

Article

Research of Feeding Effect of Ductile Cast Iron under Different Riser Conditions

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Abstract: Ductile cast iron has typical characteristics of mushy solidification and ductile expansion. The feeding effect of ductile cast iron was studied by means of numerical simulation and pouring tests. The prototypes used for experiments were designed into three types: riser without neck; riser with narrow neck; and riser-less. The corresponding molds were made of coated sand. The pouring temperature was set to 1350 °C, 1300 °C, and 1250 °C, separately. Results showed that the feeding effect could be controlled by the riser structure and the pouring temperature comprehensively. If the pouring temperature was higher than a certain value, the casting should be fed by a riser, and the riser structure would play an important role. However, it was very hard to design a riser exactly, and the unsuitable riser would cause macro porosity or surface sink. When the pouring temperature decreased to a certain value, there was no macro porosity or surface sink. It could provide a potential method to simplify the feeding process and improve the casting quality.

Keywords: feeding effect; ductile cast iron; casting; macro porosity; surface sink; mushy solidification; graphitization expansion; riser; riser-less



Citation: Wang, T.; Yao, S. Research of Feeding Effect of Ductile Cast Iron under Different Riser Conditions. *Metals* **2022**, *12*, 412. <https://doi.org/10.3390/met12030412>

Academic Editor: Alexander McLean

Received: 6 February 2022

Accepted: 24 February 2022

Published: 26 February 2022

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1. Introduction

In the casting production, the molten alloy would reduce its volume during the cooling and the solidification process. If the casting could not be fed sufficiently, internal porosity and surface sink defects would appear, especially for the alloy that has a mushy zone during the solidification process. In order to reduce the shrinkage defects of casting, the riser is usually applied for feeding casting, and a reasonable feeding process is important to improve the casting quality, the process yield, and the production efficiency [1–4].

Ductile cast iron has been a very popular and important engineering material in the past 50 years. It is much easier to manufacture complex-shaped casting than steel but with similar properties. It has been widely used in automobile, fire protection, electric power, etc. [5–9]. It has typical solidification characteristics of mushy solidification and graphitization expansion. Due to the different production conditions, practical experience, and theoretical basis, the feeding process applied for the ductile cast-iron castings is quite different. Some people follow the principle of a sequential solidification process and set a large riser on the hot spot of the casting. However, some people think that the mushy solidification and graphitization expansion of ductile cast iron should be fully considered. It is considered that a casting with dense structure could be produced only by using a small riser and even by a riser-less process [10–15].

The application of numerical simulation has become a trend in the casting industry due to its great efficiency and reliability. Based on numerical simulation, the melt flow state, solidification process, and stress distribution could be calculated step by step and displayed visually. The casting defects such as shrinkage, misrun, stress concentration,

etc. could be predicted. Afterwards, the casting process could be optimized based on the numerical simulation and analysis results [16–18].

In this paper, the solidification process and feeding effect of ductile cast iron under different riser conditions are studied by means of numerical simulation and pouring experiments. Based on the results and analysis, it could reveal the feeding effect of a ductile cast iron under different feeding conditions. Afterwards, some important points could be concluded for optimizing the feeding process of the ductile cast iron.

2. Materials and Methods

In this study, the ductile cast iron (65-45-12) was used for experiments. The ductile cast iron was melted in a medium-frequency induction furnace (brand: INDUCTOTHERM, capacity: 5 tons) and was discharged at 1500 °C. The inoculation treatment and the spheroidization treatment were carried out during the process of melting and pouring. The composition of ductile cast iron is shown in Table 1. The composition of C and S was measured by a carbon/sulfur analyzer (brand: HORIBA) and the composition of Si, Mn, and P was measured by a spectrometer (brand: SPECTRO). The morphology of graphite spheres in ductile iron after solidification was observed by a metallurgical microscope (brand: ZEISS)

Table 1. Composition of the ductile cast iron in this experiment (wt %).

C	Si	Mn	P	S	CE
3.70	2.76	0.32	≤0.07	≤0.02	4.62

In order to investigate the feeding effect of ductile cast iron during the solidification process, three types of prototypes were designed (as shown in Figure 1). The shape of casting was cubic, whose modulus was about 1.5 cm for all the three prototypes. The modulus of the cylindrical riser was about 1.1 cm for prototype A and prototype B. It should be noticed that the riser in prototype B had a riser neck whose modulus was about 0.4 cm. The prototype C had a sheet runner instead of the riser. To manufacture the prototype molds, the coated sand made of silica sand and urotropine was cured at 230 °C.

