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Escalation of Capacity and Quality PS60 Casting Production by Gating System Modification

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Abstract— **A ship tank's ventilation pipes protector, called PS60, is produced by an investment casting process using CF8M material. Shorter time production for PS60 products occurred due to the rise of PS60 demand, resulting in non class casting product quality. Reported that 15% of PS60 defective products were shown from each production group. Porosity defects are the most common defects found. Recalculating riser's, runners's, and ingates's dimensions, then remodeling designs a mold gating system done in order to reduce the percentage of defective products and increase production capacity. Remodeling gating system and casting simulation done by ProCast 2018 software using New Advanced Porocity Module (NAPM). The casting simulation output was porosity defect's location and percentage, which were further analyzed. The product produced using a mold Gating system with a new layout, had 314.73 cm3 of empty part in the mold cavity which was identified as a porosity defect which was 4.58% of the total volume of the cast product. The total value of the porosity after remodeling decreases by 2.39% from the existing product. 93.3% of the cavity inside the product is categorized as macroscopic porosity defects that are centralized in the riser and pouring basin areas, where in the casting product finishing process, these areas will be removed. Modification of the Gating System in PS60 mold escalates twice of PS60 capacity production than the origin.**

Keywords—Invesment Casting, Stainless Steel, Porosity, ProCast 2018

I. INTRODUCTION

The manufacturing industry contributed greatly to Indonesia's economic growth of 7.07% in the first quarter of 2021, in the second quarter of 2021 it experienced growth of 6.91% despite pressure from the covid 19 pandemic, while in the third quarter of 2021 the manufacturing industry grew by 3.68% and contributes 0.75% to economic growth in Indonesia. A product for protecting ventilation pipes in ship tanks, called PS60, is produced by a casting process using the investment casting method using SS CF8M material. Investment casting is metal casting using wax patterns and ceramic molds in the form of several layers of mullite sand and slurry, which produces high precision casting products. Limited production time for PS60 products, due to the increasing demand for PS60 products, has resulted in poor casting product quality. It was found that 15% of PS60 defective products from each production group were found. The high number of defective products and the imbalance in demand and production for PS60 products have encouraged efforts to improve and increase production capacity by recalculating the dimensions of risers, runners and ingates, and then designing a mold Gating system with a new layout. The casting defects found in PS60 products are ceramic inclusions, and the defects most often found in the production of PS60 products are porosity defects. Porosity defects can be caused by casting speeds that are too high, resulting in a turbulent molten metal flow that deposits air in the ceramic mold cavity into the solidified molten metal. Air in the mold cavity can be trapped in solidified molten metal in the mold cavity and can also be caused by a pouring temperature that is too low, which can be caused by excess slag on the surface of the molten metal [1]. Porosity defects can be controlled by designing a good molding system, especially in the gating system. By adjusting the cross-sectional area ratio of the casting container, runner and ingate, it is hoped that it will reduce the possibility of turbulent flow occurring in the molten metal being poured. The redesign of the mold Gating system with a new layout was carried out followed by casting simulation using ProCast 2018 software to provide an overview of the condition of the liquid metal during the casting process, and the position of the resulting porosity defects. ProCast 2018 software is able to predict and calculate casting defects that occur in the early design stages which are widely used for the process of improving mold improvements [2], [5]. The results of the casting simulation carried out were validated with the results of radiographs of cast products produced from a mold Gating system with a new layout.

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II. METHOD

A. Metal Casting Simulation

The casting process simulation is assisted by using CAE (Computer Aided Engineering) software, namely ProCast 2018, which is a product of the ESI group. This software is able to predict, analyze, measure and calculate casting defects that occur in the early stages of design. The advantages of this software include being able to simulate the melting process to the final casting stage [2]. This software was chosen because the investment casting method can be modeled quickly, easily, and accurately by entering parameter data according to the conditions at the casting site. This software is also able to predict porosity defects using the "New Advanced Porocity Module (NAPM)" feature. In the NAPM feature, micro porosity and macro porosity model predictions are combined. So the output of the ProCast 2018 software simulation results is the total volume of porosity defects in m^3 units. Before the simulation is run, it is necessary to input the required parameter settings into the ProCast 2018 software, the required parameters can be seen in Table 1., and the parameters required for NAPM can be seen in Table 2.

