

Research Article

Effect of Pouring and Mold Shell Temperatures on Porosity in Complex Investment Castings of Stainless Steel 304

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Abstract:

Investment casting offers a powerful combination of precision, design freedom, material versatility, and potential cost savings, making it an ideal choice for demanding applications across various industries. However, this technology also faces significant challenges that affect part quality, primarily due to the formation of porosity and air entrainment. These defects originate from inadequate solidification control and turbulent flow behavior during the mold filling process. This study aimed to investigate the effect of pouring and firing temperatures on the appearance of porosity in stainless steel 304 complex casting parts, to minimize casting defects. The casting geometry is characterized by intricate features and thin cross-sections, making it highly sensitive to thermal and flow behaviors. Six pouring temperatures (1580 °C, 1600 °C, 1620 °C, 1640 °C, 1660 °C and 1680 °C) and six firing temperatures (950 °C, 1000 °C, 1020 °C, 1040 °C, 1060 °C and 1080 °C) were evaluated. ProCAST software was used to analyze porosity formation and air entrainment, revealing that a pouring temperature of 1640 °C and shell temperature of 1040 °C achieved a minimal porosity (0.01 cm³) while reducing the air entrainment (0.5 mg/cm³). Additionally, the study also clarified that the relationship between pouring/shell temperature and casting defects is non-linear, with “trade-off” effects always happening in casting. Experimental validation via X-ray and microscopy inspection confirmed the simulation trends. The study recommends minimizing defects in thin-walled investment casting parts through precise thermal control, enhancing product quality and manufacturing efficiency.

Keywords: porosity, complex casting parts, air entrainment, simulation

1. Introduction

Investment casting (IC) is a preferred technique for producing stainless steel products, which can be widely used in engineering applications such as manufacturing, industrial equipment, automotive, aerospace, energy, power engineering, and other industries due to its good corrosion resistance, high toughness, and non-magnetic properties [1]. The IC method is considered a suitable processing method for manufacturing complex structure parts and high melting point metals, as it provides a near-net-shape product with high dimensional accuracy. The process usually involves building ceramic layers of the desired thickness around a disposable pattern to obtain a hollow ceramic shell upon pattern removal. The shell is heated at a high temperature to remove any traces of impurities present in it, and then it is filled with molten alloys under heated conditions. Finally, after cooling, the shell is knocked out to remove the castings [2], [3].

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Besides some advantages, IC faces many challenges, particularly in reducing defects and optimizing process parameters to achieve consistent product quality. Therefore, various studies have explored how to enhance the IC process. For instance, process design and process control are the two essential methods in producing quality casting. Process design includes designing the risering and gating systems for the casting system. Optimization of the gating system design, including changes in the ratio of downsprue [4] or shape of downsprue [5] could minimize the liquid surface turbulence during the filling of the shell cavity and the shrinkage porosity [6]. Moreover, many authors have tried to predict the position and quantity of defects [7] by using a computer simulation [8] and the Niyama criterion [9]. In addition, process control includes regulating the shell moisture content, pouring temperature, and metal flow rate [10], [11], [12]. In addition to various optimization parameters mentioned earlier, in the past few years, many researchers have also increasingly focused on thermal properties such as pouring and shell temperature, as key factors in enhancing productivity and quality castings in investment casting. Interestingly, Pattnaik et al. [10] found that suitable temperatures could lead to a decrease in linear and volumetric shrinkages, and the tensile strength of the casting increased. Cheng et al. [13] have highlighted the influence of preheat temperatures on the shell on defect formation and metallurgical properties, and investigated how different preheat temperatures affect the interaction between titanium alloys and ceramic shells. Similarly, many studies on pouring temperatures have shown their critical role in controlling solidification time and reducing porosity [11], [14]. Shi Cheng et al. [15] researched the optimal preheat and pouring temperature (950 °C -1410 °C) for Ni-based super alloy ring shape part, they focus on the impact of these parameters on grain boundary structure based on CAFÉ and thermal results. Shu Wag et al. [16] researched the optimized preheat and pouring temperature (1000 °C-1505 °C) for the nickel-based superalloy (K452) turbine blade, they found that the high pouring temperature causes uneven melt flow. Kai Lü et al. [17] research the effect of shell temperature on bending strength, which was increased and then decreased with an increasing shell temperature. Tresna Priyana Soemardi et al. [18] researched the effect of shell temperature, holding time, and the number of layers of ceramic on shell cracking. Jun Zhao et al. [19] eliminated the misruns and gas holes defects for the turbocharger Ti-Al alloy in investment casting by controlling the shell preheat temperature and centrifugal rotational rate.

Many studies have extensively investigated the effects of gating systems and temperature parameters in investment casting. However, they mostly focused on the shrinkage cavity defects, especially in complex parts like a turbocharger or turbine. The effect of temperature properties on fluidity, particularly in relation to complex geometries with varying thickness, is rarely explored in molten metal in the investment casting process. In this study, to fill this gap, we tried to evaluate how thermal variations influence porosity formation and their impact on air entrainment, misrun for the complex part of SUS 304 steel. Additionally, this work provides a detailed analysis of the influence of temperature and its trade-off effects, highlighting how excessive or insufficient thermal conditions can either improve or worsen the casting quality. Through numerical and experimental validation, this study aims to provide practical recommendations for optimizing the investment casting process, contributing to defect reduction, improving product reliability, and energy efficiency.

2. Materials and Methods

2.1 Material

There are five coating layers with different materials. For the first coating shell, selecting suitable materials is very important. The binder used for the first layer is Primcote, while the filler is Zircon Flour #350, which has a high fineness, as shown in Table 1. The stucco material used in this layer is Zircon-Al sand with a particle size of 0.1 mm. For the second layer, the slurry consisted of 25% silica sol mixed with Zircon #200 and Zircon sand (0.3 mm). The third, fourth, and last coating shells, silica fused, are added to the slurry, and Mullite sand is used for stucco.

Table 1: Composition and preparation of the shell

Coating	Slurry		Stucco	Dry time (hour)
	Binder	Filler		
1	Primcote	Zircon Flour #350	Zircon, Al (0.1 mm)	7
2	25% Silica sol	Zircon Flour #200	Zircon (0.3mm)	9
3, 4	-	Zircon # 200, Silica Fused	Mullite (0.7–1 mm)	11
5	-	Zircon # 200, Silica Fused		24

Primcote binder is used when complicated products need to add the benefit of extended slurry life to the primary slurry [20]. Primcoat binder supplied by RANSOM & RANDOLPH Co. (Ohio, United States of America), as shown in table 2.

Table 2: Typical properties of the Primcote binder.

Base composition	Colloidal silica
Other composition	Proprietary
Total solids content (Including SiO_2)	28.5–30.0%/weight
Particle dimensions (Approximate)	<15 nm
pH at 77°F (25°C)	10.3
Specific gravity	1.17
Weight/Volume	9.70 lbs/gal (1.17 kg/l)
Na_2O content (weight)	0.35 %
Particle charge	Negative

Zircon sand (ZrSiO_4) Zircon exists naturally in the form of fine sand, mined in various parts of the world. Zircon sand was supplied by Dieu Long Co., Ltd (Ho Chi Minh City, Vietnam). It is used for the fine primary coat stucco as well as, in a pulverized form, as a filler material with a melting point of 2100 to 2300 °C [21],[22].

