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Quantitative Macro Defect Analysis in Sand Casting: 3D Simulation and Porosity Assessment in Ashtray Patterns

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ABSTRACT

Simulation analysis and quantitative approaches have become very important in the foundry industry to improve product quality and minimize defects. This study aims to analyze macro defects, particularly porosity, in ashtray patterns produced through sand casting. A quantitative approach was used to identify and evaluate macro defects in the castings by utilizing 3D simulation techniques. This process involves taking macro images of the molded samples and then processing them to determine the porosity level. The porosity evaluation was carried out by comparing the simulation results with experimental data, thus enabling a more in-depth understanding of the factors affecting casting quality. The results of this study show the porosity formed by 3-dimensional simulation and the porosity percentage derived from statistical interpretation of macro photographs of sand casting materials. The findings are expected to make a meaningful contribution to the foundry industry, particularly in the effort to improve product quality through process optimization. This study also highlights the importance of quantitative and simulation approaches in analyzing and predicting casting defects, which can ultimately reduce production costs and improve product yield.

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INTRODUCTION

In metal casting, controlling defects such as porosity remains a persistent challenge, particularly in sand-casting processes (Blondheim & Monroe, 2022). Despite ongoing advancements in casting technologies, achieving defect-free casting is still elusive due to the complex interplay of variables within the casting environment. Sand casting, favored for its cost-effectiveness and flexibility, is especially susceptible to porosity defects, which can severely impact the final product's structural integrity and aesthetic quality (Sertucha & Lacaze, 2022; Singh et al., 2020).

The gap between the theoretical models that predict casting outcomes, and the actual occurrence of defects necessitates further research, particularly in integrating empirical data with advanced simulation techniques. While recent studies have underscored the potential of simulation methods to predict defect-prone areas in castings, the real-world application of these models often falls short due to the variability in casting conditions and the limitations of the models used.

A few researchers focused on uniform filling (Ingle & Narkhede, 2018), gate product (Rajkumar et al., 2021; Raza et al., 2021), microstructure (Li et al., 2022) and affect on mechanical characterization (Neuser et al., 2021). There have been limited studies concerned with the surface porosity of sand-casting product. Therefore, this research intends to simulate the contour and morphology of surface sand casting product. The objectives of this research are to investigate the contour and porosity of surface sand casting material based on a photo of macrostructure sand casting product.

This study aims to bridge this gap by performing a detailed analysis of macro defects, specifically focusing on porosity in sand-cast ashtray patterns. By combining advanced 3D simulation with empirical data, the research seeks to develop a more reliable prediction model that can be applied effectively in industrial settings. This approach contributes to the current understanding of casting defects and offers a novel methodology that could significantly reduce production costs and enhance product quality.

METHOD

Materials

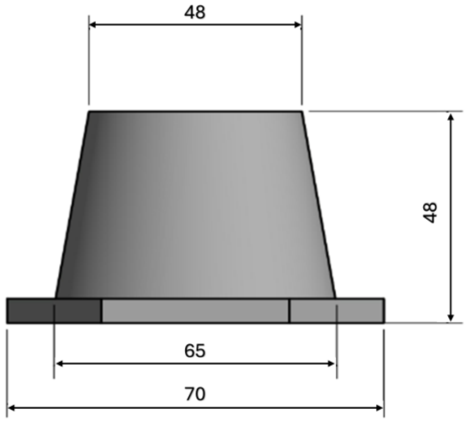
The main material used for casting is Aluminum Silica with Mn content ranging from 0.15 - 0.4g and Mg from 0.5g. As a mold, 80% silica sand (12 kg) and 20% bentonite (3 kg) are used with a water content of 4% (600 mL). The furnace used is a cylindrical crucible furnace with a capacity of 11 kg. The fuel for combustion in the furnace is LPG. The flask used is square measuring 20 x 25 x 15 cm which has a volume of 7,500 cm^3.