TABLE 1.
SIMULATION PARAMETERS [4]

Process	Invertment Casting
Alloy Material (initial temp)	Stainless Steel CF8M (1560˚C)
Mold Material (initial temp)	Refractory Mullite (1150˚C)
Interface HTC Manager	IN738-Mullite
Heat (Mold)	Air cooling (Film Coeff = 10 W/m^2K, T = 20˚C)
Inlet (mass flow rate)	Pouring Rate (after calculation)

TABLE 2.
NAPM PARAMETERS [4]

Porosity Model	Pressure Model
Alloy	Fe
Casting Process	Grafity
Imposed Pressure	Const. 5 N/m^2
Gaseous Element	Dinitrogen dihydrogen carbonmonoxyd N = 0.0002 H = 0.0001 C = 0.0001 O = 0.00002

B. Radiography Film Interpretation

Radiography inspection is a testing method which is part of Non-Destructive Test which is carried out on cast products using X-ray or gamma radiation to determine the number and existence of discontinuities. In principle, X-ray or gamma radiation is emitted through the material being examined, then the rays will be absorbed so that the intensity recorded on the film will certainly vary. The results recorded in this film will show the internal discontinuity of the material. The best casting simulation results will be validated with radiography results of cast products produced from a mold Gating system with a new layout.

III. RESULTS AND DISCUSSION

A. Study of Existing Products

Figure 1. is a depiction of the existing mold Gating system on the PS60 product. The mold system has 2 mold cavities in 1 layout, has a closed top riser type and a runner that has a rectangular cross section.

Crucial casting specifications that can influence the results of changes in casting process design and mold system improvements are listed in Table 3.

From the results of the simulation analysis on the existing mold Gating system, it is known the position of the porosity defect in Figure 2. The porosity defect is indicated by a purple volumetric area on all parts of the PS60 product. It is known from the simulation results that the total volume of porosity defects is 157.92 cm^3, which is 6.97% of the total volume of the mold Gating system. It was found that micro porosity was 34% of the total porosity defects evenly distributed throughout the

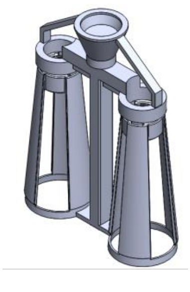


Figure 1. Layout of the existing PS60 down Gating system

TABLE 3.
CRUCIAL SPECIFICATIONS OF PS60 CASTING

Material	Stainless Steel CF8M
Volume Product	2266.94 cm^3
Density	7.9 g/cm^3
Total Weight	17.9 kg
Pouring Temperature	1550˚C

product as shown in the elliptical area in Figure 2, while 66% of macro porosity defects were in the casting container area, down sprue, riser, top and bottom of the product, as shown shown in the rectangular area in Figure 2.

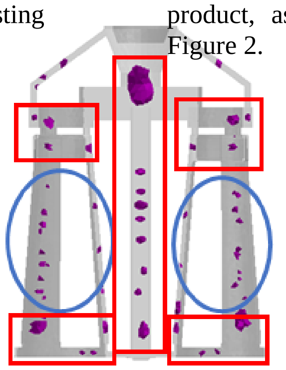


Figure 3. PS60 product new mold system layout design

Figure 2. Porosity Defects in Existing Gating Systems

B. New Molding System Design Geometry Specifications

In the process of improving a new molding system, determining the time and rate of pouring is carried out starting with calculating the estimated total weight of the molten metal to be molded. The total molten metal that will be poured into the mold can be estimated by making a 3D representation of the mold system design layout with the help of Solidwork 2015 software as depicted in Figure 3.

By entering data on the molten metal material that will be used in the casting process, namely CF8M stainless steel with a density of 7.9 g/cm^3, the total weight of the gating system design layout is obtained, namely 47.17 kg. Also obtained are the geometry specifications for the new PS60 product molding system as listed in Table 4.

