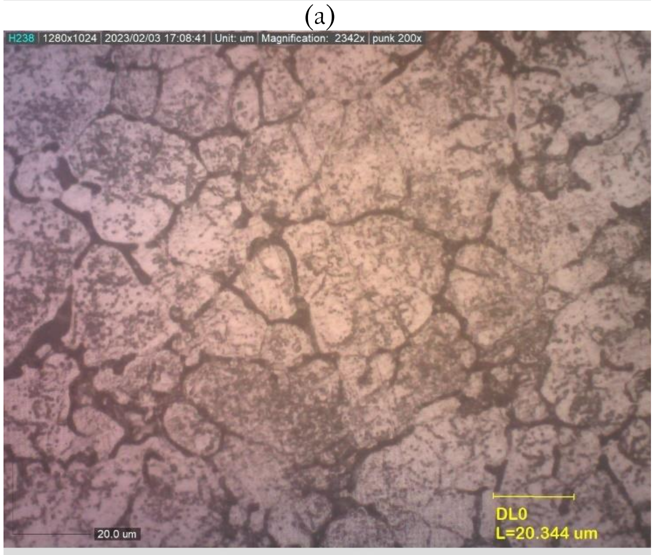
Runner shapes that cause uneven molten metal flow, such as being too long or branching asymmetrically, will result in parts of the mold receiving more molten metal, while other parts are under-supplied [1]. This leads to shrinkage and porosity in certain areas. Slow or irregular flow can cause partial solidification before the entire mold is filled, which will result in porosity and shrinkage in areas that are not receiving enough molten metal. Shrinkage and macro porosity are visible in the macrostructure as large cavities or voids. This affects the integrity of the overall macrostructure, making the material more susceptible to cracking or mechanical failure [11].

3.2 Analysis of AlSi microstructure

Below are presented the results of testing the Al Si microstructure resulting from the sand-casting process with a variety of runner applications.



(a)



(b)

Fig. 7. Microstructure of AlSi (a) variation 1, (b) variation 2.

The microstructure of AlSi alloy is presented in Fig. 7. Runner shape variations in the casting system have a significant effect on the microstructure of the resulting AlSi (aluminum-silicon) cast products. The microstructure of AlSi includes the distribution and morphology of aluminum (α-

Al), silicon (Si), and other eutectoid particles that are greatly influenced by the cooling rate and distribution of the molten metal during casting [25].

AlSi alloys consist of an α-Al matrix (aluminum phase) and Si particles dispersed within it [1]. Variations in runner shape can affect the distribution of these phases through differences in flow and cooling rates. Runners that support uniform molten metal flow will result in more consistent cooling, allowing the formation of microstructures with uniform silicon distribution. Bad designed runners (e.g., uneven or too narrow cross-sections) can cause uneven distribution of molten metal, where some areas cool faster or slower, resulting in non-uniform distribution of the silicon phase. This can cause silicon particles to collect in certain areas (micro segregation), which affects the mechanical properties of the material. Variations in molten metal distribution due to improper runner shape can cause Si phase segregation, where silicon particles can become coarse and concentrated in one place. This can reduce tensile strength and wear resistance [4].

One of the important characteristics in the microstructure of AlSi is the size and shape of the silicon particles. The morphology of silicon particles is strongly influenced by the cooling rate: at high cooling rates, silicon tends to form in the form of fine needles or globules, while slow cooling rates produce larger and coarser silicon particles. Runner shapes that allow for laminar flow and even temperature distribution help create a microstructure in which silicon particles form with smaller and more uniform sizes [22]. Suboptimal runners (e.g. with sharp bends or drastic changes in cross-section) can cause turbulent flow or uneven flow rates. Slower cooling sections will form larger and coarser silicon particles, which can be detrimental to the mechanical properties of the final product. This results in microstructure, which results in large and coarse silicon particles due to slow cooling or inconsistent molten metal flow, resulting in a more brittle microstructure that is less resistant to fatigue or deformation [26].

In AlSi alloys, the eutectoid structure is formed from the interaction between α-Al and silicon during solidification. The formation of this eutectoid structure is strongly influenced by the cooling rate, which in turn is influenced by the runner shape. Runners that support fast cooling rates produce eutectoid structures with finer and more evenly distributed particles [27]. Rapid cooling rates prevent the growth of large grains and maintain a uniform phase distribution. Runners that cause slow cooling rates or uneven distribution of the molten metal will cause the growth of larger and coarser eutectoid grains. This coarse eutectoid structure can cause a decrease in mechanical properties, such as hardness and wear resistance. Eutectoid structures with large grains formed due to slow cooling rates can reduce the hardness of the material [22].