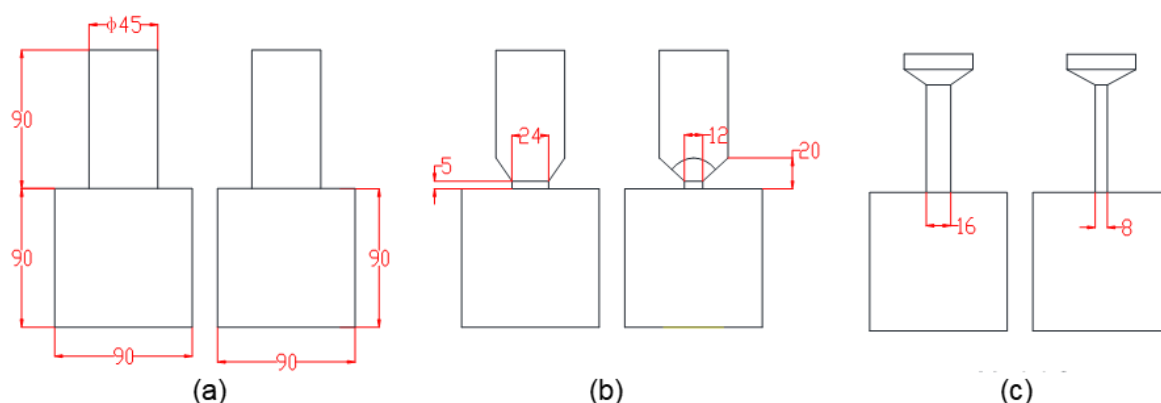


Figure 1. Front view and side view of the prototypes for investigating the solidification process and the feeding effect of ductile cast iron: (a) Model type A, cylindrical riser; (b) Model type B, cylindrical riser with riser neck; (c) Model type C, riser-less.

Before pouring, the molds made of coated sand were rigidly fastened and buried in the molding sand. The molten melt in the furnace was poured into a small lifting bag through a transfer ladle; then, we waited until the temperature dropped to the required value. The secondary inoculation treatment should be carried out in the small two-man ladle. The spheroidization rate of ductile iron casting was determined by the built-in software of the microscope, which could reflect the percentage of spheroidal graphite in total graphite (shown in Figure 2). The molten alloy was poured at 1350 °C, 1300 °C,

and 1250 °C according to the experiment scheme in Table 2. When the casting solidified and cooled to the room temperature, it would be shaken out. Afterwards, each casting should be cut in half to observe the internal macro porosity. Additionally, the surface sink of each casting was detected by a three-dimensional scanner.

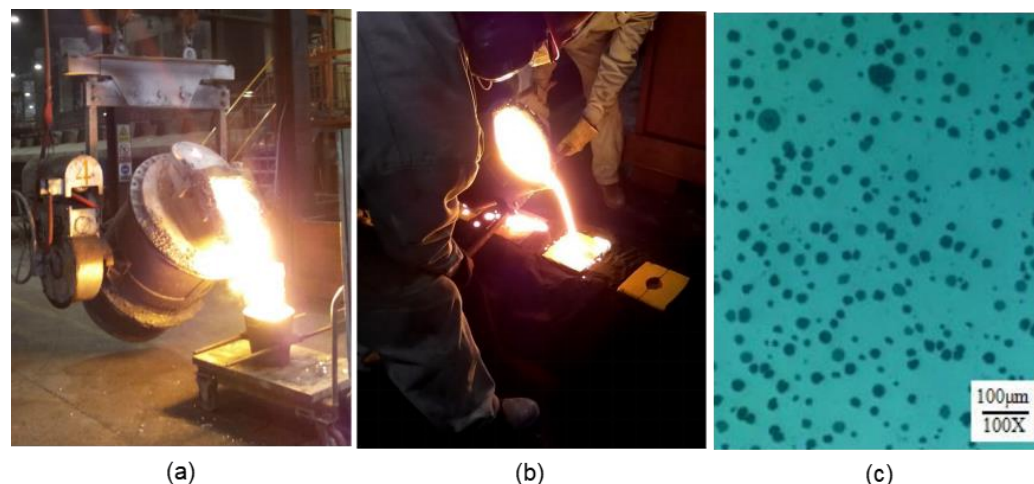


Figure 2. Transition of the molten alloy and the pouring process of prototypes: (a) Molten alloy was transferred to a two-man ladle through a transfer ladle; (b) Prototypes were poured by a two-man ladle; (c) Morphology of graphite spheres in ductile iron after solidification, spheroidization rate: 91%.

Table 2. Experimental scheme of manufacturing the prototype castings.