Aluminum sand has a high hardness, sharpness, and chemically stable composition, offering high heat resistance and corrosion resistance. Aluminum sand is supplied by Vietnam Metal Casting Mechanical Co., Ltd (Hai Phong City, Vietnam). The composition and mechanical properties of aluminum sand are referenced in Table 3. Mullite sand possesses good thermal and mechanical properties, originating from calcined and crushed clay or synthetic materials like sillimanite. The Aluminum sand has a high melting temperature of 2250 °C, with the composition of Al_2O_3 , Fe_2O_3 , SiO_2 , TiO_2 is 95%, 0.5%, 1.5% and 3% , respectively [23].

Table 3: Composition and mechanical properties of Mullite sand [24]

Al_2O_3	44–46%
SiO_2	50–53%
Fe_2O_3	1.2–1.5%
TiO_2	0.9 %
$\text{K}_2\text{O} + \text{Na}_2\text{O}$	0.4 %
$\text{CaO} + \text{MgO}$	0.5%
Bulk density g/cm^3 (min):	2.53
Refractory °C (min):	1760
Mullite % (min):	60
Grain dimensions:	150–300 μm

SUS 304 was selected as the casting material due to its corrosion resistance, mechanical properties, and widespread industrial applications. This material was supplied by Dong Luc Casting Corporation (Ho Chi Minh, Vietnam). Table 4 shows the chemical composition of SUS 304.

Table 4: SUS 304 chemical composition [25].

Chemical composition %						
$\text{C} \leq$	$\text{Si} \leq$	$\text{Mn} \leq$	$\text{P} \leq$	$\text{S} \leq$	Cr	Ni
0.08	1.00	2.00	0.045	0.03	18.00– 20.00	8.00– 10.50

2.2 Method

2.2.1 Simulation process

ProCAST (ESI Group, Bagneux, France) is a casting simulation software that has been widely used in foundry engineering industries for aerospace, automotive, and industrial products. The software provided detailed simulations of fluid flow, heat transfer, solidification, and defect prediction with an enormous material database, making it a powerful tool for casting process optimization [26]. Fig. 1 illustrates the casting simulation process, including steps from problem identification to result analysis. The process begins with defining the problem by identifying casting

defects and analyzing the structure of the casting part. Thereafter, the geometry is generated in CAD software, including the casting parts and gating system. The boundary box dimension of the casting part is 40 mm x 36 mm x 2 mm, and the gating system has been selected based on its popularity in the industry for small, thin-wall investment casting parts, as shown in Fig. 2. Then, the meshing process is generated, with the determination of important meshing areas such as casting parts, which will be divided into sizes equal to 1/3 of the smallest size as suggested as ProCAST document (Fig. 3). Considering the thin wall and uneven thickness, the localized mesh refinement was applied: 1.5 mm for runner; 0.75 mm for gate and 0.5 mm for casting part. During the numerical simulation, interface heat transfer between the casting part and gating was set as “EQUIV”, while the interface between alloy metal and shell was set as “COINC” [27]. Other boundary conditions, such as flow and material properties, were selected based on the actual production and recommendations of ProCAST documents, as shown in Table 5. Once all parameters are set, the simulation is processed based on the input conditions. Finally, the results are analyzed by evaluating key criteria such as porosity level, air entrainment, and the Niyama criterion. If the results do not meet the required standards, some adjustments could be applied to refine the simulation, as mentioned in Fig. 1.

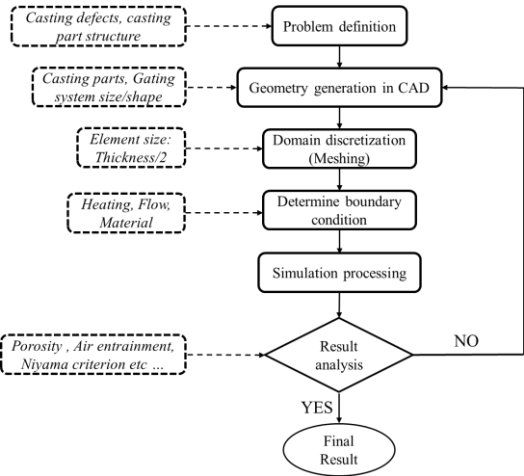


Fig. 1. Simulation casting process flowchart.

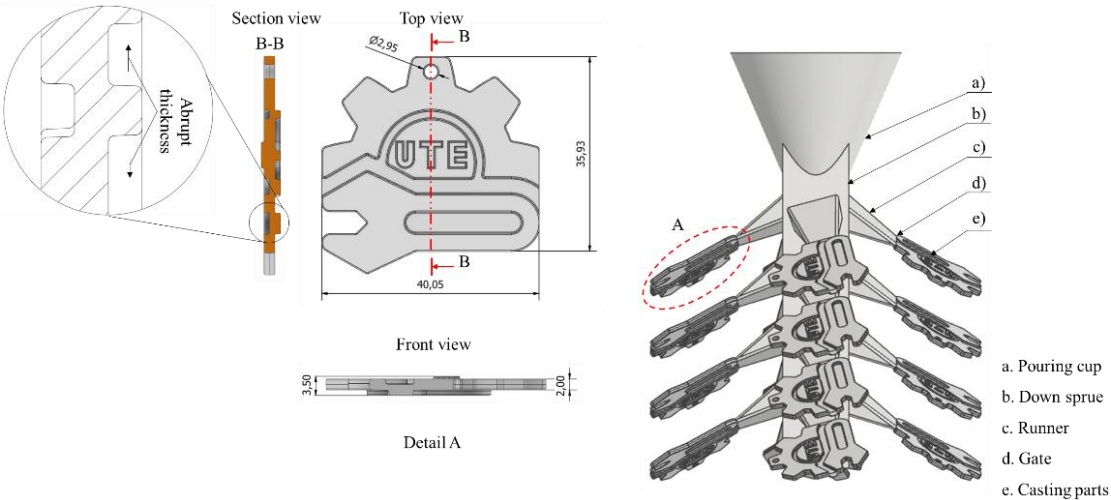


Fig. 2. 3D CAD model of the gating system

Table 5: Input parameters of the simulation

Casting material	Pouring velocity (mm/s)	Inlet diameter (mm)	Ambient temperature (°C)	Heat transfer (W/m ² K) [28]
SUS 304	200	40	37	400 (Solidus) 1000 (Liquidus)

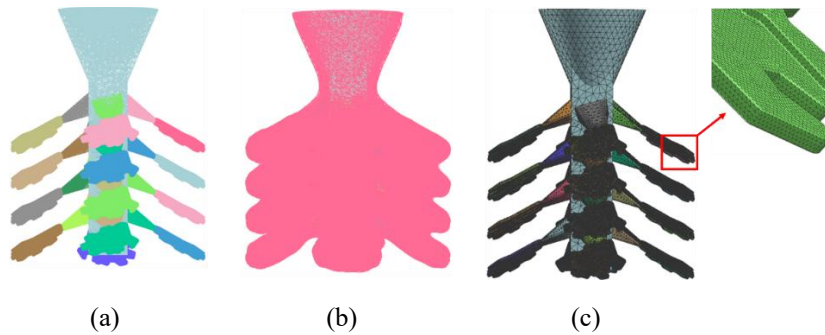


Fig. 3. 2D Mesh generation. (a) 2D mesh of the casting parts, (b) 2D mesh of the casting and shell, (c) Detailed refinement in the thin-walled areas.

