COMPUTER-AIDED ENGINEERING (CAE) SIMULATION FOR THE ROBUST GATING SYSTEM DESIGN: IMPROVED PROCESS FOR INVESTMENT CASTING DEFECTS OF 316L STAINLESS STEEL VALVE HOUSING

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Abstract

Defects in investment casting will inevitably reduce the lifetime, degrade the quality of the casting, and increase the manufacturing costs. In this paper, the potential for shrinkage porosity was numerically determined and a retained melt modulus (RMM) model was implemented to analyze highly probable regions. The proposed casting schemes of gating designs are compared by the quality of casting (shrinkage porosity) and practical feasibility in terms of small hole drilling machinability. The purpose of this study was to determine the feasible plan with the lowest PES (percentage of elements with shrinkage porosity) while promoting near-net shape casting with minimum machining cost and increasing material usage. Virtual thermo-dynamical sensors (VTDSs) were adopted in the simulations to indicate the impacts of different pattern assembly gating systems on the cooling gradient and direction of solidification. VTDSs were used in simulating and virtually monitoring the casting systems, with the aim of characterizing the rates and directions of solidification in various regions of the cast. The best-case scenario of investment casting conditions was chosen to fabricate valve housing in an investment casting foundry. The experimental results of the X-ray image differentiated nearly none of the pernicious defects that typically occurred with the proposed casting, confirming the efficacy of the proposed scheme accordingly.

Keywords: CAE, gating system design, investment casting, 316L stainless steel, valve housing, shrinkage defects

Introduction

Investment casting is one of the most versatile casting methods, allowing for near net shape castings with great dimensional precision and casting quality. It’s higher efficiency and overall manufacturing costs (machining and material yield, etc.) can be competitive as compared with typical sand casting. It is especially well-suited to produce complex-geometry components. High accuracy in the creation of products with smooth surfaces and sophisticated geometry is usually produced by investment casting.1–7 The valve housing production process through investment casting is exceptionally complicated; part of the reason is that the shrinkage during the casting process is nonlinear.7,8

The casting processes of the 316L valve housing have been simulated using the numerical method. Industrial meters are widely used in various sectors to measure velocities, flow, pressure, etc., such as the liquid valve and gas valve. These systems are subject to high-pressure or even corrosive environments and must maintain perfect sealing performance, which means that the parts are at increased risk of corrosion and leakage and require regular maintenance. The valve housing is usually manufactured by casting; however, the mechanical strength and sealing performance of the component will be substantially reduced by the presence of casting defects. If transmission material leaks or even toxic materials, unpredictable rupture of the valve housing can cause serious damage, economic loss, or instability of the industrial process.9–11
With the advancement of computer technology in recent years, numerical modeling and simulation have become a popular method to describe the solidification process. Technologically advanced computer-aided engineering (CAE) simulation and nondestructive testing technology are desirable for the design alternative. They possess many advantages, such as improving quality, reducing cost, and shortening the development schedule. CAE simulation is the most efficient and profitable technology from the perspective of quality and defect prediction to analyze and evaluate the quality and defects of casting products. The dataset created in this way will help to enhance investment casting simulation accuracy. To effectively simulate solidification and predict shrinkage, investment casting shell molds require reliable and realistic thermal characteristics data. Many previous casting research methods have chosen trial-and-error methods, often unreliable, time-consuming, and costly. One of the fundamental dilemmas is that it is difficult to build reliable predictions about the casting defects arrangement because we cannot inspect the flow of molten metal in the cavity and the tendency of solidification. Using CAE software can predict the scope and approximate the number of defects that can be formed during the casting process and the direction of solidification. A lot of development time and costs can be minimized compared to traditional trial-and-error methods. Manufacturers yield, verify, examine, and improve the design schemes assisted by CAE simulation technology.