No.	Test No.	Model Type	Pouring Temperature (°C)
1	A1	A	1350
2	B1	B	1350
3	C1	C	1350
4	A2	A	1300
5	B2	B	1300
6	C2	C	1300
7	A3	A	1250
8	B3	B	1250
9	C3	C	1250

In this study, the commercial software ProCAST was employed to solve the casting process. This commercial software is based on the finite element method, which includes three interactive modules: Visual-Mesh, Visual-Cast, and VisualViewer for FEM mesh generation, model discretization/calculation, and result analysis, respectively. Various mesh sizes should be defined according to the geometrical features and the desired calculation precision. The initial and boundary conditions of the casting process were defined as follows: pouring temperature was 1350/1300/1250 °C according to Table 2, and the heat transfer coefficient (HTC) between mold and casting was 500 W/m²/K.

3. Results

3.1. Simulation Results

All of the nine groups of process conditions have been simulated, and a large number of simulation results have been obtained. In order to focus on the typical cases, several representative results are selected for interpretation and analysis.

The solidification process of A1 is shown in Figure 3. At the beginning, the liquid level of molten alloy in riser dropped significantly. However, the alloy in the axis area of the riser could keep as a liquid phase for a longer time to feed the lower casting. Until the riser solidified, it had fed much molten alloy to the casting. Compared with the pouring

temperature (1350 °C), the temperature of molten alloy in the casting had been dropped to a lower value (1250 °C).

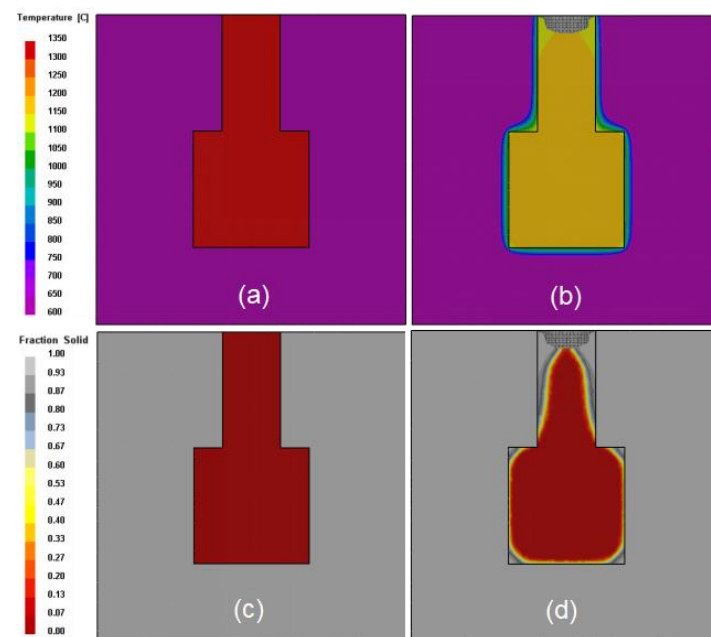


Figure 3. Solidification progress and riser top state of prototype A1 poured at 1350 °C: (a) Initial temperature of casting, 1350 °C; (b) Casting temperature and riser top dropped significantly; (c) Initial solid rate of casting, 0%; (d) Solid fraction distribution when riser top solidified.

The solidification process of A2 is shown in Figure 4. At the beginning, the liquid level of molten alloy in the riser just dropped slightly. Therefore, it was not easy for the mushy zone to form a hole connected outside at the axis of the riser. When the riser top completely solidified, most of the liquid alloy in the riser had not solidified, and the casting had only solidified a thin shell. During the subsequent solidification process, negative pressure would be generated in the riser. It had obvious mushy solidification characteristics, which would limit the feeding effect of molten alloy.

The solidification process of B2 is shown in Figure 5. It applied a riser with a riser neck to feed the casting. Due to the cooling effect of the mold, the thin riser neck solidified rapidly. When the riser top solidified, the riser neck was also solidified and closed. Although the riser solidified faster than the casting, the solidified riser neck could prevent the molten alloy and mushy zone in the casting and the riser. Meanwhile, the mold was heated by the heat released from the casting, especially in the area around the riser neck. Therefore, the corresponding area of the casting would have a higher temperature, whereas it would have a lower shell strength during the solidification.

The solidification process and the effect of ductile expansion of C3 are shown in Figure 6. We applied a riser-less and low pouring temperature process. In the early stages of solidification, there was almost no reduction in the volume of the molten alloy. Under the cooling and constraint effects of coated sand mold, the molten alloy gradually solidified and formed a high-strength solidified shell. When graphitization expansion occurs, compressive stress will be formed under the constraint of a high-strength solidified shell. At the end of solidification, the density of the residual liquid metal increases with the decrease in temperature. The central area of the casting bears compressive stress, and the flow direction in the mushy zone showed the direction of centripetal direction. Finally, the ductile expansion would compensate for the shrinkage of molten alloy, and a casting with dense structure would be obtained based on the riser-less process.