2.2.2 Experimental process

The experimental process follows the traditional IC method, as described in Fig. 4. The process begins with creating the wax pattern. The wax pattern is injected from an aluminum mold to ensure the accuracy of the casting pattern, while the thermal conductivity of aluminum also allows for faster wax cooling time (Fig. 5a,b,c). Next, the components are attached to the downsprue using special sticky wax to prevent them from detaching from it (Fig. 5d). The wax pattern is then coated with multiple layers of ceramic (6.0 mm) to form the shell, with each layer consisting of different materials. The pattern will be dipped into a slurry, followed by stuccoing to build a strong shell (Fig. 5e). This coating and drying cycle is repeated multiple times to achieve the required shell thickness. The shell is then fired to strengthen and completely remove the remaining wax before pouring molten 304 stainless steel [29], [30]. Once the metal solidified, the ceramic shell was broken off during the knock-out process. Finally, the cast parts are sand-blasted in the finishing process and inspected to ensure quality [31]. The cast part is checked for chemical composition by the SPECTROMAXx machine (Fig. 5f).

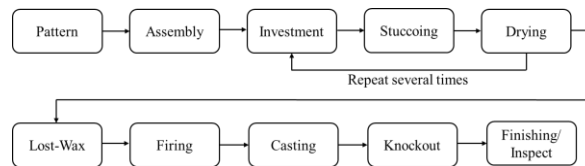


Fig. 4. Flowchart for the investment casting process.



Fig. 5. Experiment process (a) mold for pattern, (b) mold for pouring cup and pouring basin pattern, (c) pattern, (d) tree of pattern, (e) mold shell, and (f) SPECTROMAXx spark optical emission spectrometry machine.

3. Results and Discussion

3.1 Formation and location of porosity

An abrupt change in section thickness (Fig. 2) of the casting can lead to interruption of the feeding path during solidification. This discontinuity in feed length restricts the ability of liquid metal to compensate for shrinkage, which increases the formation of porosity. To evaluate this behavior, the initial conditions were set with a shell temperature of 950°C and a pouring temperature of 1650°C. The corresponding results are presented in Fig. 6. As shown in Fig. 6a, the hotspot appears in the isolated region with the longest solidification time. This region could lead to the formation of shrinkage and microporosity, as shown in Fig. 6b [32]. Chvorinov's Thermal Modulus formula (1) shows that the effectiveness of the gate is insignificant for feeding because the modulus ratio between the feeding gate and the longest solidification region of casting is too small:

$$M = \frac{V}{A} \quad (1)$$

In this case, M is calculated as follows: $\frac{0.2782}{0.2607} = 1.067$. This value is lower than the recommended value of 1.2 for effective feeding [33],[34]. Since the modulus ratio is lower than the recommended value, the feeding gate solidifies before the critical region, preventing effective feeding and leading to shrinkage defects (Fig. 6c). As a result, the formation of porosity observed in Fig. 6b is the inevitable outcome. Besides the M value, the Niyama criterion is also an important parameter that indicates the probability of the formation of microporosity [35]. The Niyama criterion (Ny) uses a formula to define the effect of the thermal gradient (G) and cooling rate (R) [36]:

$$Ny = \frac{G}{\sqrt{R}} \text{ (K.}\sqrt{s}.cm^{-1}) \quad (2)$$

Fig. 6d shows that the purple areas indicate regions where porosity is likely to form, with values below 1 for steel [37]. Notably, these regions not only align with the total porosity result in Fig. 6a, but also correspond to the fraction of solid results in Fig. 6e, where porosity forms in the mushy zone due to the low thermal gradient value, resulting in lower Niyama (Ny) values [38]. Besides the Modulus value and the Niyama criterion, the metal flow simulation results of the parts are also an important specification for gas porosity formation. Fig. 7 shows the formation and location of gas porosity through fluid analysis. If the ratio of the runners is less than the ratio of the sprue, the system is identified as a pressurized gating system. In this case, the gating system is 1:0.385:0.026, indicating that it is classified as a pressurized system. The characteristics of a pressurized system make it easier to fill thin-walled parts, but it will cause rapid turbulence on the surface, as shown in Fig. 7a, b. Previous studies have indicated that when the flow velocity exceeds 0.5 m/s, the trend of turbulent formation significantly increases [12]. To determine the characteristics of fluid, the Reynolds number is calculated to determine whether the flow will be laminar or turbulent (3). As shown in Fig. 7 and

(c)

Fig. 9 the measurement results at the ingate outlet show the high velocity (1.23 – 1.4 m/s) and low viscosity (3.53 mPa.s). This corresponds to a very high Reynolds number of 7274 (>4000), indicating the flow was turbulent at that moment. The presence of turbulence makes the probability of the formation of gas porosity increase because it will increase gas involvement [39], [40].

$$N_{Re} = \frac{R_H \cdot v \cdot d_1}{\mu} \quad (1)$$

3.2 The effect of shell temperature on casting defects

In the traditional IC method, the mold shell temperature is usually set in an appropriate range based on experience or trial-and-error. However, it wastes a lot of time and incurs significant costs. In addition, it is difficult to know how a defect can occur. In this part, six different shell temperatures were selected, including 950 °C, 1000 °C, 1020 °C, 1040 °C, 1060 °C, and 1080 °C, with the pouring temperature of 1650 °C. The filling time is set as 1.15 seconds, and the casting process parameters are listed in **Error! Reference source not found.** by using ProCAST software. Fig.

8 shows the effect of shell temperature on the porosity of the casting. The results illustrate that changing the mold shell temperature significantly affects the formation of porosity. There is a downward trend, indicating that higher shell temperature leads to a reduction in total porosity, with the value decreasing from 0.021 cm^3 at $950\text{ }^{\circ}\text{C}$ to 0.009 cm^3 at $1080\text{ }^{\circ}\text{C}$ Fig. 11. To separate microporosity from total porosity, ProCAST provides an additional module based on the Niyama criterion, as shown in Fig. 11. Notably, the results show that microporosity also exhibits a gradually decreasing trend as shell temperature increases. The shell temperature range of $1040\text{--}1080\text{ }^{\circ}\text{C}$ exhibits a more pronounced effect compared to $950\text{--}1020\text{ }^{\circ}\text{C}$, confirming it is the optimal temperature range to minimize the porosity formation. Based on the Niyama criterion equation (1), many articles have shown that the cooling rate is the main factor that influences the formation of porosity [35], [36].

