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COMPARISON OF THE HARDNESS VALUE AND MICROSTRUCTURE OF Al6061 IN HORIZONTAL CENTRIFUGAL CASTING WITH AND WITHOUT MOLD COOLING

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The object of this research is the horizontal centrifugal casting process of the Al6061 alloy. Usually, cast products experience some casting defects, so the horizontal centrifugal casting process is applied to reduce the possibility of casting defects arising. In some casting processes, especially in the production of cylindrical specimens, casting defects such as porosity are encountered. Therefore, horizontal centrifugal casting was applied to overcome this problem. The test results show that the average hardness value for aluminum 6061 specimens resulting from centrifugal casting products with water cooling was 73.3 HR_E, while the average hardness value for aluminum 6061 specimens resulting from centrifugal casting products without water cooling was 86.4 HR_E. The microstructure results show that the grain size of centrifugal casting products with water cooling was 82.5 μm, whereas without water cooling it was 75 μm. Higher hardness values were obtained in specimens without mold cooling, this is because the conductivity in molds without cooling was higher compared to molds that experienced water cooling. The higher the heat conductivity of the mold, the faster the cooling process of the cast product. The casting process using the horizontal centrifugal method can be carried out to produce cylindrical spare parts

Keywords: metal casting, horizontal centrifugal casting, mold cooling, hardness, microstructure, Al6061

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1. Introduction

Aluminum alloy is one of the materials widely used in the industrial field and its application is steadily increasing [1], including in automotive, aerospace, and marine engineering [2]. Much research about aluminum alloy has been conducted on centrifugally cast products manufactured from aluminum alloy [3]. Aluminum is a soft metal with an attractive appearance, light weight, corrosion resistance, relatively high heat and electrical conductivity, and is easy to shape into other metal properties [4]. A mixed material that has metallic properties, consisting of two or more elements. (incomplete sentence) The mechanical strength of aluminum can be increased by adding alloying elements such as Cu, Mg, Zn, Mn, and Ni. The Cu element in the Al alloy will increase the mechanical properties, which is hardness [5].

Metal casting is a manufacturing method where the main material used is liquid metal. The aim of the mold is to produce products according to the desired needs. Metal casting is a process where solid metal is melted and then poured into a formed mold, or cavity with the desired shape. These molds can be made from metal, sand, and ceramic [6]. Centrifugal casting is a casting process that uses a mold that is rotated so that centrifugal force spreads the liquid metal to the walls of the mold cavity until solidification occurs [7]. In the centrifugal casting process, there is no core, this method is typically used to make cylindrical pipes or cylindrical products, and it also has the advantages of low porosity, solid casting structure and high productivity to produce cylindrical products [8]. Apart from that, the disadvantages of centrifugal casting itself are uneven thickness distribution, unequal structure due to uneven freezing, cracks appearing in the castings due to rotation being too high, and less dense structure due to rotation speed being too low. These disadvantages can be minimized by adjusting the mold rotation speed, temperature and tilt angle [9]. The quality of casting results depends on several parameters, for example, pouring temperature, mold temperature, rotation speed, composition, etc. [10]. Centrifugal casting can be one of the options for low-cost alloy manufacturing [11].

Much research has been carried out related to centrifugal casting. This is because the practice of metal casting by the centrifugal method is still widely used today, especially in Indonesia [12, 13]. There are several foundry industries in Indonesia, which produce ship spare parts, automotive spare parts, sugar processing machine spare parts and coconut oil processing machine spare parts.

Research on the topic of metal casting is still relevant today. Material technology continues to develop, including new metal alloys and more sophisticated casting methods. Research is needed to develop materials that are stronger, lighter, or more resistant to corrosion, as well as to improve the efficiency of the casting process. Metal casting is an important process in the manufacturing industry, especially for machine, automotive, and heavy equipment components. Research can lead to more efficient casting techniques, which can reduce production costs, improve product quality, and reduce waste.

Therefore, research related to casting of aluminum alloys by various methods aimed at improving the mechanical properties of aluminum alloys is of scientific relevance.