Methods

a) Casting Process

The mold-making product process involves the following steps: First, an ashtray-shaped pattern is placed between the drag (bottom half of the mold) and the cope (top half of the mold). Silica sand is then filled around the pattern and compacted to create the mold cavity, ensuring the inclusion of runners and risers in the cope to facilitate the flow of molten metal. A thin layer of graphite powder is applied as a separator to prevent the sand from sticking to the mold, while lime is added to improve the strength of the mold.

Next, 6 kg of Al-Si alloy is heated in a furnace to a temperature of 600-750°C until it becomes fully molten. The molten metal is then carefully transferred from the furnace using a preheated ladle to prevent thermal shock. The liquid metal is poured into the mold through the runner opening. After allowing sufficient time for the metal to cool and solidify, the mold is broken open, and the cast workpiece is removed for surface finishing. The model of the molding is illustrated in Figure 1.



Gambar 1. Model of molding

b) Analysis of Casting Defects with Macro Photos

Following the casting process, the surface defects of the castings were analyzed using macro photography with a magnification of 20x. The images were taken using a Fujifilm camera paired with a 7Artisans macro lens to capture detailed views of the surface imperfections. These defects were identified as key parameters for assessing the overall surface quality of the castings. The high-resolution images were then used to create a 3D simulation of the casting surface, allowing for more accurate quantitative analysis of the defects and their potential impact on the final product.

c) 3D Porosity Simulation

The 3-dimensional simulation of porosity is used to determine how much porosity is produced in the casting process, providing a clearer picture of the distribution and intensity of porosity in the material structure. Using 3D simulation, macro visualization can be achieved through ImageJ application, which enables high-precision, photo-based measurements of the area simulated. This visual analysis is then integrated with quantitative testing, providing a deeper understanding of the relationship between casting process parameters and the quality of the final product, and opening up opportunities for further optimization in the production process.

d) Quantitative Analysis of Casting Surface Morphology

Quantitative analysis of casting surface morphology is performed through the conversion of macro photographs and 3D simulation results into a number matrix. This matrix allows measurement of values on the X, Y, and Z axes, providing a detailed description of the porosity distribution on the material surface. The resulting porosity data is then further processed using Originlab for statistical analysis software to convert the resulting photos into a matrix, then processed to see the height and produce the porosity value of the sand casting materials. These results are expected to be a reference for further research and optimization of the casting process.

RESULTS AND DISCUSSION

1. Analysis of Casting Defect Results

Figure 2 shows a casting sample with three specific areas marked for defect analysis. Three arrows pointing to the different positions (marked as 1, 2, and 3) on the surface of the casting. These positions represent the locations where macro defects were identified and analyzed. Position 1 displays a close-up view of the surface with a visible defect, possibly a porosity or cavity, indicated by a red circle. Position 2, Shows another close-up of a different area, revealing multiple defects or cavities on the casting surface, highlighted with a red circle and position 3 provides a close-up of a third area, featuring a defect similar to the others, also marked with a red circle. Figure 2 are used to document the specific locations of surface defects in the casting product, which helps in understanding the distribution and nature of these defects for further analysis.