In this study, a commercial software package (C3P) was used to perform simulations of investment casting. The investment casting systems were meshed using hexahedral elements of appropriate size. The continuity equation, Navier–Stokes equation, energy conservation, the volume-of-fluid (VOF) function, and k-equations were used to estimate the pressure field, velocity field, and temperature field during filling and solidification. For each casting system, a statistical RMM model was used to evaluate the probability of cavity shrinkage formation, as follows: \[ M_R = \frac{V_R}{S_R} \] , where \( M_R \) represents the volume and surface area of isolated melt at the time that each mesh reached the critical solid fraction. A lower RMM value indicates a higher chance of shrinkage occurrence. The finite difference method was utilized to solve differential equations and analyze the flow through the mold using this commercial code. Finally, non-uniform patterns in the cooling and solidification of the liquid metal, the complicated thermophysical properties of the alloy, the structure of the cast, and the cooling conditions during casting are all factors that contribute to the production of shrinkage cavities and/or porosity defects.

In this paper, four types of pattern assembly gating systems are designed and analyzed. In the initial scheme, a closer casting pattern assembly method is used and some shrinkage porosity is found on the surface of the simulation result and the trial casting. Minimizing closely related PES to the gating system is the ultimate goal of the optimization of the casting gating system. The feeding system is a structure that stores the molten material to compensate for possible shrinkage in the solidification phase during the casting process.

Figure 1 shows the simple size and front and back views of the industrial meter body we want to produce. The schematic diagram of the component is shown in Figure 1a–c shows the front view and the back view of the solid valve housing model. In this research work, a square component with three screw holes is used. This component has applications in various industries. The weight of the casting is approximately 5.23 kg, and the material used is stainless steel (316L).

Figure 2 illustrates the shrinkage porosity observed on the surface of the meter body housing manufactured via investment casting. During the solidification process, accurate predictions related to the percentage of elements with shrinkage defects (PES) should be eliminated. Figure 2a and b displays photographs of frequently encountered production casting defects, both on the casting surface and revealed after machining. The key reasons can be attributed to the following: (1) The isolated retained melt during solidification resulted from the insufficiently filled molten metal from the runners. The shrinkage porosity defects can be formed. (2) A severe temperature gradient occurred in a specific region of a large flat surface during the casting process. Thus, molten iron overflow causes wrinkled surface defects in the valve housing. (3) The geometry-dependent solidification property of the corner screw hole with the highest volume-to-surface ratio resulted in isolated residual melts. The PES value was significantly increased, which is derived from the excellent corrosion resistance of 316L.

Investment casting is an ancient casting process that uses loss wax and ceramic shell molds made of mullite slurry, zircon slurry, binder, and other associated materials. The typical investment casting processes include wax injection, wax pattern assembly, stuccoing, loss-wax, pouring, mold breaking, and sandblasting. There are machining, heat treatment, and surface treatment in the post-processing stage according to casting requirements. Multiple factors such as equipment, processing, materials, and shell mold-related factors are positively correlated in the routinely exercised process flow. Therefore, investment casting has a complicated and lengthy manufacturing system with the primary process, as illustrated in Figure 3.

**Materials and Methods**

Figure 4 shows an illustrated schematic with the original scheme used to cast the valve housing, where the molten
steel was poured into the sprue cup and flowed through the lateral runner to the mold cavity. The initial air of the cavity was exhausted from the vent hole to liberate the pressure of the gating system. The dimensions of the gating system are shown in Figure 4. In our CAE simulations, we selected the trial conditions in Table 1, which are widely used in the fabrication of investment casting in our trial casting. The chemical composition standard of 316L stainless steel is shown in Table 2. Before each pour stage, the casting operator will pick up a small ladle of molten metal from the heating furnace, and it into a small cake test piece, and send it to the chemical composition analysis via optical emission spectrometer (ThermoFisher ARL 3460 Advantage, USA) to confirm that the composition of the material meets international standards. The physical properties of 316L stainless steel are shown in Table 3. For each batch of casting, several tensile test bars are cast at the same time, and after the mechanical strength test, the data and test bars are sent to the customer together with the product to confirm that the mechanical strength of the material is acceptable. Details of the FEM model and casting simulation parameters are indicated in Table 4. The side length of the fem grid we established is 1 mm because this size has a balance between the simulation speed and the revivification of the model in the comprehensive evaluation. The shell mold temperature in the simulation is set at 1100 °C because according to the results of our observation with a thermal camera, the temperature of the shell mold out of the furnace will not reach 1180 degrees set by the heating furnace, but around 1000–1100 degrees.
Figure 5, respectively, presents interpretations of the gating systems in Case A, Case B, Case C, and Case D. To ensure a reasonable comparison, all numerical simulations of the casting schemes in Figure 5 are produced using the same conditions in real trial casting.