2. Literature review and problem statement

This paper presents the results of research related to centrifugal casting. Several studies have shown that using the centrifugal casting method can improve the quality of cast products compared to using the conventional gravity casting process [7]. This can happen because in centrifugal casting the liquid metal fills all the mold gaps, which causes the workpiece to have a high density.

The key process parameters include mold rotation speed, G factor, pouring temperature, and mold pre-heating temperature. Horizontal centrifugal casting machines are typically employed to produce pipes, tubes, bushings, and cylinder liners. In contrast, vertical centrifugal casting machines have a much broader range of applications, such as manufacturing gears, pulleys, wheels, impellers, rotors, brackets, and more [10]. Casting by the centrifugal method is very effective for producing various components with cylindrical shapes. In centrifugal casting, the quality of the workpiece depends on several parameters [14]. The final workpiece quality is affected by differences in pouring temperature and mold rotation speed. This can be proven by characterization of the resulting workpiece, which can be seen from its mechanical strength and microstructure.

Several previous studies carried out variations of centrifugal casting parameters, for example, by conducting centrifugal casting horizontally and vertically [3]. The difference in the rotation axis of centrifugal casting is based on the shape of the specimen to be made. Apart from that, there are other parameters that are often varied by researchers, including pouring temperature and initial mold temperature [14–16]. Some studies show that the higher the pouring temperature, as well as the higher the initial mold temperature, the better the mechanical properties will be. However, this result is inversely proportional to the varying rotation speed [17]. The slower the mold rotation speed, the lower the resulting mechanical properties. Of course, this must be tested further to prove that there is an increase or decrease in mechanical properties for each variable parameter.

The paper [18] considers the development of other centrifugal casting methods in sample formation. The centrifugal slip casting method was used to produce samples. This method allows the production of finished products in the form of sleeves by combining the classic slip casting method with the simultaneous action of centrifugal force. One of the main advantages of centrifugal slip casting over traditional methods such as slip casting or injection molding is the reduced production costs for advanced ceramic components with tubular shapes. The use of the centrifugal casting method is due to its efficiency so it can reduce manufacturing costs.

Some of the studies mentioned above investigated the preheating parameters of the mold. Improper casting temperature can cause product defects. So research by cooling during the casting process has not been done.

Cooling of the mold during the casting process has not been encountered in the studies related to centrifugal casting above. Therefore, this study aims to compare the hardness value and microstructure of the Al6061 alloy in the horizontal centrifugal casting process with and without air cooling variations. The hardness value and microstructure formed are interrelated and influenced by the cooling rate.

All this allows us to assert that it is expedient to conduct a study on casting of the Al6061 alloy using the horizontal centrifugal casting method.

3. The aim and objectives of the study

The aim of the study is to compare the hardness value of Al6061 through cooling variation of the horizontal centrifugal casting mold. This will allow determining the correlation between the hardness value of the casting product and the microstructure formed.

To achieve this aim, the following objectives were set:

– to conduct the horizontal centrifugal casting process with certain parameters;

– to perform the hardness test on the casting product;

– to carry out microstructure tests on the casting product.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study was the horizontal centrifugal casting process on the Al6061 alloy. The casting process is carried out by performing two treatments. The first is to cool the mold during the process using water. While the second process does not cool the mold. The main hypothesis of the study was that cooling the mold with water during the horizontal centrifugal casting process can affect the casting results, both in terms of mechanical properties or minimizing casting defects. The assumption made in this study is that by cooling in the casting process, it is expected that the cast product will experience increased hardness and reduced product defects. The simplification adopted in the work is to carry out cooling during the casting process.

4. 2. Research methods

The methods used in this research were experimental-laboratory scale, conducted in the Material Testing Laboratory of Universitas Merdeka Malang. The material used in this research was Aluminum Alloy 6061. The research started with the preparation of materials and tools, and then the casting process was conducted. The casting product was tested for its hardness and microstructure, and the result was analyzed descriptively. The following were the procedures of research.

4. 2. 1. Casting mold preparation

The mold on the centrifugal casting machine that will be used is a permanent mold type shown in Fig. 1. This mold is a metal mold with ST-37 material. The mold used in the centrifugal casting process has an outer diameter of 90 mm, an inner diameter of 78 mm, and a length of 100 mm. The inside of this mold also has a regulator or adjuster, which functions to control the length or volume of the cast product according to the casting specimen planning [9].