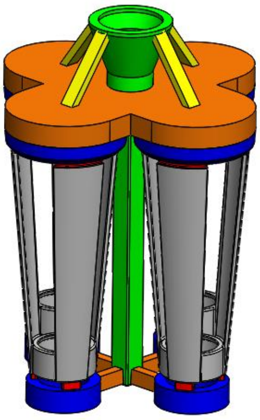


Figure 3. PS60 product new mold system layout design

TABLE 4.
PS60 NEW PRODUCT MOLD SYSTEM GEOMETRY SPECIFICATIONS

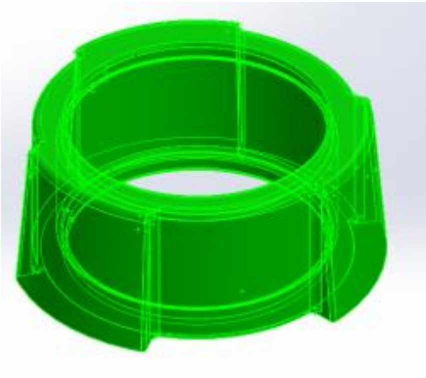
Mass (kg)	Volume (cm^3)	Surface Area (cm^2)
47.17	5970.98	10883.95

From the geometric specification calculations can be used as input values for modulus casting calculations. Modulus Casting is obtained from the comparison between volume and heat release area. The area of the heat release area is determined with the help of Solidwork software due to the complex shape of the object. Modulus Casting calculations are useful for knowing the part of a cast product that solidifies most recently. The modulus casting value is calculated using Equation 1.

$$\text{Modulus Casting} = \frac{\text{Volume}}{\text{Surface area}} \quad (1)$$

From the volume of the heat release cross-sectional area (LPP) parts 1 and 2 as shown in Figure 4. (a) and (b), the modulus values are obtained as in Table 5. Where the PS60 product has 1 piece for Part 1 and 3 pieces for Part 2 which are identical.

The improved molding system with a new layout is planned to have 4 molding cavities, 6 ingates for each molding cavity, 3 at the top and 3 at the bottom. The addition of mold cavities to the mold system with the new layout provides a 100% increase in productivity.



(a)

(b)

Figure 4. (a) Part 1 (b) Part 2

TABLE 5.
CASTING MODULUS VALUE ON CAST PRODUCT PARTS

Product Part Number	Part 1	Part 2
Volume (cm^3)	400.60	103.60
LPP (cm^2)	25.17	34.80
Modulus Casting (cm)	1.6	0.30

C. Planning of Adder (Riser)

The volume and placement of the riser must be planned well. In accordance with the function of the riser, which is the space provided for metal of adder which compensates for the shrinkage phenomenon in the solidification process. The metal of adder must be planned to have sufficient volume and strive to be the last area for solidification to occur in the molding system. In a mold system, the riser planning is divided into 2 parts, namely the upper and lower risers. Riser planning is carried out by calculating several values, including:

1) Shrinkage total ($\propto$)

The total shrinkage value is calculated using Equation 2. General liquid shrinkage for all types of metal materials is 2% for every 100°C drop.

$$\propto = \frac{\text{Casting temp.} - \text{Temp.Liquidus}}{100°C} \text{ x } ls\,(\%) + cs\,(\%) \quad (2)$$

Where, *ls* is liquid shrinkage and *cs* is crystal shrinkage. The average casting temperature taken in practice is around 100°C above the liquidus temperature, the liquidus temperature for stainless steel is 1435°C, so the average liquid shrinkage for each cast object is 2% for every 100°C decrease. Crystal shrinkage for stainless steel is 2.6 – 2.85% [7], so the total shrinkage is 4.55%.

2) Volume of additional requirements (V_f)

The volume of additional requirements (V_f) is calculated using Equation 3.

$$Vf = \propto \text{ x } (V_{cast} + V_{adder}) \quad (3)$$

3) Volume of supply adder (V_s)

The volume of supply adder (V_s) is calculated using Equation 4.

$$V_s = \varepsilon \text{ x } V_{adder} \quad (4)$$

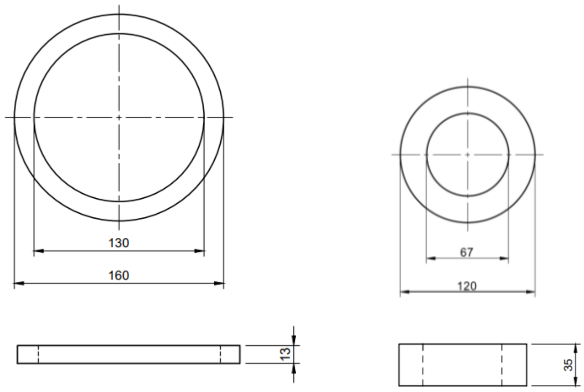
4) Efficiency of adder (EP)

The efficiency adder value can be obtained by calculating using Equation 5.