The original design and the major difference between Cases A and B will be the relative location of valve housing casting, primarily for the screw hole facing outward in Case A and inward for Case B, as indicated in red rectangle in Figure 5.

Cases A and C have similar assembly patterns, as do Cases B and D. Case C and D are the versions of Case A and B to extend the casting distance to add ceramic cores to avoid the difficulty of processing the inner hole of the valve housing. The extension of the casting distance is designed to place the ceramic cores in the wax model. In the case of D, the outer screw holes are additionally filled in, and the screw holes are processed after casting to reduce the excessive change in the thickness of the casting, thereby avoiding defects on the inner side of screw holes. The brown-colored shapes in Cases C and D are CAE models of ceramic cores.

Results and Discussion

Figure 6 shows the predicted defect regions that appeared by the solidification shrinkage. The modulus method in a commercial software package (C3P) indicates these areas of shrinkage defects. In light of the casting theory, the irregular cooling temperature areas usually cause shrinkage defects. It is considered to avoid those defects, which is what a good pattern of assembling needs. Figure 6a displays the PES distributions of the gating system in Case A. In addition, the simulated porosity prediction is mainly located in the thicker area of the casting geometry, which roughly corresponds to the high-risk area of defects. Inset of Figure 6a reveals the color distribution on the porosity prediction such that the red and the blue colors indicated PES of 0.756 and 0.011, respectively. PES indicates the
probability of cavity shrinkage formation such that a higher PES value indicates a higher chance of shrinkage occurrence.

Shrinkage porosity appeared inside the ring on the front side of the casting and on the inner side of the screw hole, as shown in Figure 7a. It can be attributed to the tangible fact that the geometric thickness and cooling rate around the screw hole are higher than that of the screw hole itself during the cooling phase. Therefore, the molten metal in the riser cannot supplement the screw hole.
Figure 6b presents the PES distributions of the gating system in Case B as the front view of the pattern. In Case B, the combination of the pattern with the assembly method of placing the thick side of the casting in the middle diminished the PES values observed in the ring and the part near the screw hole in Case A. However, we reduced the rate of shrinkage by changing the assembly method. In the case of the same material yield and the same pouring geometric design, the number of shrinkage defects can be reduced only by placement of the castings.

Figure 7 shows a graph of the method of pattern assembly versus the percentage of shrinkage elements and indicates that the shrinkage percentage of the casting will be reduced by nearly 45% with the different assembly methods. Changing the placement method and placing the thick side of the casting in the middle of the pattern can make the solidification trend more continuous. The feeding function of the runner could be better. The area where the isolated liquid region is reduced from Case A to Case B and the location where shrinkage porosity occurs will also be reduced.

Figure 8a illustrates the cracking of the shell mold during trial casting in Case A for the real trial casting photograph, as indicated in the red ellipse inset. One of the attributed reasons for the cracking of the shell mold is the unanticipated change in the magnitude of the velocity. The corresponding simulated results in Figure 8b show the velocity magnitude higher than 2500mm/s in the red rectangle inset, and the magnify view reveals that the maximum value can exceed 2850mm/s. A similar trend is also observed in Figure 8c the pressure magnitude can locally accumulate 1.11 MPa in the red rectangle inset. In addition, the precipitous gradient of the pressure and velocity magnitude (the velocity gradient is about 1025.5 1/s, the pressure gradient is about 0.015 MPa/mm) has a similar position with the cracking part of the shell mold in Figure 8a.