Fig. 1 shows a casting mold used in this research. Fig. 1, *a* presents a permanent mold that has been made, while Fig. 1, *b* is an initial design that has been determined. The horizontal centrifugal casting process uses a machine that was designed and built by students from the Department of Mechanical Engineering, Universitas Merdeka Malang, shown in Fig. 2.

The specifications of the centrifugal casting machine are shown in Table 1 below.

Centrifugal casting process stages:

1. Metal smelting process.

After checking the machine and preparing the equipment in this process, the material has been cut and weighed using a digital scale according to the weight of the material that has been planned for the cast specimen. The aluminum is melted until it is liquid using a heating furnace with a melting temperature of 800 °C, at a mold rotation speed of 1,240 rpm.

2. Motor rotation speed setting.

The centrifugal casting process is carried out using a mold rotation speed of 1,240 rpm at a melting temperature of 800 °C. In this process, the rotation of the electric motor is adjusted using a motor rotation speed control tool and to read the motor rotation speed, a digital rotation speed reader (tachometer) is used.

3. Mold and inlet pre-heating.

The process of heating the mold and inlet (pre-heating) is carried out to reduce the occurrence of too high a temperature difference with the molten metal during the process of pouring the molten metal into the mold. Pre-heating of the mold and inlet (pouring) is carried out using a welding blender to a temperature of 300 °C.

4. Molten metal pouring.

After carrying out the process of melting the metal, setting the rotation speed, and heating the mold and inlet, the liquid metal pouring process is performed. In this process, the liquid metal is poured through the inlet into the mold. The process of pouring molten metal is carried out while the mold is rotating.

5. Cast object cooling process.

In this cooling process, the outer surface of the mold is cooled with water, then the liquid metal that has entered the mold cavity will be allowed to rotate in the mold for 2 minutes until the liquid metal in the mold cooled. Apart from that, there are molds without using water cooling.

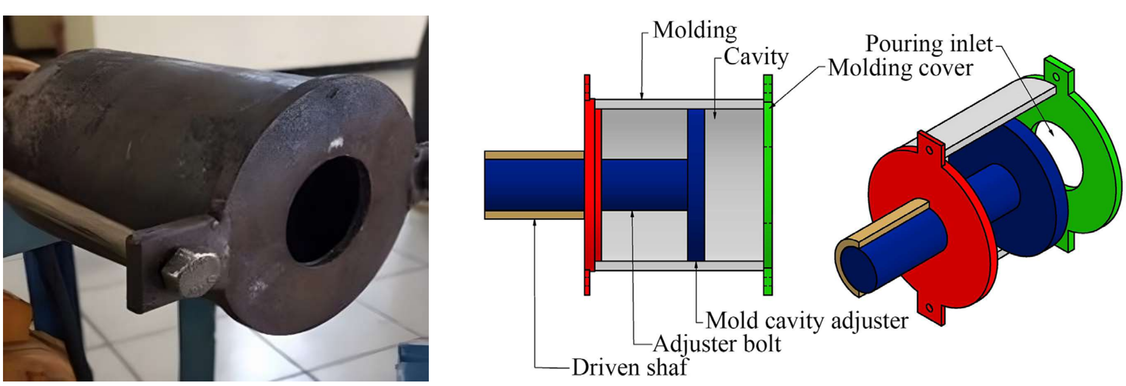
6. Casting results dismantling process.

This is the process of releasing the cast product or the casting specimen has been cooled and solidification occurs. In this process, the mold rotation is stopped, and the cast specimen is removed from the mold.