$$EP = \frac{V_s}{V_f} \quad (5)$$

TABLE 6.
RISER SPECIFICATIONS ON THE MOLD SYSTEM BEFORE AND AFTER IMPROVEMENTS

Element	Existing Design		New Design	
	Upper Riser	Bottom Riser	Upper Riser	Bottom Riser
Total Volume (cm^3)	120.77	24.26	138.63	209.92
Total of Depreciation (α) (%)	4.55			
V_f (cm^3)	23.72	5.82	11.02	27.23
V_s (cm^3)	24.15	4.85	27.73	41.98
EP	1.01	**0.83**	2.51	1.54



(a) (b)

Figure 5. Top and bottom risers design on the new molding system

If the value $V_s > V_f$ provides information regarding the adequacy of the volume of metal of adder to meet the shrinkage requirements of cast products. Calculations of riser elements for the mold system before and after improvements can be seen in Table 6.

It is known that the V_s value in the bottom riser of the existing molding system is smaller than the V_f value, giving rise to an EP value that is less than zero (EP<0), this provides information that when planning the bottom riser in the existing molding system it cannot compensate for the shrinkage that occurs in mold cavity, this increases the possibility of defects in the cast product. So, improvements were made to the lower riser design in the new molding system which was proven to have an EP value greater than 0 (EP>0), because the V_s value was greater than V_f, which means that the metal of adder was sufficient to fill the shortfall resulting from shrinkage due to the solidification process in the mold cavity. The design of the top and bottom risers in the new molding system is presented in Figure 5.

D. Mold System Planning (Gating System)

The mold system specifications are obtained from the results of pouring rate and time calculations, dimension calculations of adder (riser), inlet calculations (ingate), and down Gating calculations carried out using Equation 6-10, as follows:

1) Pouring rate

The pouring rate value can be determined using Equation 6. where the constant value for an object thickness of less than 6 mm is 0.99, for objects with a thickness between 6-12 mm it is 0.87, while for an object thickness of more than 12 mm the constant value is 0.47 [3].

$$R = b\sqrt{W} \tag{6}$$

Where, R is the pouring rate, b is a constant and W is the total weight of the mold system.

2) Pouring time

The pouring time value is calculated using Equation 7.

$$t = \frac{W}{R} \tag{7}$$

Where, t is the pouring time, W is the total weight of the molding system and R is the pouring rate.

3) Inlet (ingate)

In the gating system layout, the PS60 product uses a bottom gating system model so that the hydrolysis height factor equation is as follows:

$$h = \frac{a-b}{2} \tag{8}$$

The ingate design for the PS60 product is that there are 6 ingates in each product, so the ingate calculation is divided into 6 equal sizes. It is planned that ingate has a rectangular geometric shape according to the shape of the riser. The flow resistance factor chosen is 0.7 because the product is rather difficult due to the rather thin casting, namely 6-7 mm, so the calculation of the cross-sectional area of the ingate is as follows:

$$I_A = \frac{22{,}6 \; x \; W}{t \; x \; \rho \; x \; \xi \; x \; \sqrt{H}} \tag{9}$$

4) Down Gating (runner)

Runner calculations can be calculated from comparisons with commonly used Gating systems as in Equation 10.

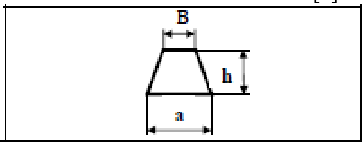
$$\text{Sprue : Runner : Ingate} = 1 : 2 : 2 \tag{10}$$

There are 2 different runner shapes planned for the top and bottom of the PS60 product. The runner at the top is rectangular, and the runner at the bottom is trapezoidal in shape according to the down Gating catalog presented in Table 7.

The calculation of the mold system elements with the new layout after improvements can be seen in Table 8.

It is known in Table 8. that the cross-sectional area of the ingate and runner actual is larger than the theoretical one. This aims to reduce the ratio of the cross-sectional area to the cross-sectional area of the casting container. Planning the cross-sectional area of the ingate and runner actual to be smaller than theoretical causes the ratio of the cross-sectional area of the casting container and runner or ingate to be larger, this increases the possibility of turbulent flow due to the higher flow rate in the mold cavity, thus increasing the occurrence of defects.