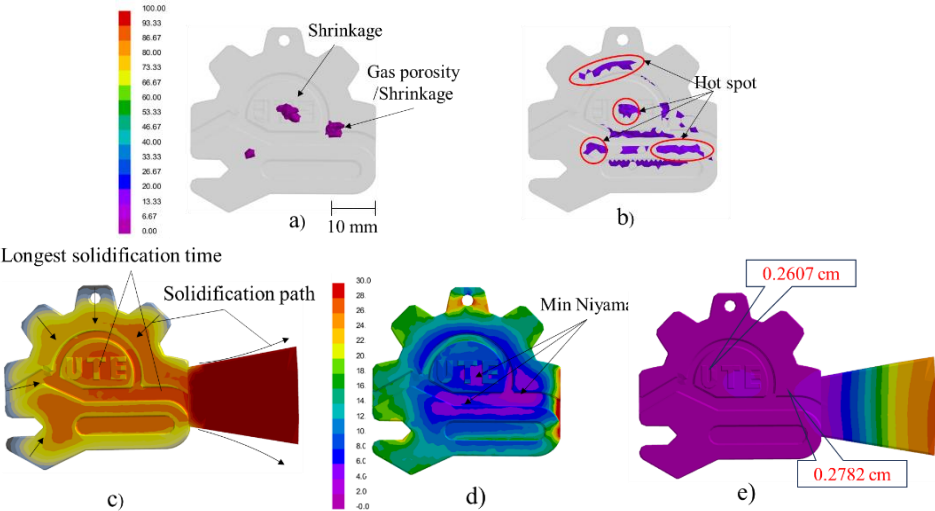


Fig. 6. Prediction of casting defects by investigating the formation and location of porosity through thermal analysis. (a) Hot spot region, (b) Total shrinkage porosity, (c) Fraction solid, (d) Niyama criterion (micro-porosity), and (e) Thermal Modulus.

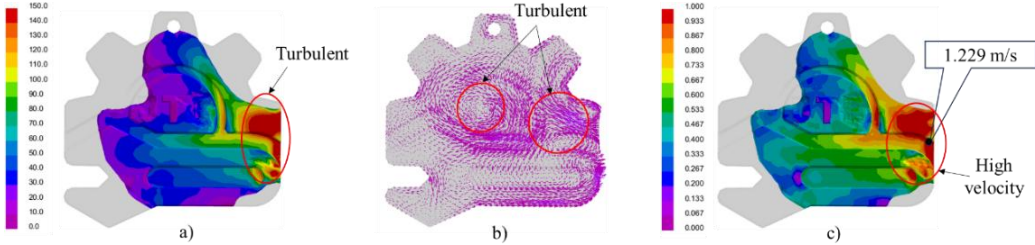
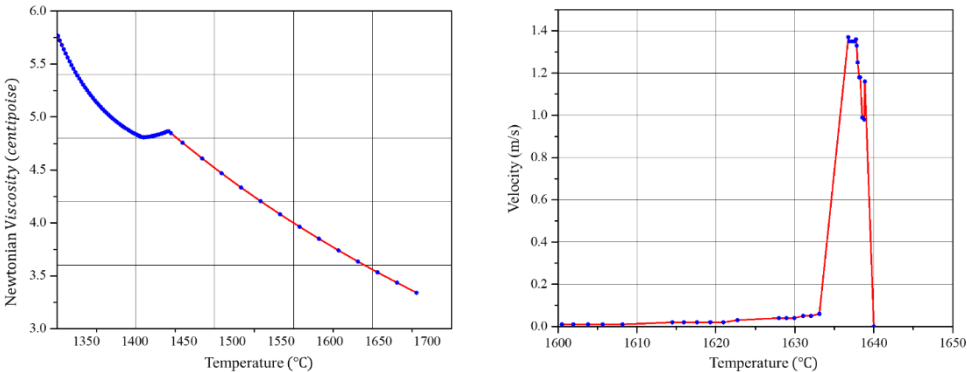


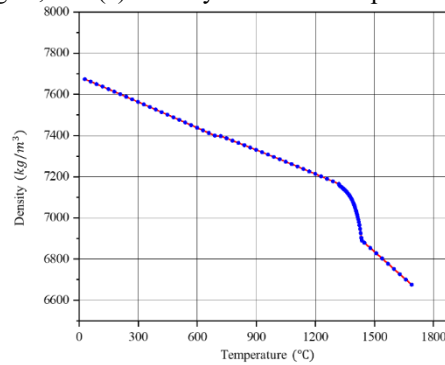
Fig. 7. Investigate the formation and location of air porosity through fluid analysis: (a, b) turbulent energy, and (c) velocity of molten alloy



(a)

(b)

Fig. 8. (a) Effect of temperature on Newtonian viscosity (ProCAST database), (b) Velocity of molten stainless steel 304 at the ingate, and (c) Density of material depends on temperature.



(c)

Fig. 9. (a) Effect of temperature on Newtonian viscosity (ProCAST database), (b) Velocity of molten stainless steel 304 at the ingate, and (c) Density of material depends on temperature.

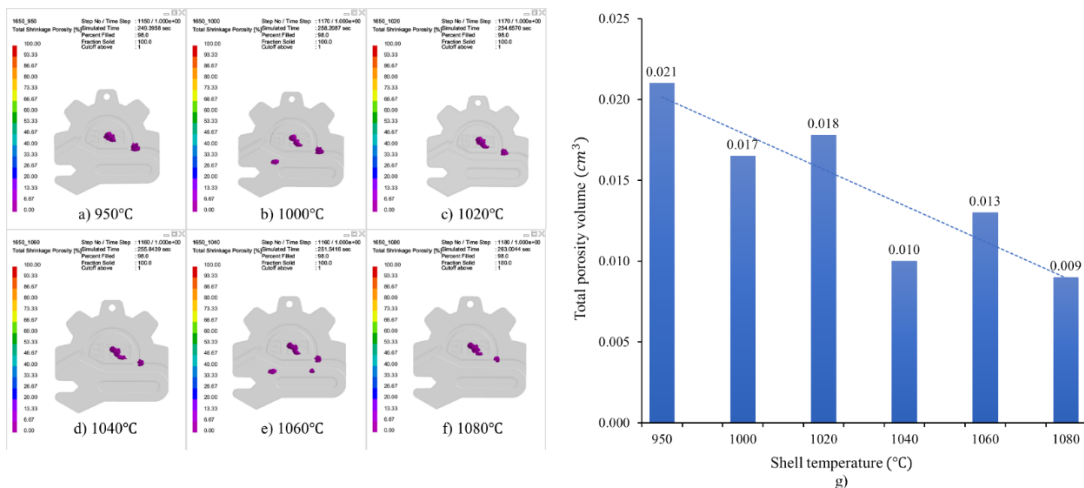


Fig. 10. Porosity formation probabilities were analyzed using ProCAST software for different shell temperatures (950–1080 °C). (a) 950 °C, (b) 1000 °C, (c) 1020 °C, (d) 1040 °C, (e) 1060 °C, (f) 1080 °C, and (g) comparison of total porosity volume on temperature.