Table 1

Specifications of the horizontal centrifugal casting machine

No.	Component	Dimensions
1	Machine frame	Length: 370 mm
		Width: 280 mm
		Height: 480 mm
2	Drive	Electrical motor
		Rotation: 1,420 rpm
		Power: 220 V
3	Mold	Material: ST-37 Steel
		Outer diameter (*D*): 90 mm
		Inner diameter (*D*): 78 mm
		Length: 100 mm
4	Mold rotation speed	1,420 rpm
5	Transmission type	Transmission: belt
		Drive pulley diameter: 86 mm
		Driven pulley diameter: 51 mm



a *b*

Fig. 1. Casting mold: *a* — permanent mold; *b* — design

Fig. 2. Horizontal centrifugal casting machine

4. 2. 2. Hardness test

The hardness testing carried out in this research used the indentation method, namely hardness testing using the Rockwell method. Before hardness testing by the Rockwell method, preparation of the material to be tested is carried out. Preparation of the material to be tested for hardness using the indentation method (Rockwell), namely, cutting the specimen to a small size according to the cross-sectional size of the indent holder. After cutting the specimen to be tested, a sanding process is carried out to produce a flat specimen surface. After the surface of the specimen becomes flat, it will then be tested using a hardness testing tool, which is the Hardness Testing Machine. In testing the hardness of cast specimens according to the HR_E scale, 1/8" ball indenter type with a major load of 100 kg is used.

4. 2. 3. Microstructure test

After the casting process has been carried out and produced a cast product, the cast product is subjected to microstructure testing. This microstructure testing uses an optical microscope. The specification of the optical microscope used to test the microstructure of the casting product was Nikon Eclipse LV100ND. Specimens were prepared by polishing and etching using standard E407-07 hydrofluoric Acid solution (0.5 %) as dissolved and water (95 %) as a solvent, then the test was conducted at 200x magnification. The observation result was tested by planimetry methods (Jeffries).

This planimetric method uses a circle, which generally has a circle area with a diameter of 8 cm [19]. The grain size is calculated by multiplying the number of grains by the Jeffries multiplier (f) and determining the average grain diameter by adjusting the G value in the ASTM E-112 reference table. The grain size calculation formula used in the planimetry method:

$$Na = f\left[n_1 + \frac{n_2}{2}\right], \quad (1)$$

$$G = \left[3.32\log(Na) - 2.95\right], \quad (2)$$

where:

– G – the grain size is referred to the ASTM E-112 table to find the grain diameter value (μm);

– Na – the number of grains;

– n_1 – the number of grains in the circle;

– n_2 – the number of grains that intersect with the circle;

– f – excavation factor in the Jeffries table.

5. Results of the casting product and its characterization

5. 1. Casting product of Al6061

Fig. 3 shows the results of cast products made from the Al6061 alloy, Fig. 3, *a* demonstrates the results of cast products with mold cooling using water, while Fig. 3, *b* presents the results of cast products without mold cooling. At first glance, there is no visual difference between the two. However, the hardness test results show that cast products without mold cooling have a higher hardness value compared to cast products with mold cooling by water.

a

b

Fig. 3. Casting Product of Al6061: *a* – with mold water cooling; *b* – without mold water cooling

Fig. 3 shows the result of horizontal centrifugal casting. Fig. 3, *a* gives the result of casting with cooling the mold by water during the casting process, while Fig. 3, *b* presents the result of casting without cooling. At first glance, there is no striking difference. However, in the water-cooled specimen (Fig. 3, *a*), there are lines on the outer surface, which are defects in the casting product. This is likely due to rapid cooling when the water is poured. Meanwhile, in Fig. 3, *b*, the casting defect is in the form of a pinhole defect, which is characterized by small holes in several parts.

5. 2. Hardness test results

Hardness testing was carried out using a Rockwell Hardness Tester type machine, which is included in the ASTM test standard, and the Rockwell index, E scale, major load of 100 kg, for the 1/8" ball indenter type on the test specimen, namely Aluminum 6061. In the casting process, horizontal centrifuges with water cooling in the mold and without water cooling in the mold were used.

Table 2 shows the results of hardness testing of cast products using the Rockwell hardness testing method.

Table 2 shows that the hardness of cast products with mold cooling using water is lower than that of cast products without water cooling. Where the hardness of cast products using water cooling in the mold reaches 73.8 HR_E, while the hardness of cast products without cooling in the mold reaches 86.4 HR_E. This means that the hardness value of cast products without cooling in the mold is 17 % higher than that of cast products with water cooling in the mold.