The laser flash method was utilized to determine the thermal diffusivity of the shell, according to the correspondence from the technical scientist of the commercial software package (C3P). In a laser flash thermal diffusivity test, the thermal diffusivity ($\alpha$) is calculated from specimen thickness ($L$) and time ($t_{1/2}$) required for rear face temperature to reach 50% of its maximum value:

$$\alpha = \frac{0.1388 L^2}{t_{1/2}}$$

Eqn. 1

The temperature rise (DT) of the reference with known

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Table 1. Trial Casting and Simulation Conditions for Every Casting Project

| Casting material | Pouring temperature (°C) | Shell mold temperature (°C) | Shell mold thickness (mm) |
|------------------|--------------------------|----------------------------|--------------------------|
| 316L             | 1680                     | 1180                       | 6                        |

Table 2. Chemical Composition of 316L Stainless Steel

| Element | Composition |
|---------|-------------|
| Cr      | 16.5-18.5%  |
| Ni      | 10-13%      |
| Mn      | <2%         |
| Mo      | 2-2.5%      |
| Si      | <1%         |
| N       | 0.11%       |
| P       | 0.045%      |
| C       | <0.03%      |
| S       | 0.02%       |

Table 3. Physical Properties of 316L Stainless Steel

| Property               | Value          |
|------------------------|----------------|
| Density ($\rho$)       | 8 g/cm³        |
| Elastic modulus (E)    | 193 GPa        |
| Hardness (H)           | 215 Max HB     |
| Tensile strength (σ_t) | 500–700 MPa    |
| Yield strength (σ_y)   | 200 MPa        |
| Coefficient of thermal expansion ($\alpha$) | 1.59E-5 1/K |
| Thermal conductivity ($\lambda$) | 16.3 W/(m*K) |
| Melting point (T_m)    | 1400°C         |

Table 4. FEM Model Conditions and Simulation Setting Parameters

| Element size | Casting elements | Shell mold elements | Pouring temperature setting | Shell mold temperature setting | Heat transfer coefficient from casting to mold | Environment temperature |
|--------------|------------------|---------------------|-----------------------------|-------------------------------|---------------------------------------------|-------------------------|
| 1mm          | 222985           | 144809              | 1680°C                      | 1100°C                        | 2500 W/(m*K)                                | 30°C                    |

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specific heat capacity (Cp) and the specimen is measured. If the density (\( \rho \)) of the shell is known, then specific heat capacity of the shell can be calculated:

\[
(p_c)_M = \frac{L_R \Delta T_R}{L_M \Delta T_M} (p_c)_R
\]

Finally, thermal conductivity (K) of the shell can be calculated by substituting the measured value of specific heat capacity along with the thermal diffusivity:

\[
K = \rho c_p \alpha
\]

Figure 9 shows (a) density, (b) specific heat capacity, and (c) thermal conductivity values of the shells inspected by the laser flash method, and these temperature-dependent
values were implemented in the commercial software package (C3P) for simulating molten metal filling process and solidification of different gating scheme. The heat transfer coefficient (HTC) assumed between the casting and shell was 2000 W/m² K.\textsuperscript{26} These heat transfer coefficients were calculated, assuming that there was no additional boundary thermal ceramic shell and that the casting had no substantial resistance. For example, any air gap between the effect and the large difference in thermal diffusivity between the shell and the metal is due to the predominance of radiant heat transfer.

Figure 7. Comparison of Cases A and B in the prediction of shrinkage porosity.