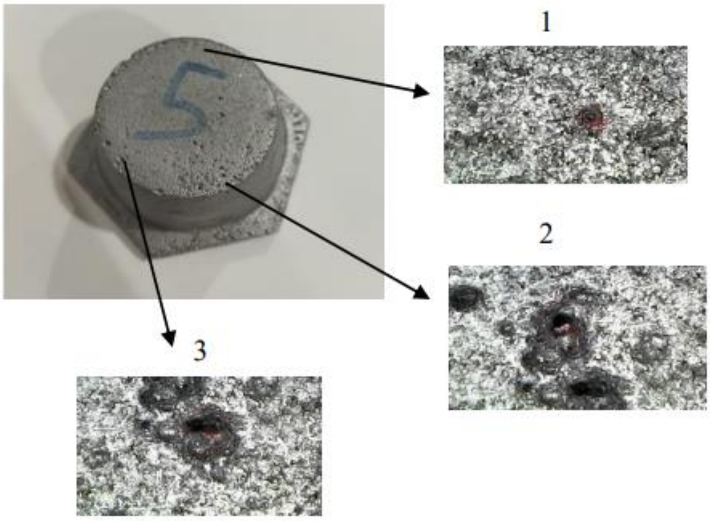
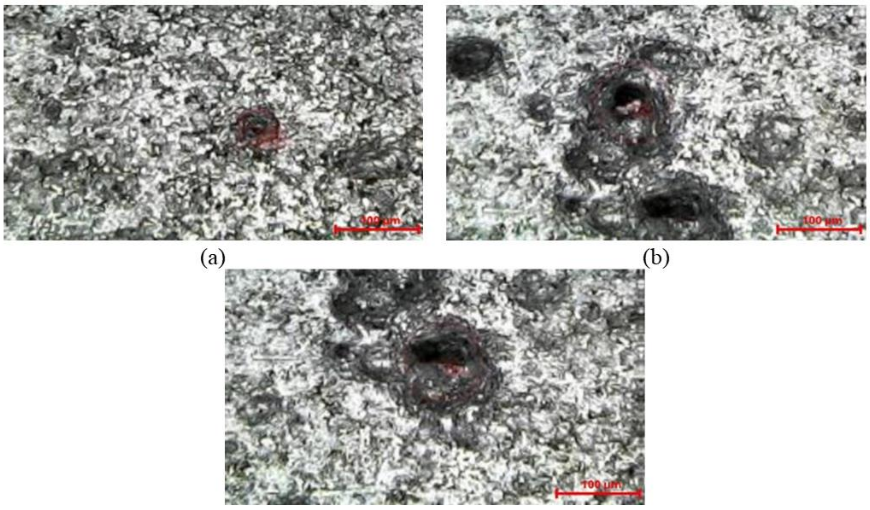


Figure 2. Photo of Product Surface and Sampling at Point

In Figure 3. Presented the results of the analysis of defects in castings using a Fujifilm brand macro camera with a 7-artisans macro lens with a magnification of 20 times. Point-taking is done using the random sampling method. Where taking sample members from the population are taken randomly without regard to the strata that exist in that population. Figure 3 shows the positions where samples were randomly taken from the cast product to analyze surface defects. The selection of samples in random sampling is carried out randomly so that each member of the population has the same opportunity to be selected.



(a) (b) (c)

Figure 3. Macro Photo Sampling at Point 1 (a), Point 2 (b), Point 3 (c)

Macro photo testing is used to determine the morphology and product surface. Based on the results of macro camera analysis, it is found that on a macroscopic scale, the surface produced by casting is uneven and there are many pores due to the use of sand as a molding material. The surface of a material that has pores can affect the mechanical strength and resistance of the material to forces from outside the material. (Tammas-Williams et al., 2017). After knowing the morphological shape of the product surface, the calculation of the diameter of the porosity formed is analyzed.

In Figure 3A, the average diameter formed is 26.32µm, in Figure 3B, the average diameter formed is 49.31µm, in Figure 3C, the average diameter formed is 31.99µm. These results are following existing research, where the average diameter of the casting results is ~40µm (A. Samuel et al., 2021). The macroscopic cavities that occur in castings are usually a type of shrinkage due to poor transformation. In general, the shrinkage in the volume of Al-Si transformed from liquid to solid form can range from 5-8%. Another major source of porosity is caused by the dissolution of hydrogen gas in the hardened solid as a result of poor hydrogen flue gas removal (Giovanni et al., 2020; Kuchariková et al., 2018; A. M. Samuel & Samuel, 1992).

2. 3D Porosity simulation

In Figure 4. Presented the results of 3-dimensional simulation analysis of porous shapes and defects in product surface results using the ImageJ application. 3-dimensional simulation allows researchers to get contour images and predict the depth of porous holes. After knowing the surface shape produced by the casting, then a quantitative test is carried out to determine the porosity produced.