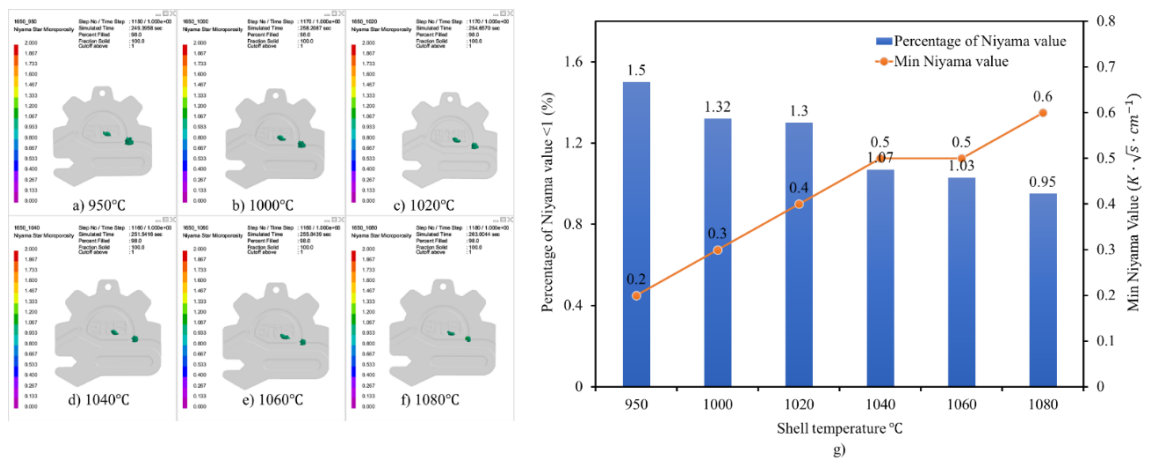


Fig. 11. Micro-porosity predicted by Niyama dimensionless module in ProCAST for different shell temperatures (950–1080 °C). (a) 950 °C, (b) 1000 °C, (c) 1020 °C, (d) 1040 °C, (e) 1060 °C, (f) 1080 °C, and (g) effect of shell temperature on Niyama value

The cooling rate can be visualized through the time to solidus and solidification time parameter in Fig. 11, indicating that it increases as the shell temperature increases, thereby improving the feeding efficiency [36]. Consequently, this enhances the Niyama value and reduces the formation of porosity. These findings are aligned with Raza et al.'s study [38], where a shell temperature that is higher than 1000 °C improved feeding efficiency in Ni-base alloy, although their optimal range (1050–1150 °C) differs due to material properties. Shell temperature of 1080 °C results in the lowest formation porosity of 0.009 cm³. However, it is not recommended as the optimal temperature due to the chemical reaction between the shell material and the molten metal at extremely high-temperature conditions, leading to not only sand burn defects but also air entrainment [13], [41], [42]. Fig. 12 shows the air entrainment volume at different shell temperatures. The results reveal that the effect of shell temperature on air entrainment is generally not obvious. However, the probability of air entrainment increases at 1060 – 1080 °C in the filling stage (40 – 70%). At this stage, the viscosity of molten metal decreases, leading to the flow being more dilute. Therefore, turbulence happens more easily, thereby increasing the formation of porosity. Remarkably, it is necessary to balance the temperature level to avoid wasting energy and increasing the presence of casting defects. In general, the shell temperature strongly affects the formation of porosity. The higher the temperature, the lower the porosity and microporosity. However, higher temperatures lead to more casting defects, such as shell cracking, gaseous defects, and consume a lot of energy. The optimized temperature in this case is 1040 °C, which minimizes casting defects.

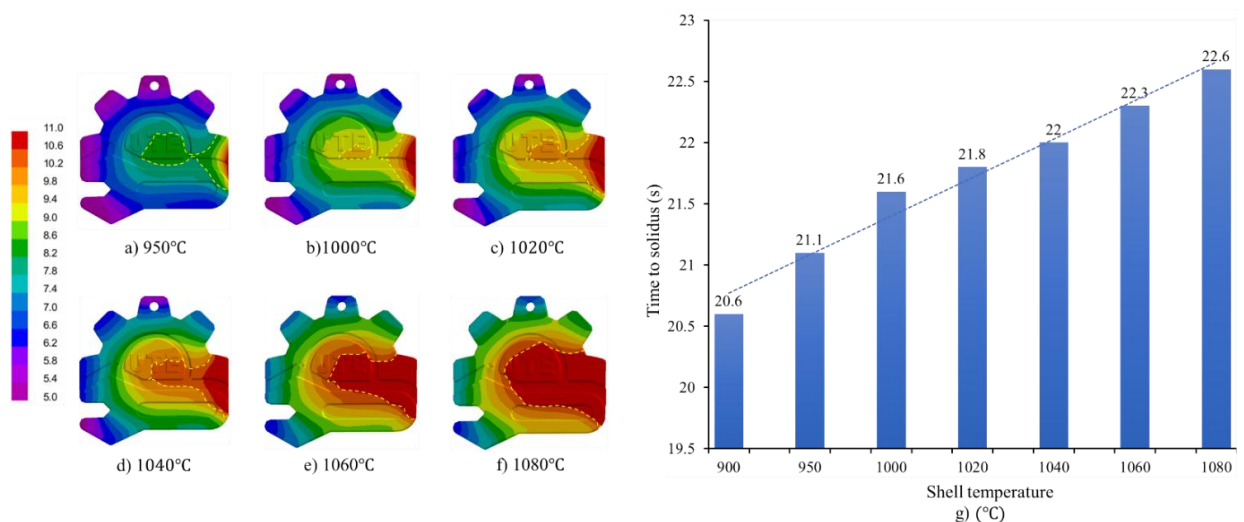


Fig. 12. Time to solidus at different shell temperatures (950 °C – 1080 °C). (a) 950 °C, (b) 1000 °C, (c) 1020 °C, (d) 1040 °C, (e) 1060 °C, (f) 1080 °C, and (g) effect of shell temperature on time to solidus

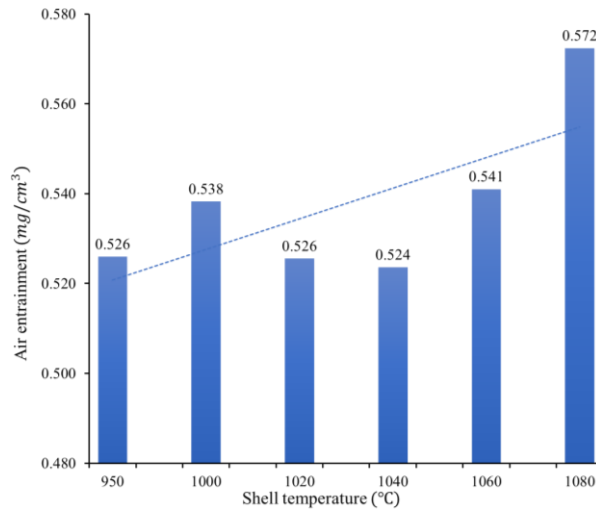


Fig. 13. Air entrainment volume at different shell temperatures.

3.3 The effect of pouring temperature on casting defects

In this section, the filling and solidification of the casting process were analyzed with six different pouring temperatures (1580 °C, 1600 °C, 1620 °C, 1640 °C, 1660 °C, and 1680 °C). The shell temperature was selected at 1040 °C, which is the optimal result in the previous section. Fig. 13 and 14 show the porosity and microporosity at different pouring temperatures. These results indicate that the pouring temperature has a significant impact on the formation of porosity. It can be seen that the trend in Fig. 13 indicates an increase in porosity as the pouring temperature rises. This trend can be further explained through the analysis of the solidification time module in thermal properties, as shown in Fig. 15 (a-f). The excessively high temperatures lead to slower solidification; thereby, the mushy zone with red color expands due to the heat retention tendency [43]. If this zone is not properly fed (an issue discussed earlier), localized shrinkage is expected to occur [44]. Nevertheless, due to the complex and thin-walled geometry of the casting, the cooling rate remains relatively high. As a result, increasing the pouring temperature slows down the cooling rate, which helps reduce the formation of microporosity ($N_y < 1$), decreasing from 1.6% at 1580 °C to 1.09% at 1680 °C, as seen in Fig. 14. Furthermore, within the temperature range of 1580 °C to 1640 °C, the risk of porosity formation is relatively low, as shown in Fig. 14. This is largely attributed to the thin-walled structure, which not only facilitates efficient heat transfer but also stabilizes the thermal gradient. These findings are in good agreement with the study conducted by Huafeng Ding [44]. Their result demonstrated that an optimized pouring temperature around 1620 °C leads to more uniform solidification and reduced shrinkage defects. This similarity reinforces the important role of pouring temperature control, particularly for thin-walled components, in improving the quality of cast products.