Figure 8. Case A encountered cracking of the shell mold during the trial casting. (a) Real trial casting photograph. Corresponding the simulated results, (b) velocity magnitude and (c) pressure magnitude.
Heat radiation flux between two facing bodies is computed using the Stefan–Boltzmann law:

\[ Q_{\text{rad}} = h_{\text{rad}} (T_{\text{Cast}} - T_{\text{mold}}) \]  

Eqn. 4

where the \( T_{\text{Cast}} \), \( T_{\text{mold}} \) are the temperature of casting and mold, respectively, in Celsius. Heat radiation coefficient \( h_{\text{rad}} \) depends on the emissivity of the two bodies, \( e_{\text{cast}} \) and \( e_{\text{mold}} \), respectively, and Stefan’s constant \( \sigma_a \) can be expressed as:

\[ h_{\text{rad}} = \frac{\sigma_a}{\left( \frac{1}{e_{\text{cast}}} + \frac{1}{e_{\text{mold}}} - 1 \right)} \]  

Eqn. 5

Figure 10 illustrates the shell mold temperature with time in Case B with measured temperature with a thermal camera (Ching Hsing Computer-Tech Ltd P384 series, Taiwan) (solid line) and simulated temperature (dotted line). Generally speaking, the simulated temperature was higher than the measured temperature, and the temperature difference was in the range of 100–200°C for the positions P1–P3. The possible discrepancy was mainly attributed to forced convection of the wind in the open space; measurement error is due to the heat photography distance.

Figure 11 shows the areas of expected defects from Case A to Case D that result from the solidification shrinkage. The results of Figure 11a and b are discussed in Figure 6. Figure 11c shows the Case C PES distributions as the front view of the pattern. Casting defects appeared inside the ring on the front side of the casting and on the inner side of the screw hole, as shown in Figure 11c. These areas with shrinkage defects in Case C are similar to Case A’s location while extensively distributed and can be primarily attributed to the solidified tendency to become less continuous as a result of the distance between the castings being extended. As the distance between the castings becomes more extensive, the heat preservation effect caused by heat radiation is also reduced, causing the solidification tendency to worsen. It also causes the
influence of runner feeding in Case C to be worse than in Case A.

Figure 11d shows the Case D PES distributions as the front view of the pattern. The phenomenon observed between Cases B and D is similar to that observed between Cases A and B. The reason for the slight increase in the percentage of shrinkage defects is the extending of the casting distance.

Figure 12 shows the prediction of shrinkage porosity in Cases A to D. When the distances between castings increase in patterns, the percentages of elements with shrinkage increase (Case C has 5% more PES than Case A, and Case D has 20% more than Case B). Although Case D has more PES, it can prevent shrinkage defects on the inside of the screw hole, and we must choose the final case in Case C or D in order to avoid the difficulty of processing the inner hole on the casting by adding ceramic cores. Cases A and B have difficulty in terms of ceramic cores extraction, while Cases C and D extend the distance between two casting parts from 12mm to 60mm such that the ceramic cores extraction can be practically operable.

In addition, the design of Case A acquires high possibility of shell cracking due to the relatively higher velocity of molten metal flow, as indicated in Figure 8. And the 12-mm gap in Case B will inevitably cause uneven shell thickness of the casting body inner faces during the stuccoing process due to the presence of the protruding parts of the ceramic cores.

Figure 13a–d reveals the positions of the virtual thermodynamic sensor (VTDS) placed in each gating system: (a) Case A, (b) Case B, (c) Case C, (d) Case D. In the schematic diagram, mark the VTDS from numbers 1 to 5.
on the red dots. The VTDS was placed in the center of the runner, gate, and structure of the valve housing, where the solidification trend of the entire casting can be clearly described.

Figure 14a–d presents temperature alternations of molten metal at the VTDS in different casting schemes as a time function: (a) Case A, (b) Case B, (c) Case C, (d) Case D. The results in Figure 13 illustrated the following significant findings: (1) The time required for the molten iron from the liquidus temperature (1400 °C) drops to the solidus temperature (1375 °C) of the alloy 316L at points 4 and 5 was as follows: 100 s (Case A) and 120 s (Case B), as shown in Figure 14a and b. This time discrepancy demonstrates that the pattern assembly method will delay solidification for 20 s and allow enough molten metal to flow into the mold cavity. (2) The time required for the molten iron from the liquidus temperature (1400 °C) drops to the solidus