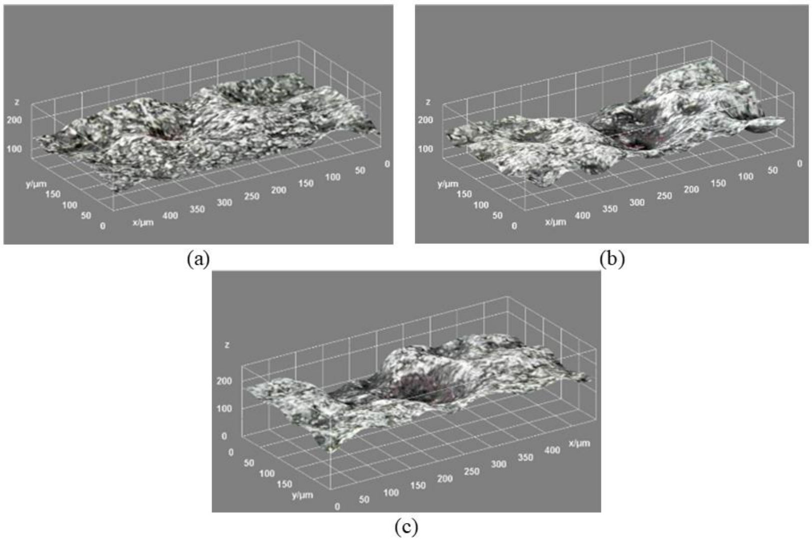


Figure 4. 3-dimensional morphology simulation of casting surface results at point 1 (a), point 2 (b), point 3 (c).

The 3-dimensional simulation is used to visually predict the surface shape of the product surface. Based on the results of the 3-dimensional simulation, it is found that the average depth of porosity produced by the casting process is 57.89µm with a standard deviation of 22.78µm. The amount of porosity hole depth produced is almost the same as the diameter of each hole. This is because the porosity formed is a side effect of the molding sand used (Chadha et al., 2024). Furthermore, the results of this 3-dimensional simulation are converted to a statistical application to be converted into a matrix form based on the difference in brightness produced in the top view image.

3. Quantitative Analysis of Casting Surface Morphology

Figures 5 and 6 present the results of quantitative analysis of the surface morphology of the product surface. The results of macro photos and simulations in the previous discussion (Figure 2 and Figure 3) are converted into a matrix form which is then determined by the resulting porosity value.

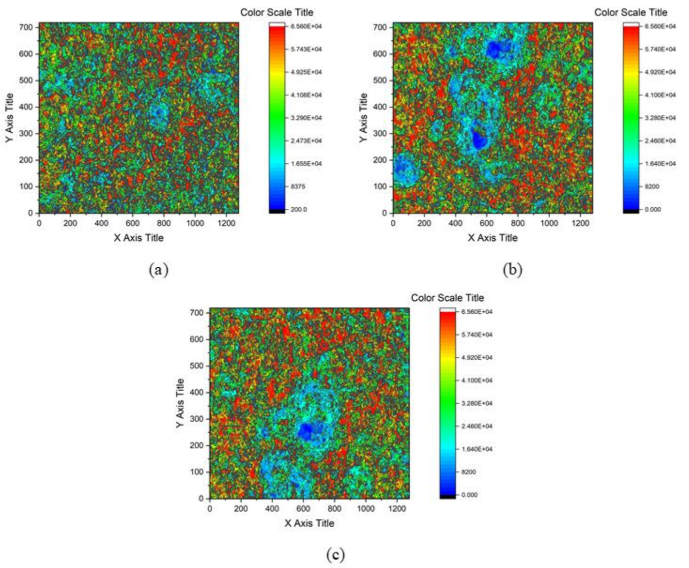
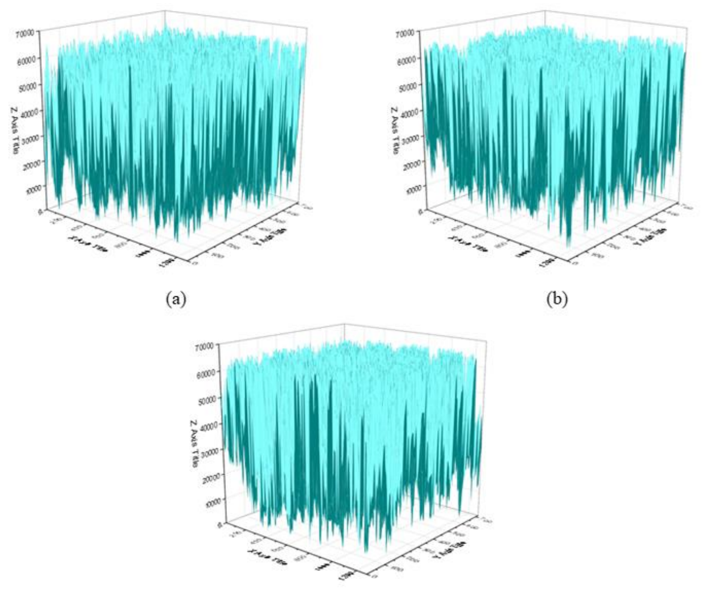