Grain size in AlSi alloys is affected by the cooling rate during the casting process. Variations in runner shape will affect how cooling occurs in different parts of the mold, thus affecting the grain size that is formed [28]. Runners that distribute the molten metal evenly will allow for more controlled solidification, resulting in smaller, more uniform grains. Runners that are too narrow or have sharp bends can cause the molten metal to pool in certain areas, causing those parts to cool more slowly. This can result in larger, more non-uniform grains [3].

The variation of runner shape in AlSi alloy casting has a great influence on the microstructure of the casting. A good runner design can ensure uniform molten metal flow, controlled cooling, and reduce defects such as porosity or shrinkage [29]. With optimal cooling distribution and molten metal flow, the resulting microstructure will be more uniform, with good phase distribution, small grain size, and fine silicon particle morphology, all of which contribute to improving the mechanical properties of AlSi cast products [17].

3.3 Analysis of AlSi hardness test

The following are the results of hardness testing on AlSi alloys from casting with variations in runner application.

Table 3. Hardness test result

Specimen	Test point					Average
	1	2	3	4	5	(HR_E)
Var. 1	99	97	98	97	99	98
Var. 2	86	83	87	82	85	84.6

Table 3 shows the results of hardness testing on cast products with variations in runner shapes. Testing using the Rockwell test method was carried out at 5 points, and an average of 98 HRE was obtained on specimen variation 1, and 84.6 HRE on specimen variation 2. Runner shape variations in the AlSi casting process greatly affect the hardness of the cast product. Hardness is one of the important mechanical properties influenced by the distribution of molten metal flow, cooling rate, and microstructure formed during solidification.

A good runner design can affect the cooling rate of the molten metal in the mold. A faster cooling rate will result in a microstructure with finer grains, a more uniform distribution of the silicon phase, and smaller silicon particles. This microstructure directly contributes to increased hardness. A well-designed runner allows for even distribution of the molten metal and faster cooling throughout the mold. This results in fine grains and fine silicon particles, which increase the hardness of the casting [30]. A runner that causes restricted or uneven molten metal flow (e.g., too narrow or too branched) can slow the cooling rate in some areas. Slower-cooling areas tend to form large grains and coarse silicon particles, which decrease the hardness of the casting. A rapid cooling rate from a good runner will result in a casting with higher hardness. Conversely, slow cooling leads to large grains and coarse particles, which decrease hardness [31].

In AlSi alloys, the silicon phase is the hard component that contributes significantly to the hardness of the product. Variations in the runner shape affect how the molten metal flows and solidifies, which in turn affects the distribution of the silicon phase [32]. A runner that distributes the molten metal evenly can allow the silicon particles to be dispersed uniformly in the aluminum matrix, resulting in an even distribution of hardness throughout the product. With a uniform distribution of silicon due to a good runner, the hardness of AlSi cast products will be more consistent. If the silicon is not distributed evenly, the cast product will have a large variation in hardness, with some parts being harder than others [26].

This is related to the previous discussion. The grain size in the microstructure of AlSi alloys is affected by the cooling rate, which in turn is affected by the runner shape. Smaller grains tend to increase hardness because they offer more grain boundaries, which act as barriers to plastic deformation. Runners that can support uniform flow distribution will produce finer grains due to uniform cooling. Fine grains strengthen the material and increase hardness, and vice versa. Fine grains resulting from good runner design will increase hardness. Conversely, large grains resulting from slow cooling will decrease the hardness of the casting product [14], [33].

4. Conclusions

Based on the research results, it can be concluded that variations in the runner shape in the sand mold can affect the quality of the casting results. The best results were obtained in variation 1, which is a variation that uses a runner with a truncated cone shape. The results of the macrostructural characterization showed that the specimens in variation 1 experienced shrinkage and had minimal casting defects. This is supported by microstructure tests and hardness tests. Microstructure testing showed that the specimens in variation 1 had a denser structure compared to the specimens in variation 2 which found several porosity points. Meanwhile, the phases formed in each specimen were the Al phase and the AlSi phase with finer grains in variation 1. This is in line with the results of the hardness test which showed that variation 1 had a hardness number 13.4% higher than the specimens in variation 2.

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