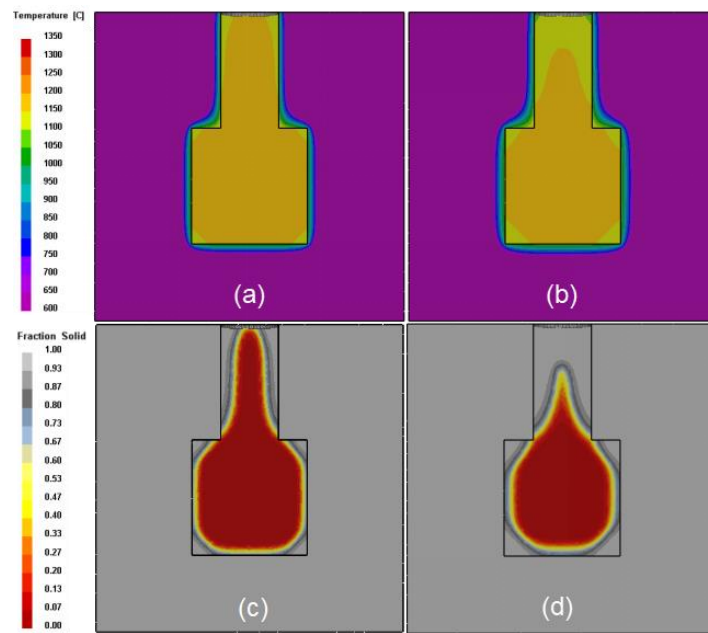


Figure 4. Solidification progress and riser top state of prototype A2 poured at 1300 °C: (a) The casting temperature decreased and the riser top dropped slightly; (b) Casting temperature continued to decrease; (c) Solid fraction distribution when the riser top solidified; (d) Mushy zone in casting was isolated outside.

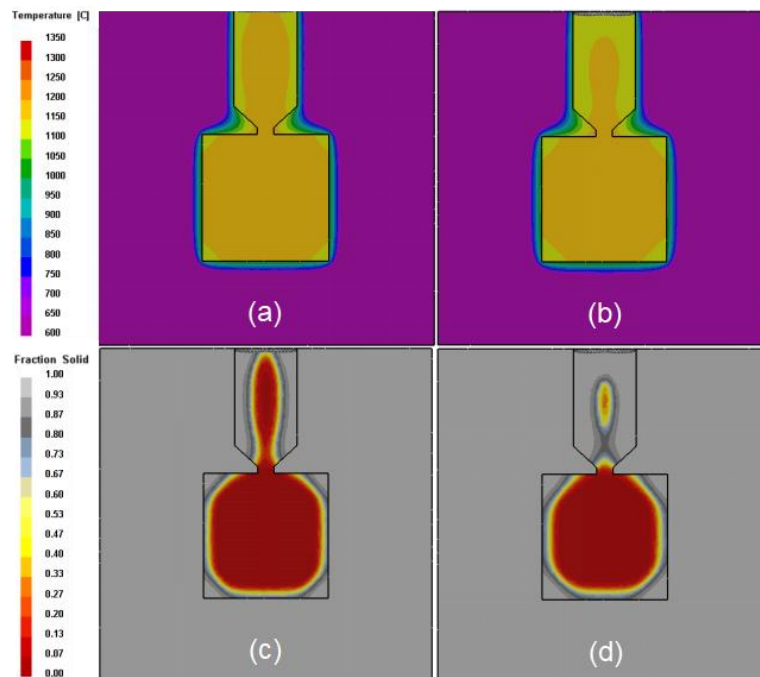


Figure 5. Solidification progress and riser top state of prototype B2 poured at 1300 °C: (a) Temperature field of casting and mold at the early stage; (b) Temperature field of casting and mold during further cooling and solidification; (c) Solid fraction distribution when the riser top solidified; (d) Mushy zone in the casting and riser was isolated by the riser neck.