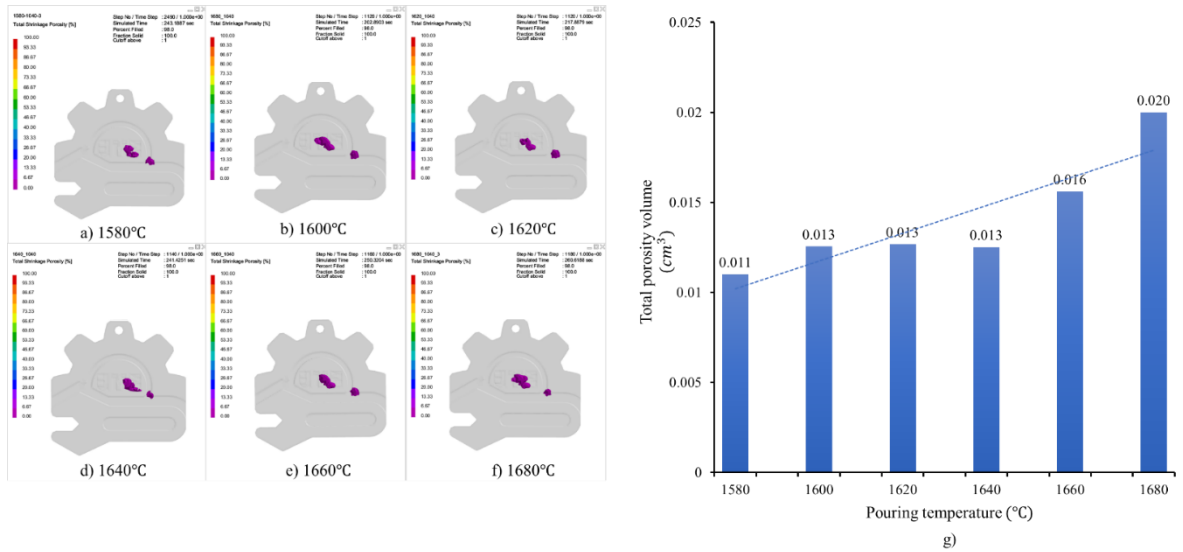


Fig. 14. Porosity at different pouring temperatures (1580 °C – 1680 °C). (a) 1580 °C, (b) 1600 °C, (c) 1620 °C, (d) 1640 °C, (e) 1660 °C, (f) 1680 °C, and (g) effect of pouring temperature on total porosity.

Based on the simulation results above, the mechanism of porosity formation under different pouring and shell temperatures can be explained by the relationship between heat transfer, solidification, and feeding path in the mushy zone as expressed in Eq. (4) [45].

$$\underbrace{(\rho_s - \rho_l) \frac{\partial g_s}{\partial t} + \frac{\partial g_l}{\partial t} (1 - g_s - g_p) + g_s}_{\text{pore formation}} \underbrace{\frac{\partial \rho_s}{\partial t} - \rho_l \frac{\partial g_p}{\partial t}}_{\text{solidification shrinkage}} = \underbrace{\nabla \cdot ((\rho_l \frac{K}{\mu} (\nabla \rho_l))}_{\text{feeding}} \quad (4)$$

Increasing the pouring temperature raises the superheat and causes thermal retraction inside the casting, delaying solidification and weakening the thermal gradient. This, combined with poor feeding efficiency in the mushy zone, leads to a higher tendency for shrinkage porosity formation [46]. In contrast, the shell temperature slightly reduces the thermal gradient but maintains a more stable and directional heat path. This condition favors the formation of coarser grains and higher permeability, improving the compensation of shrinkage [45]. From the above analysis, it can be concluded that pouring and shell temperature significantly influence porosity formation. However, adjusting the shell temperature is more effective for reducing shrinkage defects.

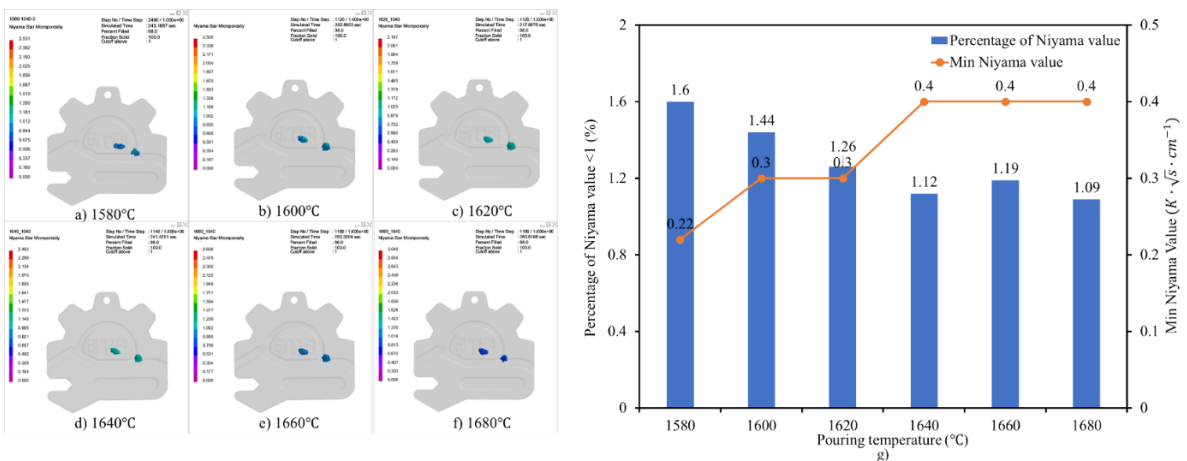


Fig. 15. Micro-porosity at different pouring temperatures (1580 °C – 1680 °C). (a) 1580 °C, (b) 1600 °C, (c) 1620 °C, (d) 1640 °C, (e) 1660 °C, (f) 1680 °C, and (g) effect of pouring temperature on Niyam value.