TABLE 7.
SLAG GATING CATALOGUE [9]



Slag Gating					
1 Gating			2 Gating		
23	19	28	17	14	20
25	21	30	18	15	22
27	22	32	19	16	23

TABLE 8.
SPECIFICATIONS FOR THE NEW LAYOUT MOLDING SYSTEM RESULTING FROM IMPROVEMENTS TO THE PS60 PRODUCT

Specificaton	Value
Pouring rate (kg/s)	5.98
Pouring time (s)	8
High hydrolysis factor (cm)	8.05
Theoretical total ingate cross-sectional area (mm^2)	848.5
Cross-sectional area of each theoretical ingate (mm^2)	141.42
Ingate actual cross-sectional area (mm^2)	197.1
Ingate dimensions (mm)	25.5 x 8.76
Theoretical total runner cross-sectional area (cm^2)	8.48
Actual total runner cross-sectional area (cm^2)	36.75
Actual top runner cross-sectional area (cm^2)	32
Actual top runner dimensions (mm)	160 x 30
Actual bottom runner cross-sectional area (cm^2)	4.75
Actual bottom runner dimensions (mm)	(21+17) x 25

E. Analysis of Yield Casting Criteria and Volume Gating System

An analysis of the casting process was carried out from the perspective of yield casting value criteria and gating system volume. The Yield Casting value and gating system volume can represent the quality of the casting process, which is the efficiency of the casting process in the use of liquid metal. Where ideally the liquid metal required in the gating system area should be less than that required for cast products. The ideal value for yield casting in the investment casting method is more than 40% [1]. It can be said that the gating system volume is permitted to be larger than the product volume. This is because the investment casting method requires many rods in the gating system with the aim of strengthening the gating system during handling. The yield casting value is a comparison between the weight of the casting object and the entire casting (product + gating system), as presented in Equation 11.

$$\%\ Y_c = \frac{W_{product}}{W_{Total\ of\ pour}}\ x\ 100\ \% \tag{11}$$

Meanwhile, the gating system volume value is the total casting volume minus the gating system volume, as presented in Equation 12.

$$V_{Gating\ System} = V_{Total\ of\ pour} - V_{product} \tag{12}$$

The values of Yield Casting and Design Gating System Volume before and after improvements are presented in Table 9. It is identified that the value of the gating volume of the new mold system design has increased significantly, more than three times the gating system volume of the existing mold system design.

If reviewed more closely at the yield casting value, the yield casting value of the new mold system design is lower, which is produced by the new mold system design which is 14.03% lower. It can be said that the quality of the PS60 product casting process has increased due to the efficient use of molten metal in the gating system part less than the molten metal used in the product. The material used in the gating system must be optimized to a minimum in relation to reducing the amount of scrap produced from the casting process from pieces of the gating system.

F. Casting Simulation

The casting simulation was carried out with the help of ProCast 2018 software to produce a cast product as seen in Figure 3. It can be seen that porosity defects are still visible spreading throughout the PS60 product but are located on the surface of the cast product. In the bottom riser of the product and casting container, macro porosity is visible which is shown in the rectangular area in Figure 6.

The volume of porosity defects identified using the New Advanced Porocity Module (NAPM) method in ProCast software can be seen in Table 10.

The total volume of porosity defects in the new mold system design is almost twice as large as the existing mold system design, however, in terms of total porosity percentage, the gating system improvements provide a reduction in porosity percentage of 2.39%. The new mold system design also reduces the volume of micro porosity. The volume of macro porosity does increase significantly in the design of the new molding system, but if reviewed at the location where macro porosity occurs in Figure 6., this does not have much of an impact on the final PS60 product because after the solidification process, the gating system will be cut and will become scrap and possibly be remelted.

TABLE 9.
CRITERIA FOR YIELD CASTING AND VOLUME GATING SYSTEM DESIGN BEFORE AND AFTER IMPROVEMENTS

Criteria	Existing Design	New Design
Yield Casting (%)	58.28	44.25
Volume Gating System (cm^3)	945.76	3328.62