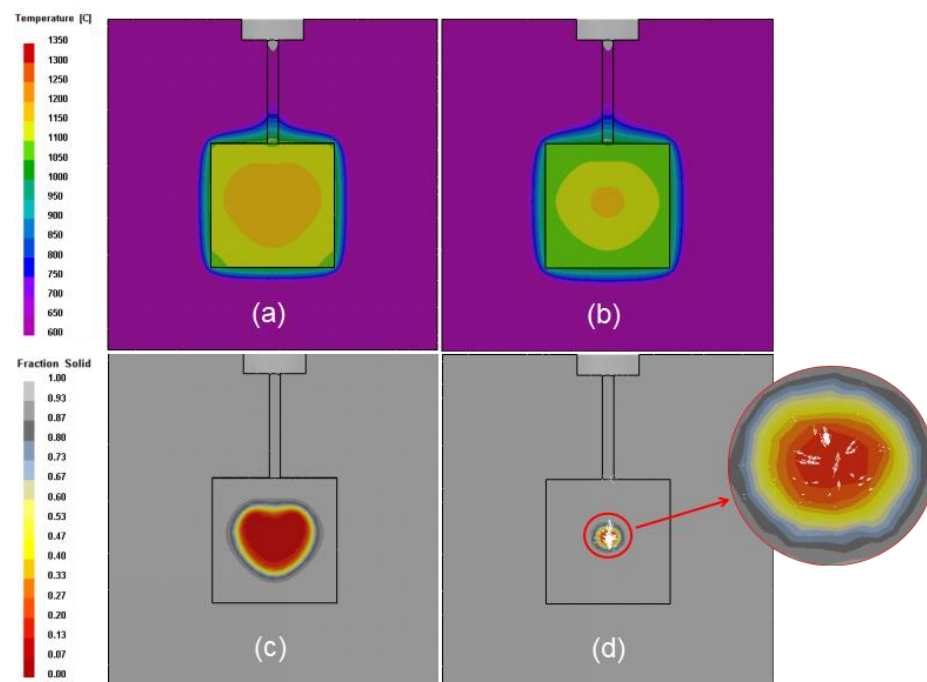


Figure 6. Solidification progress and riser top state of prototype C3 poured at 1250 °C: (a) Casting temperature decreased during solidification; (b) Casting temperature filed at the end of solidification; (c) Solid fraction distribution during solidification; (d) Flow field in mushy zone at the end of solidification.

3.2. Solidification Process and Feeding Effect

After the molten alloy was poured into the molds at different temperatures, the liquid level of molten alloy in the risers changed differently for prototypes A and B. After being poured at 1350 °C, the liquid level in the risers dropped significantly at the beginning. When the riser top solidified, deep macro porosity holes would form in the axis area to communicate with the atmosphere. After being poured at 1300 °C, the liquid level in the risers dropped slightly during the cooling process. During the solidification, there was a small sink on the upper surface of the risers, but there were no macro porosity holes. After being poured at 1250 °C, the liquid level in the riser remained almost unchanged during the solidification process. Since there was no riser for the prototype C, it was not necessary to observe a liquid level situation during the solidification process.

To investigate the shrinkage conditions inside, the prototypes were cut in half through the central axis, and the dye penetrant inspection method was applied. The shrinkage conditions in the prototypes are shown in Figures 7–9.

When being poured at 1350 °C, all the three prototypes generated macro porosity holes. For the prototype A1, the macro porosity holes were generated at the riser top and connected to the atmosphere. For the prototype B1, the macro porosity holes were also located at the riser top but looked smaller than those of B1. Additionally, it had an obvious sink around the riser neck. For the prototype C1, it had an obvious hole on the upper surface of casting where the molten alloy was filled (as shown in Figure 7).

When being poured at 1300 °C, the morphology of macro porosity changed accordingly. For the prototype A2, the macro porosity was generated at the junction of the casting and the riser. It should be noticed that there was obvious sink on the lateral surface of the casting. For the prototype B2, there was obvious sink around the riser neck, and the macro porosity hole was found below the sink area. For the prototype C2, it had obvious sink on the upper surface of the casting (shown in Figure 8).

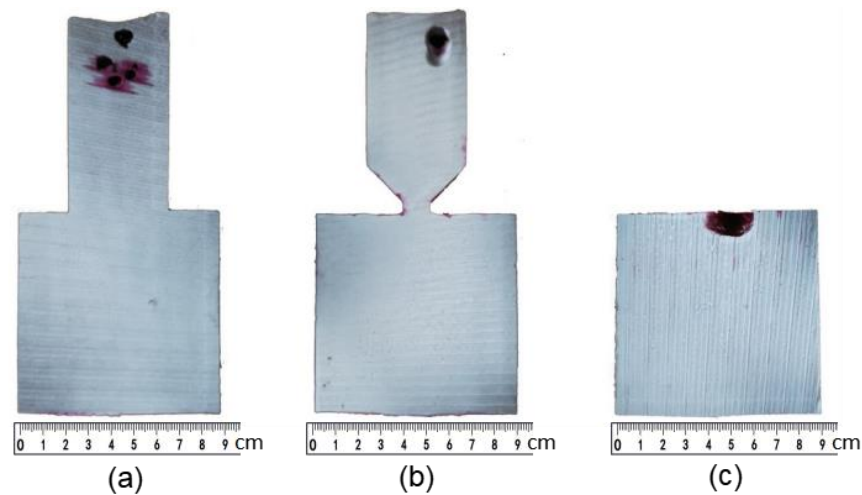


Figure 7. Cross-section topography of the prototypes poured at 1350 °C: (a) Prototype A1, macro porosity hole at the top of the riser; (b) Prototype B1, macro porosity hole at the top of the riser; (c) Prototype C1, macro porosity hole at the top of the casting.