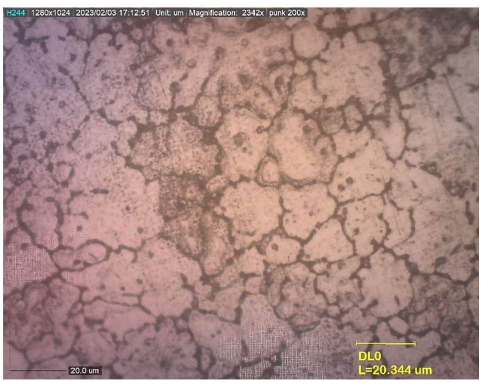
Table 2

Hardness test results

Specimens	Hardness Value (HR_E)					Averages (HR_E)
	Point					
	1	2	3	4	5	
Water cooling	71	72	71	77	78	73.8
Without cooling	85	88	83	88	88	86.4

5. 3. Microstructure test results

Fig. 4 shows the results of microstructure testing on cast Al6061 alloy products, where Fig. 4, *a* displays the microstructure of the Al6061 alloy with water cooling in the mold, and Fig. 4, *b* demonstrates the microstructure of the Al6061 alloy without cooling in the mold. Visually, it can be seen that the grain size in Fig. 4, *b* is smaller and denser than in Fig. 4, *a*.



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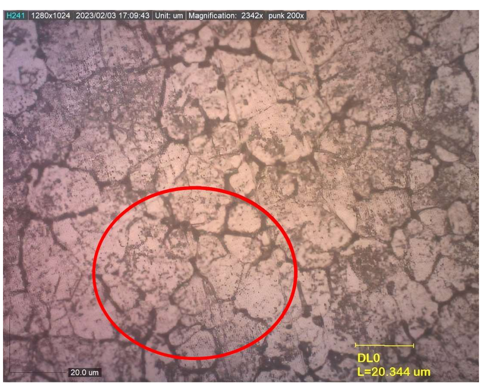

b

Fig. 4. Microstructure of Al6061: *a* – with mold water cooling; *b* – without mold water cooling

Through calculations using the Jefferies method, the data obtained are shown in Table 3.

Table 3

Grain size of Al6061

Specimens	*G* value	Averages (μm)
Water cooling	4.25	82.5
Without cooling	4.0	75.0

The Jefferies method in microstructure calculations is a technique used in the field of metallurgy to analyze and calculate grain size in materials. The results of calculations using the Jeffries method are given in Table 3. The calculation results show that the grain size in the specimen with mold cooling is 82.5 μm, while in the specimen without mold cooling it is 75 μm. This grain size is important because it affects the mechanical properties of the material, such as strength, toughness and ductility.

6. Discussion of the casting product and its characterization

Casting of the Al6061 alloy is carried out using the horizontal centrifugal casting method with a rotational speed of 1,240 rpm at a melting temperature of 800 °C. The casting product can be seen in Fig. 3, showing that there are different types of casting defects. In Fig. 3, *a*, there is a line defect, while in Fig. 3, *b*, there is a pinhole defect. However, there is not many product defects in both specimens. Based on Table 2, it can be seen that the hardness value of horizontally centrifugally cast products with water cooling in the mold is lower compared to cast products without mold cooling. The hardness value for the specimen with water cooling in the mold was 73.3 HR_E, while the hardness value for the specimen without mold cooling reached 86.4 HR_E. Cast products without mold cooling have a 17 % higher hardness. This is in line with previous research, where the results of quenching the Al6061 alloy in water media experienced a decrease in hardness of 13 % compared to raw material, which ranges from 98 HR_E to 84.6 HR_E [20].

Molding with higher temperatures produces higher hardness. This is consistent with previous research, where the highest hardness values for centrifugally cast products were obtained at the highest molding temperatures of variations 100, 200, and 300 °C [10]. Meanwhile, other researchers had different results, where the highest physical and mechanical properties of the aluminum alloy were obtained at lower mold temperatures [15].