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**Figure 11. Prediction of shrinkage porosity for all simulation schemes. (a) Case A. (b) Case B. (c) Case C. (d) Case D.**

**Figure 12. Comparison of Cases A–D in the prediction of shrinkage porosity.**
temperature (1375 °C) of the alloy 316L at points 4 and 5 was as follows: 70 s (Case C) and 92 s (Case D), as shown in Figure 14c and d. This time discrepancy demonstrates that the pattern assembly method will delay solidification for 22 s and allow enough molten metal to flow into the mold cavity. (3) We can also find that Case C and D’s cooling rate at points 4 and 5 is faster than that of Case A and B, resulting in a slight drop in Case C and D’s casting quality compared to Cases A and B. It can be approved in Figure 13. (4) The cooling rate of points 1, 2, and 3 is slower than points 4 and 5 in Figure 14.; it proves that when the casting starts to solidify, the molten metal can continue to be fed into the casting due to the higher temperature of the runner and pouring cup, reducing the generation of shrinkage defects. The slower cooling rate significantly reduced the likelihood of shrinkage porosity and shrinkage cavity.

Figure 13. Schematic of the locations of the virtual thermodynamic sensor (VTDS) in the gating system and casting. (a) Case A. (b) Case B. (c) Case C. (d) Case D.

Figure 15a and c illustrates the predicted spots of shrinkage defect distribution on the workpiece surface in simulation. The areas where shrinking defects formed are shown in blue areas. Figure 15 b and d reveals the casting defects on the surface of the valve housing in the photograph. These effects can be attributed to the placement method of the assembly pattern. In Case C, the thicker part of the casting was placed on the outer side of the tree, where a higher cooling rate would be. An isolated liquid region occurred at the rapidly cooling place and caused a shrinking porosity. Figure 16 presents some of the cavitation defects on the surface manufactured by investment casting, including microporous forming due to shrinkage between the corner screw hole’s inner side due to geometric inequality of the casting. Designers must have the ability to make precise predictions about shrinkage during the cooling process to develop solutions to eliminate defects.

Ceramic cores were utilized in our Cases C, D because inner holes are hard to process. However, the ceramic cores were easily broken, while molten iron was poured into
when the first trial casting was carried out in Case C and Case D. The ceramic core fracturing problem caused the valve housing shape to deform, as shown in Figure 17. In order to mitigate ceramic cores fracturing problem, the chemical composition of the ceramic cores had been modified with the experimentally validated satisfactory results. Table 5 presents the modification of the core ingredients, and the purpose of increasing the concentration
of ZrO₂ is to reinforce its mechanical strength so that the ceramic cores can better withstand the pressure from the molten metal flow.

Figure 18a illustrates wrinkled surface defects in shell mold cracks caused by a high temperature gradient in the solidification process during the trial casting in Case D for the real trial casting photograph. Simulation results in regions with a large temperature gradient (Case D) coincide in the same position with some surface defects on the actual casting. After pouring 645 seconds in simulation, the orange rectangle inset temperature can rise from 1037 °C to 1178 °C within a 3-cm distance shown in Figure 18b, and the temperature gradient is about 47 °C/cm. The red rectangle inset in Figure 18c reveals that the temperature after

**Table 5. The Modified and Original Ceramic Core Ingredients**

|          | SiO₂ | Al₂O₃ | ZrO₂ |
|----------|------|-------|------|
| Original | 84.45| 2.62  | 12.94|
| Modified | 34.27| 0     | 65.73|

Figure 16. Simulation results of the shrinkage porosity on the inner side of the screw hole (Case C) in the same position as the actual casting photograph.

Figure 17. The ceramic core fracturing problem occurred on several trial castings in Case C and Case D.
pouring 364 s can rise from 1059 °C to 1161 °C within a
distance of 3 cm, and the temperature gradient is about 34
°C/cm. The large temperature gradient may cause the
casting to expand unevenly, which will cause some micro-
cracks on the surface of the shell mold and cause wrinkled
surface defects of the casting.