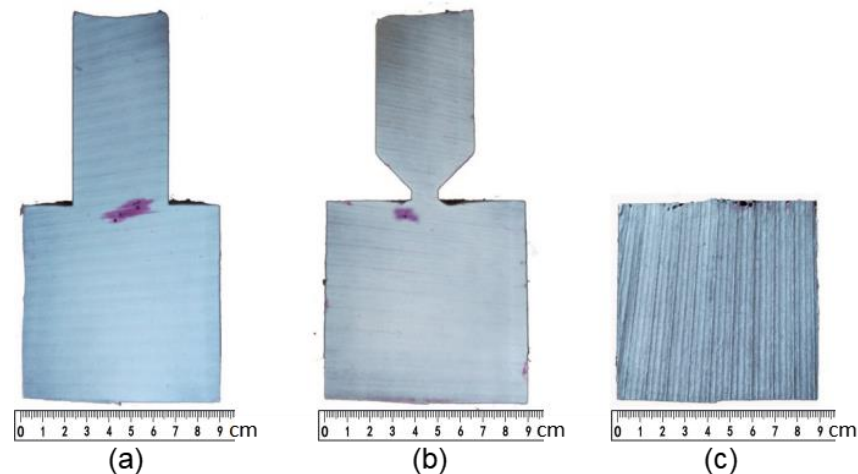


Figure 8. Cross-section topography of the prototypes poured at 1300 °C: (a) Prototype A2, macro porosity at the connection of the riser and casting; (b) Prototype B2, macro porosity and surface sink near the riser neck; (c) Prototype C2, surface sink at the upper surface of the casting.

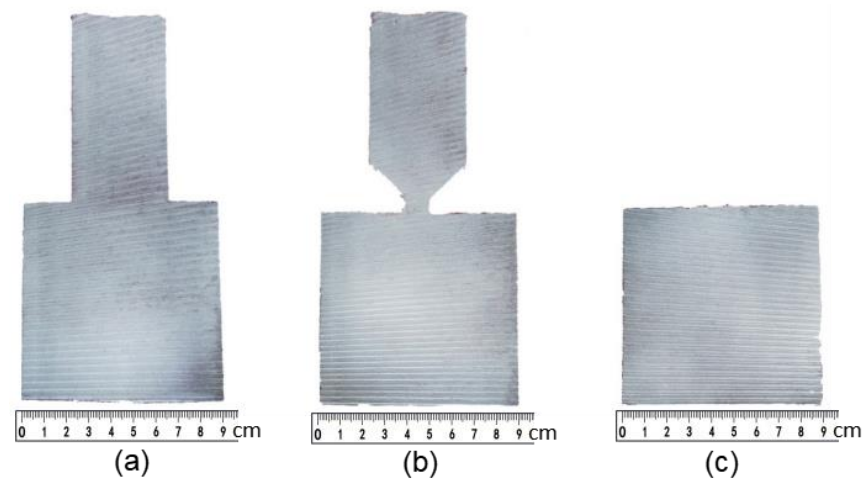


Figure 9. Cross-section topography of the prototypes poured at 1250 °C: (a) Prototype A3, no macro porosity or surface sink was found; (b) Prototype B3, no macro porosity or surface sink was found; (c) Prototype C3, no macro porosity or surface sink was found.

When being poured at 1250 °C, there was no macro porosity in both the risers and the castings of all the prototypes. Additionally, there was no obvious sink on the surface of the castings or the area around the riser neck. The castings with dense structure could be obtained whether or not there was a riser (as shown in Figure 9).

3.3. Scanning Results of the Prototypes

The scanning results of the prototypes are shown in Figures 10–12. It could be found that the surface dimension varied with the pouring temperature and the riser structure.

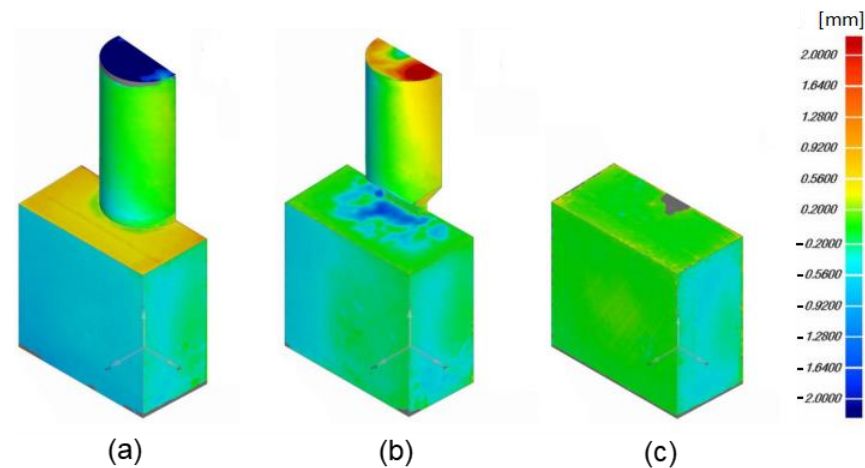


Figure 10. Scanning results of the prototypes poured at 1350 °C: (a) Prototype A1, smooth surface; (b) Prototype B1, surface sink around the riser neck; (c) Prototype C1, a hole at the top surface.