Figure 5. Surface Plotting of casting surface results at Point 1 (a), Point 2 (b), Point 3 (c)

Based on Figure 5. It shows that the red point is a representation of the highest point in the sample field, while the blue area is a representation of the lowest point or can be interpreted as a sample porosity hole. The green field is the middle point where it becomes a transition field which can be interpreted as the main size of the workpiece later. After knowing the height difference in the sample, it is then applied to the 3-dimensional plane in Figure 6.

Based on Figure 6. obtained data is presented in Table 1. Where the total contour height on the simulation surface is 2535.20 µm high, 4947µm long, and 2785.20 µm wide. Then the calculation is carried out to produce a total volume of predicted dimensions of 34,937,731,467 µm3 or a range of 34.93 mm3. After the calculation, the resulting porosity is 43.39% for point A, 41.75% for point B, and 41.38% for point C, where the overall average is 42.17%.



(a) (b) (c)

Figure 6. Quantification results of 3-dimensional morphology of the casting surface at Point 1 (a), Point 2 (b), and Point 3 (c).

Table 1. Details of Quantitative Surface Sample Test Result Data

Data Output	Dimensions A Point (µm)	Dimensions B Point (µm)	Dimensions C Point (µm)
H max	2535.20	2535.20	2535.20
H min	0	0	0
X	4947.77	4947.77	4947.77
Y	2785.20	2785.20	2785.20
V total	34937731467	34937731467	34937731467
V solid	19775396045	20349768313	20478625565
V porous	15162335412	14587963154	14459105891
Percentage	43.39%	41.75%	41.38%

It is shown that the red point is a representation of the highest point in the sample field, while the blue area is a representation of the lowest point or can be interpreted as a sample porosity hole. The green field is the middle point where it becomes a transition field which can be interpreted as the main size of the workpiece later. After knowing the height difference in the sample, it is then applied to the 3-dimensional plane in Figure 5.

CONCLUSION

Based on the findings of this research, it can be concluded that the integration of three-dimensional (3D) simulation and statistical testing in the analysis of porosity in sand casting provides a more detailed and accurate understanding of the distribution and severity of macro defects in cast products. This study effectively identified and mapped porosity within the casting patterns at a high resolution, utilizing a combination of macro photography and 3D simulation, along with rigorous statistical analysis. The analysis revealed a porosity level of 42%, indicating a significant need to control critical variables in the casting process, such as pouring temperature, mold material composition, and cooling rate, to minimize defects. The high porosity rate suggests that improper sand compaction, inadequate gating design, or insufficient mold preparation could be contributing factors. By addressing these areas, manufacturers can reduce the occurrence of defects, improve the structural integrity and surface quality of cast products, and thereby enhance their overall competitiveness. This research not only deepens the theoretical understanding of defect formation in sand casting but also provides practical guidelines for optimizing the casting process. The proposed method offers significant advantages, including better defect prediction, improved quality control, reduced production costs, and increased product reliability. These contributions can be directly applied in industrial settings to enhance product quality and strengthen market position.

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