According to Case D, submit photographs of the trial
casting to certify the simulation results with a filled corner
screw hole are shown in Figure 19. Figure 19a shows
simulation model of Case D without surface defects, Fig-
ure 19b shows finished product of the casting after
machining, Figure 19c, d shows enlarged images showing
the perfect screw hole of Case D. After machining, the
inner wall of the screw hole in Case D is perfect without
defects, which meets the customer’s needs for this casting.
There are no apparent shrinkage defects in the finished
product, as revealed in Figure 16b–d. In addition, no black
spots in the X-ray photograph were detected inside the
valve housing by nondestructive tests, as shown in Fig-
ure 19e–f. The quality of the stainless steel valve housing
trial (316L) in Case D contributes convincing evidence
supporting the effectiveness of our valve housing casting
strategy.

To validate the accuracy of simulation results, the valve
housing was investment casted in the casting factory using
the CAE-derived casting parameters. X-rays were used to
evaluate the suitability of optimized casting conditions to
reduce or avoid casting defects. Figure 21b presents a
photograph of the wax pattern. Figure 21c presents a front
view of the casting on the left side and back view of the
casting on the right side without surface defects of the final
casting under Case D. Figure 21d demonstrates X-ray
images of the casting results, which prove the efficacy of
the casting parameters under Case D. No black spots were
detected in the X-ray photograph inside the valve housing
under Case D, as shown in the image in Figure 21d. The
quality of the stainless steel valve housing (316L) trial
(316L) trial from Case D contributes convincing evidence
supporting the effectiveness of our valve housing casting
strategy.

Conclusions

In this study, numerical simulations based on the modulus
method were used to predict where and how shrinkage
defects can form in the stainless steel (316L) industrial
meter housing of the valve. Our results from previous
casting experience, preparatory simulations, and experi-
ments were used to formulate four simulation casting
schemes. The plan with the smallest and acceptable PES
with operable ceramic cores removal of Case D was
selected for the final gating system. We set virtual TDSs in
every casting system simulation to characterize the cooling
rates and solidification directions in different casting
Figure 19. (a) Simulation results, (b), (c), (d) images of actual casting (Case D). (e) X-ray images of the thick side of the casting in Case D; (f) X-ray images of the screw hole that has shrinkage porosity in Case A and B but perfect in Case D.
regions after pouring. Our simulation results illustrate that the extended gating system (Case D) could reduce most casting defects, while the removal of the ceramic cores can be operable, even though Case D has 20% more PES than Case B.

Moreover, filling of the case D screw hole can eliminate the shrinkage defects after processing on the inner side of the screw hole. At the same time, the design of adding the ceramic cores to Case D can avoid the problem of processing the inner hole, so we can perfectly meet the requirements of the client. We then applied the casting conditions as the simulation set to manufacture a meter body for a real casting valve. X-ray photographs illustrate that the suggested gating system and prearranged casting conditions removed most of the destructive casting defects typically associated with this casting method. The strategy revealed in this paper provides a helpful reference for the investment casting of the valve body in terms of quality and cost-effectiveness.

Figure 20. Temperature of the case D shell mold with time during the solidification process in three different positions, i.e., P1 on the center of the runner, P2 on the central side of the front side of the casting shell mold, and P3 on the central side of the backside of the casting shell mold. Actual temperature measured with the thermal camera (solid line) and temperature predicted in simulation result (dotted line).
Authors’ Contributions All authors contributed equally to the generation and analysis of experimental data, and the development of the manuscript.

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Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

Conflict of interest Author declare that they have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Ethics Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate All authors declare they have agreed for authorship, have read and approved the manuscript, and have given the consent for submission and subsequent publication of the manuscript.

Consent for Publication All authors are consenting to publish this article with its included data in The International Journal of Advanced Manufacturing Technology and approve its final version.

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Figure 21. Images and X-ray photographs of casting in Case D. (a) Wax pattern. (b) A different view of the ceramic shell mold with the die head. (c) Front view (left) and back view (right) of Case D casting. (d) Cross section of the product X-ray image.
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