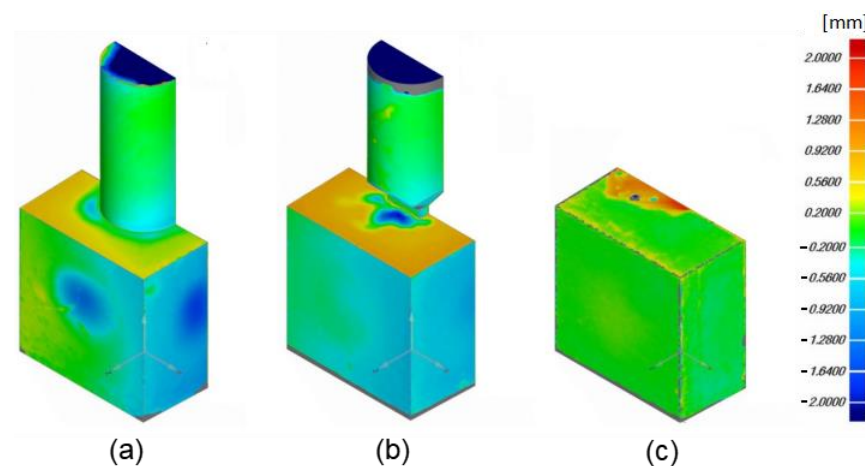


Figure 11. Scanning results of the prototypes poured at 1300 °C: (a) Prototype A2, obvious surface sink; (b) Prototype B2, surface sink around the riser neck; (c) Prototype C2, unevenness of the top surface.

When being poured at 1350 °C, the lateral surfaces of all the three castings were smooth and did not appear to have obvious sink. However, it had a slightly annular sink around the riser neck on the upper surface of the prototype A1. Additionally, for the prototype B1, it had obvious but irregularly shaped sink around the riser neck on the upper surface. For the prototype C1, it had a hole at the center of upper surface (shown in Figure 10).

When being poured at 1300 °C, it showed representative sink on the surface of the prototypes. For the prototype A2, it had obvious sink on the center position of lateral surfaces, whose depth was more than 1.28 mm. It also had annular sink around the riser neck on the top surface. For the prototype B2, it had obvious sink around the riser neck on the upper surface, whose depth was more than 1.64 mm. For the prototype C2, the top surface was uneven and had holes (shown in Figure 11).

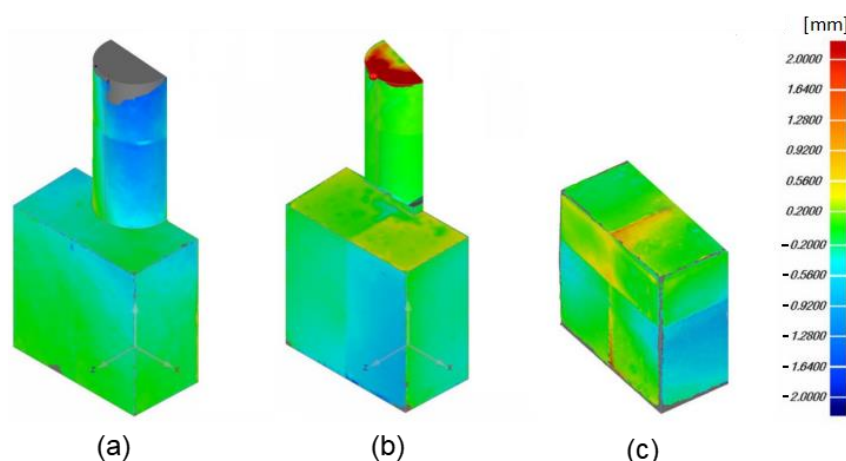


Figure 12. Scanning results of the prototypes poured at 1250 °C: (a) Prototype A3, smooth surface; (b) Prototype B3, smooth surface; (c) Prototype C3, smooth surface.

When being poured at 1250 °C, all the surfaces of the three prototypes were smooth, and there was no obvious sink on the lateral surfaces and the upper surfaces. Additionally, it did not have sink around the riser neck. For all the three prototypes, the shape error of almost all the surfaces was within ± 0.2 mm (shown in Figure 12).