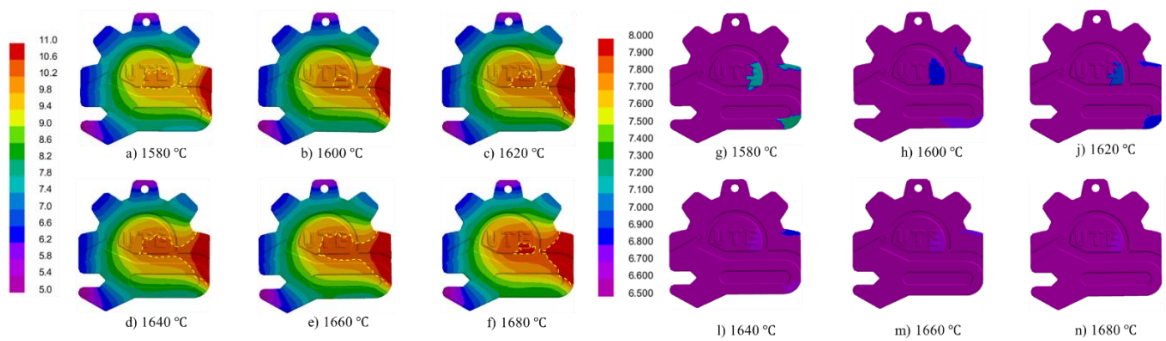


Fig. 16. Solidification time (a-f) and Maximum gas pressure at different pouring temperatures (g-n) at different pouring temperatures.

For thin-walled structure casting parts, selecting the appropriate pouring temperature is a crucial step to prevent misruns, a common casting defect caused by incomplete filling. The results on maximum gas pressure in fluidity properties show that as the temperature increases, the maximum pressure tends to decrease, indicating improved filling performance at higher temperatures shown in Fig. 15 (g-n) [47]. This is further supported by the relationship shown in Fig. 9, which demonstrates a clear decrease in Newtonian viscosity with increasing temperature. At higher temperatures, viscosity decreases significantly, and the mobility enhances, while at lower temperatures, viscosity increases [48]. As a result, optimizing the pouring temperature, which is 1640 °C, minimizes defects and ensures uniform filling. Fig. 16 shows the Reynolds number and comparison of air entrainment at different pouring temperatures. The pouring temperature plays an important role in fluid flow behavior, affecting air entrainment probability. As the pouring temperature increases, the viscosity of molten metal decreases, enhancing the fluidity and reducing the maximum gas pressure. However, at excessively high temperatures (1660 – 1680 °C), as shown in Fig. 16b, a rapid increase in air entrainment is observed. The extremely high turbulent energy, as an initial analysis, causes rapid air entrainment. The characteristics of highly molten metal, which have low density and viscosity, amplify the instability of the molten metal fluid. This instability leads to air aspiration, forming gas bubbles that become entrapped in the casting. Although the relationship between air entrainment and temperature properties is small, it should be quantified for a better understanding of air entrainment. This instability leads to air aspiration, forming gas bubbles that get trapped in the casting. These effects create a trade-off situation; while higher pouring temperatures reduce viscosity and improve mold filling, they also raise the risk of air entrainment. The simulation results indicate that a pouring temperature of 1640 °C offers the best balance, maintaining good fluidity without excessive turbulence, thereby minimizing both porosity and air entrainment.

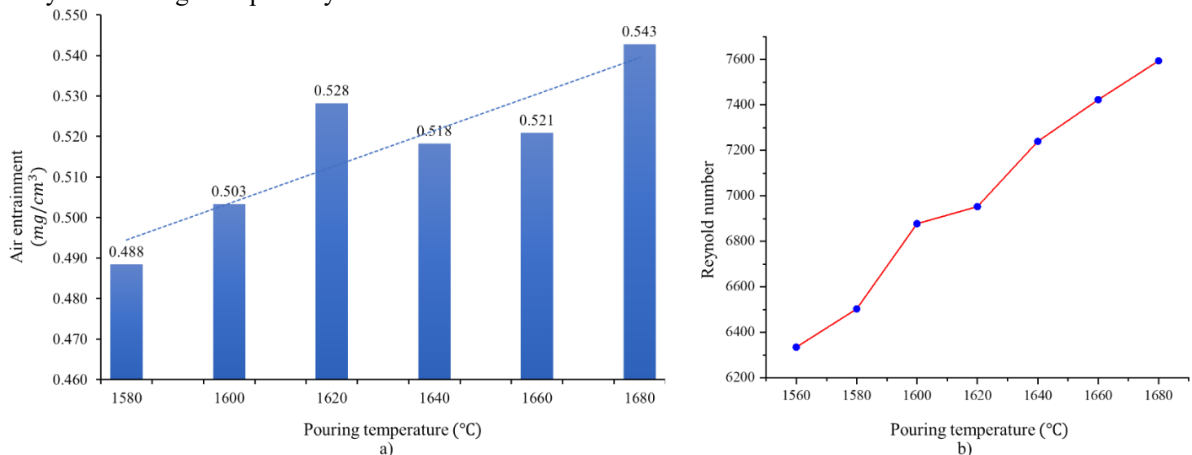


Fig. 17. (a) Air entrainment at different pouring temperatures (1580 – 1640 °C), and (b) effect of pouring temperature on Reynolds number (1560 – 1640 °C).

3.4 Experimental result

To verify the simulation results, the design was experimentally cast in a foundry using optimized process parameters (1640 °C pouring and 1040 °C shell temperature). Fig. 17 shows the experimental results using X-ray analysis and macro, micro visual inspection. The results demonstrate the correlation between the simulated and experimental results while also clearly revealing the defects present in the casting. Hardness also varies by location, with location 1 having the highest hardness of 90 ± 2 HRB due to the fast cooling rate. At location 2, the hardness achieved is 80 ± 2 HRB, while at location 3, the hardness is only 75 ± 3 HRB, as this location still has shrinkage defects and porosity (Fig. 17b). As shown in Fig. 17c- d, the gas porosity forms in areas where the most turbulent region occurred, which aligns with the simulation result. Additionally, the center shrinkage has been identified as a microshrinkage by optical microscopy. Although the results did not completely resolve the defect, a significant reduction in porosity defects can be observed. In addition to the process parameters analyzed in this study, other approaches, such as redesigning the gating system or adding insulating materials to optimize the solidification direction, could further minimize or even eliminate these defects.

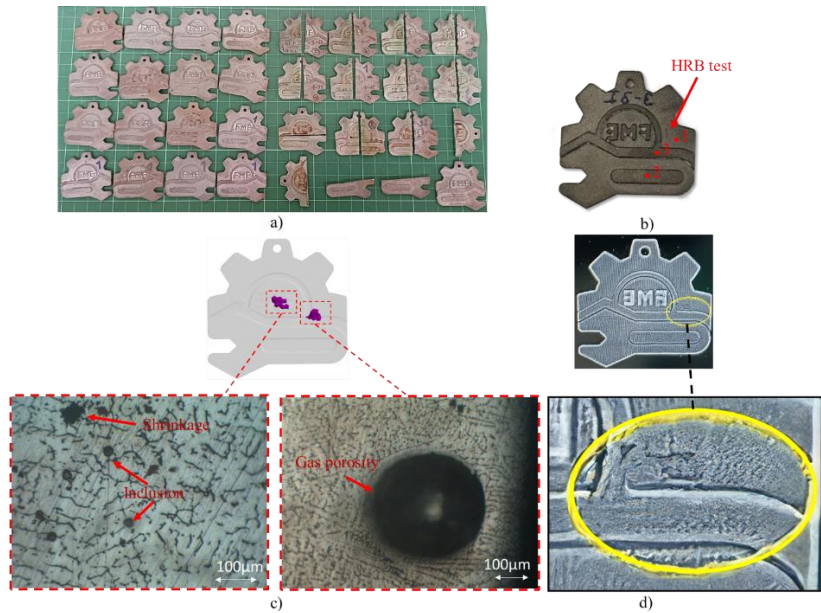


Fig. 18. Experimental results using X-ray analysis and visual inspection (a) Cast part and sample preparation, (b) Hardness test position, (c) a prediction of porosity formation by ProCAST, and (d) X-ray inspection