Other research shows slightly different results. The hardness value of the Al6061 alloy is influenced by the cooling rate with variations in the coolant (water, dromus, and radiator coolant). The Al6061 alloy goes through a casting process at a temperature of 700 °C, is poured into the mold and held for 40 seconds, then cooled using a variety of cooling media. The results show that the highest hardness value was obtained in the specimen with variations of quenching with water cooling media, namely 68.6 HR_B, while the lowest hardness value was obtained in specimens with variations of quenching with radiator coolant cooling media, namely 62.8 HR_B [16].

Other research related to the effect of mold rotation speed in horizontal centrifugal casting without cooling on the hardness value of the Al6061 alloy shows that hardness tends to increase with increasing mold rotation [17]. Meanwhile, the hardness of the Al6061 alloy through the horizontal centrifugal casting process decreases as the melting temperature increases [18]. This is supported by the results of the microstructure test in Fig. 4, showing that the grain size of the cast product with water cooling in the mold is larger than that of the cast product without cooling. Of course, this is related to fact that high hardness values are possessed by materials with relatively small grain sizes [19].

After carrying out a microstructure test to determine the grain size of aluminum through analysis using the Jeffries method (1), (2), it was found that the grain size was different on each part of the aluminum 6061 surface, due to different cooling in the centrifugal casting process [20]. The results of the microstructure analysis show that the number of grains and grain size of the products obtained in centrifugal casting with water cooling in the mold obtained a *G* value of 4.25 with an average grain size of 82.5 µm, while molds without water cooling obtained a *G* value of 4.5 with an average grain size of 75 µm, as can be seen in Table 3. The microstructure resulting from horizontal centrifugal casting tends to be more uniform.

The grain size of horizontal centrifugal casting at a mold rotation speed of 1,240 rpm with a melting temperature of Aluminum 6061 at 800 °C shows that horizontal centrifugal casting with water cooling in the mold has a larger grain diameter, while molds without water cooling have a smaller grain size. The effect of cooling on the mold is different from the influence of the mold rotation speed, which shows that the higher the mold rotation speed, the smaller the grain size [17], while the effect of melting temperature on grain size shows that the higher the melting temperature, the larger the grain size [18].

There is other research that supports the results of this study, where the lower mold rotation speed can affect the microstructure formed. This means that if the rotating speed is lowered, it is decreased. The results of this research show that a lower mold rotation speed reduces the grain size [11]. These results are also in line with other research related to the impact of centrifugal casting on the wear of aluminum alloys, where the best results were obtained on specimens with lower rotational speeds [3].

The results of this research show that the impact of water cooling in the mold in the horizontal centrifugal casting process on the hardness and microstructure of the Al6061 alloy lies in a reduction of the hardness value and an increase in the grain size. This is thought to be because cooling has occurred more quickly during the casting process. Thus, specimens with water cooling in the mold are more ductile compared to specimens without cooling.

The limitation in this research is that the centrifugal casting machine that was made was not equipped with a rotational speed controller. If it is equipped with a mold rotation speed controller, it can be seen whether variations in this parameter affect changes in the mechanical properties of the cast product. Meanwhile, the weakness in this research is the lack of specified parameters, for example, the initial temperature in the mold and the pouring temperature. Since this study only determined one parameter, namely the mold cooling ratio during the horizontal centrifugal casting process, the research results were very limited.

The disadvantage of this research lies in the mold cooling parameters during the casting process. Providing mold cooling treatment during the casting process is not able to increase the mechanical strength of the material, so for subsequent research, this parameter can be omitted. Development of centrifugal research can be carried out on other parameters, or additional reinforcing material can be provided with the aim of improving the mechanical properties of the material.

Practically, the casting process using the horizontal centrifugal method can be applied in the industrial world, to reduce casting defects on the specimen surface.

7. Conclusions

1. This research was successful in carrying out the centrifugal casting process using a machine designed and built by ourselves. The casting results look neat at a glance and there are no visible casting defects.

2. The hardness value for the specimen with the variation without cooling was 17 % higher compared to the specimen that underwent a water cooling process during casting. The hardness of cast products can be increased by determining several other centrifugal casting parameters, including pouring temperature and mold rotation speed.

3. Microstructure testing supports the hardness testing results, shown by calculations using the Jeffries method, where the grain size of the specimen without mold cooling is smaller. Characterization of the microstructure can be improved using other methods such as SEM.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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