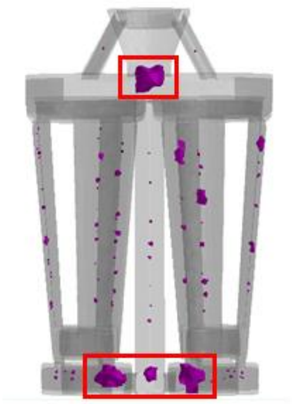
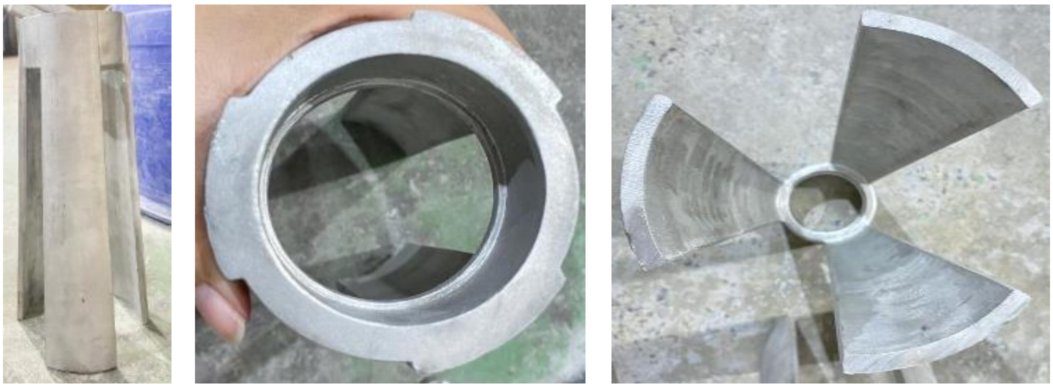


Figure 6. Porosity defects of molding system with new layout simulation results with ProCast 2018

TABLE 10.
THE AMOUNT OF POROSITY IN THE DESIGN BEFORE AND AFTER IMPROVEMENTS

Criteria	Existing Design	New Design
Micro Porosity Volume (cm^3)	53.25	21.18
Macro Porosity Volume (cm^3)	104.66	293.55
Volume Total Porosity (cm^3)	157.92	314.73
Porosity Percentage (%)	6.97	4.58



(a) (b) (c)

Figure 7. Cast PS60 products use a new molding system
(a) side view (b) bottom view (c) top view

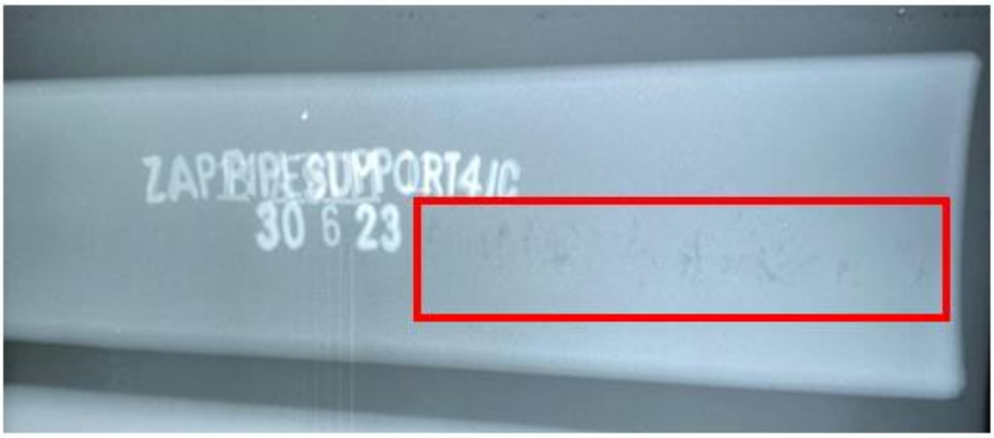


Figure 8. Radiography photo results of cast PS60 products using the new molding system

G. Interpretation of Radiography Films

Validation of the simulation results was carried out by conducting experimental casting using the investment casting method using casting process parameters and new mold designs. The casting process experiment was carried out 4 times starting from the process of making patterns from wax, followed by making ceramic molds, making molten metal, pouring, and cooling, producing cast PS60 products as shown in Figure 7.

In non-destructive testing carried out using the radiographic method it was validated that micro porosity did occur along the product fin as shown in Figure 8. in the area indicated by a rectangle.

IV. CONCLUSION

Casting products produced using a new layout Gating system had 314.73 cm^3 of cavity in the product which were identified as porosity defects which constituted 4.58% of the total volume of cast products. The porosity defect decreases by 2.39% from the original product. 93.3% of the cavity inside the product is categorized as macroscopic porosity defects that are centralized in the riser and pouring basin areas, where in the casting product finishing process, these areas will be removed. Modification of the Gating System in PS60 mold escalates twice of PS60 capacity production than the origin.

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