3.5 Recommendation

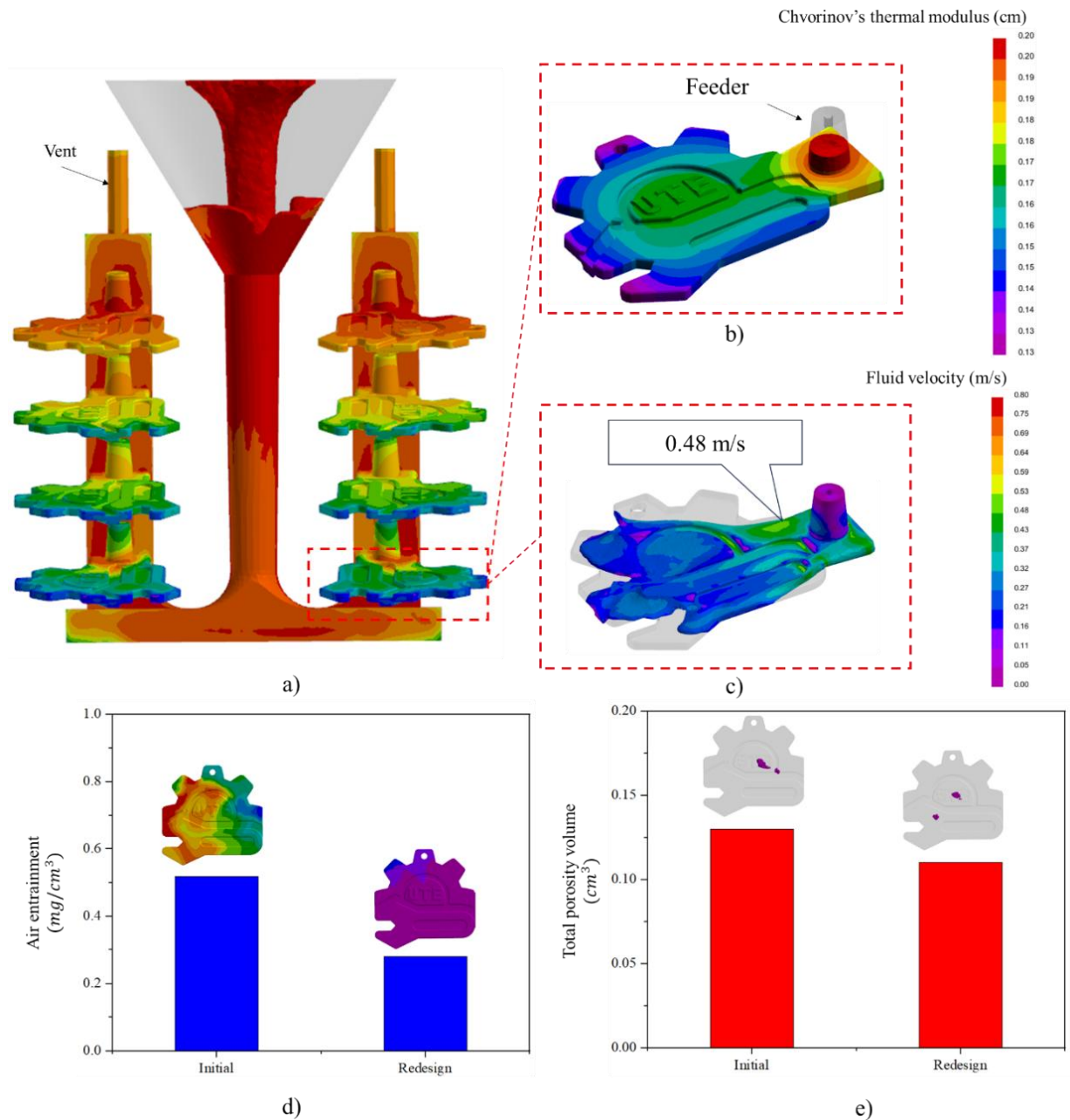


Fig. 19. Redesign of the gating and feeding system to minimize casting defects

Through the evaluation and analysis in the above section, we have identified the optimal thermal parameters. However, the abruptness of the feeding path caused by uneven thickness and the improper functioning of the gating system is the main reason for the formation of defects. To address these problems and improve the overall casting quality, the gating system was modified by providing feeders and vents, as well as redesigning the gating system layout. To improve the quality of the casting, the gating system will be modified by providing the feeder, vent, and adjusting the design of the gating system as shown in Fig. 18 (a), with the new gating design. Fig. 18 b-e shows that the air entrainment and gas porosity have significantly reduced from 0.5 to 0.2 mg/cm³, and the suitable critical velocity is 0.48 m/s (~0.5 m/s). Although there has been a reduction, the shrinkage porosity of the castings still exists due to the complex structure (Fig. 18d, e) and the decrease in casting yield.

4. Conclusion

In this study, the combination of simulation and experiment is used to control the casting defect. Two technical parameters in the investment casting method were designed, each varying a single parameter. The main process parameters, the effects of mold shell temperature and pouring temperature on casting quality, are analyzed. The conclusions are summarized as follows:

- The higher the mold temperature and pouring temperature, the more the shrinkage tends to decrease; however, if the temperature is too high, the energy consumption is significant, and other defects, such as air entrainment, oxidized inclusion, can easily occur.
- The optimized shell temperature has been determined to be 1040 °C. This temperature effectively reduces the cooling rate of the metal, improves the shrinkage compensation efficiency, and minimizes shrinkage porosity. This finding indicates the importance of maintaining an optimal shell temperature to improve overall casting quality
- The optimized pouring temperature is identified as 1640 °C, at 1040 °C. shell mold temperature. This temperature lowers the viscosity of the molten metal, thereby improving both the filling and venting capabilities. As a result, air entrainment and microporosity are significantly reduced.

By simulating and experimenting with the optimized parameters, the porosity defects are reduced by approximately 47% compared to the initial temperature. This demonstrates the significant influence of temperature parameters on casting quality.

Nomenclature

A	Heat transfer surface, cm^2
d_l	Density of liquid, kg/m^3
G	Thermal gradient, K.cm^{-1}
V	Volume, cm^3
M	Modulus ratio (V/A)
N_{Re}	Reynolds number
N_y	Niyama criterion, $\text{K} \cdot \sqrt{s} \cdot \text{cm}^{-1}$
R	Cooling rate, $\text{K}/\sqrt{s}$
R_H	Hydraulic radius, m
T	Temperature, °C
v	Velocity, m/s or mm/s
μ	Viscosity, mPa.s
<i>COINC</i>	Coincident interface
<i>EQUIV</i>	Equivalence interface
<i>SUS 304</i>	Stainless steel 304
p_l	Pressure liquid, Pa
K	Permeability, mm^2
t	time, s
ρ_s	Solid density, kg/m^3
ρ_l	Liquid density, kg/m^3
g_s	Solid fraction
g_l	Liquid fraction
g_p	Pore fraction

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