4. Discussion

During the solidification process, the volume change of the ductile cast iron could be expressed as:

$$\Delta V = F + G - \alpha_1 - \alpha_2 - \beta \quad (1)$$

ΔV —volume change, the negative value indicates it would generate shrinkage; F —feeding volume from riser; G —graphitization expansion for feeding casting shrinkage; α_1 —liquid contraction; α_2 —solidification contraction; β —mold expansion.

In this study, the solidification contraction α_2 and the mold expansion β could be considered as a fixed value, and Equation (1) could be simplified as:

$$\Delta V = F + G - \alpha_1 + C \quad (2)$$

C —a constant value.

Therefore, the feeding effect of ductile iron cast would be mainly controlled by the following factors: liquid contraction, feeding volume from riser, and graphitization expansion for feeding casting shrinkage.

When the pouring temperature was higher than a certain value (1350 °C in this experiment), the liquid contraction of the casting was large, which needed a lot of feeding alloy from the riser. Since the liquid level in the riser dropped significantly, the molten alloy in the riser could connect with the outside through the macro porosity hole and feed the casting continuously. In this situation, the feeding volume from riser F would be a relatively large value. When the pouring temperature was down to a lower value (1300 °C in this experiment), the molten alloy in the riser dropped slightly and was isolated with the outside by the solidified top shell in a short time. In the subsequent solidification process, the casting could hardly be fed by the riser, and the feeding volume from riser F would be a relatively small value. When the pouring temperature was down to a certain value (1250 °C in this experiment), the liquid contraction α_1 of the casting was small, and the graphitization expansion could fully compensate the shrinkage of molten alloy during the solidification process.

The ductile cast iron has a typical mushy solidification process. At the beginning of solidification, the shell thickness of the casting was thin and the strength was low, especially in the areas of the surface center or around the riser neck. If the upper surface of the riser was closed and negative pressure was generated in the riser, the feeding process would be

restricted. As a result, the casting shrinkage could hardly be fully fed by the riser, which would cause internal macro porosity and surface sink correspondingly.

The riser for ductile iron casting could be considered as a pressure control riser. The utilization effect of graphitization expansion was largely affected by the state of the riser's upper surface and the structure of the riser neck. In the solidification process, the molten alloy in the riser would compensate the casting shrinkage. Meanwhile, the graphitization expansion would occur as the mushy zone solidifying. The coated sand mold had relative high strength and stability, which could be used to resist the graphitization expansion for compensating casting shrinkage. However, if the riser neck did not close in time, the mushy metal would be squeezed out of the casting and returned to the riser, which would cause internal shrinkage or surface sink of the casting.

In the foundry production, it is not easy to design the riser and the riser neck exactly. If an unreasonable riser and riser neck are used, internal shrinkage and surface sink defects might be induced. Therefore, it is advised to apply the riser-less method whenever possible.

5. Conclusions

The ductile cast iron casting normally needs to be fed through the riser when the pouring temperature is high. With the increase in pouring temperature, the shrinkage volume of casting increases, and more molten alloy needs to be fed from the riser. If the liquid level in riser drops significantly, it would be beneficial to form a hole connected with the outside so as to drive the high-temperature molten alloy in the riser to feed the casting. If the pouring temperature drops to a certain value, the top of the riser would solidify prematurely, and negative pressure would be generated in the riser, which would adversely affect the feeding effect of the riser.

The ductile cast iron has typical characteristics of mushy solidification and graphitization expansion. The shell formed at the initial stage of solidification has thin thickness and low strength, so the casting would have obvious surface sink without sufficient feeding. Reasonable design of the riser neck can effectively improve the feeding effect of the riser. At the beginning, the molten alloy in the riser can feed the casting through the riser neck. When graphitization expansion occurs, the riser neck solidifies in time to prevent molten alloy feeding back from the casting to the riser and make full use of graphitization expansion for feeding shrinkage. However, the casting would have higher temperature around the riser neck, where it is easier to have surface sink.

In practical production, it is very hard to accurately design a riser to compensate for the shrinkage in the casting effectively. When the pouring temperature drops to a certain value (1250 °C in this experiment), the graphitization expansion could be used to fully compensate the shrinkage of casting in a coated sand mold. The riser-less method would be helpful to simplify the casting process design, and it provides a potential technical direction for improving the casting quality.

Author Contributions: Conceptualization, T.W. and S.Y.; methodology, T.W. and S.Y.; software, T.W.; investigation, T.W.; resources, S.Y.; writing—original draft preparation, T.W.; writing—review and editing, T.W. and S.Y.; supervision, S.Y.; project administration, T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their thanks to Baoliang Zhang and Xi-angyu Lu who provided their technical assistance in Dalian Bingshan Metal Technology Co., Ltd. Dalian, China.

Conflicts of Interest: The authors declare no conflict of interest.

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