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Optimization of the Feeding Process for a Cast Steel Bucket Tooth Based on Anycasting Simulation

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Abstract. Cast steel bucket teeth are susceptible to shrinkage cavity and shrinkage porosity because of wall-thickness variation, local hot spots, and limited feeding paths. A feeding-process optimization route combining modulus analysis and AnyCasting simulation is proposed. The molding material, pouring orientation, parting surface, and semi-closed gating system were first designed. Hot spots and the final solidification region were then identified through modulus analysis and verified by filling, solidification, and defect-prediction simulations. An obround blind riser and external chills were subsequently introduced to improve feeding. Region 7 was identified as the main shrinkage-sensitive zone, with the largest modulus of 1.22 cm. After optimization, filling remained stable, the thermal gradient became more favorable, and shrinkage defects were transferred from the casting body to the riser, leaving no obvious defects in the casting body. The comparison confirms that coordinated riser-chill design is more effective than relying on a single feeding measure. The proposed route improves the reliability of hot-spot identification and feeding-system design, clarifies the effect of coordinated riser-chill design on shrinkage control, and provides an effective process-design method for similar cast steel wear-resistant components.

Keywords: Cast steel bucket teeth, shrinkage porosity, modulus analysis, feeding optimization

1. Introduction

Bucket teeth are key wear-resistant components mounted at the front edge of excavator buckets. In service, they withstand repeated impact, severe abrasion, and complex cyclic loading. As a result, the internal quality of the casting is directly related to the reliability and service life of the component. For cast steel bucket teeth, shrinkage cavity and shrinkage porosity are among the most critical defects because the geometry typically includes thick tooth sections, transition zones, mounting holes, and locally restricted feeding paths. Once these defects form in the working section or in adjacent load-transfer regions, the load-bearing capacity and wear resistance of the component are significantly reduced. Therefore, the identification of the final solidification region and the design of an effective feeding system are key issues in process development.

Numerical simulation has become an important tool for defect-oriented process design in complex castings. Previous studies have investigated mold filling, solidification, hot-spot prediction, and simulation-based optimization in metal casting [1-4]. Additional work has shown that shrinkage behavior can be assessed through defect diagnostics, riser redesign, thermal-field control, and validated simulation workflows [5-8]. These studies indicate that reliable process optimization depends on consistent boundary conditions, rational geometric layout, and quantitative interpretation of hot spots rather than on empirical adjustment alone [9-12]. However, for engineering components such as cast steel bucket teeth, studies that combine hot-spot identification, feeding-system design, and comparative analysis of initial and optimized schemes within one compact framework remain limited.

In this study, a ZG30CrMnSi cast steel bucket tooth is used as the target component. A process route that integrates modulus analysis and AnyCasting simulation is proposed to identify the final solidification region and optimize the feeding process. The contribution of the study lies in two aspects. First, modulus analysis is linked with numerical simulation to establish a direct connection between hot-spot identification and defect prediction. Second, an obround blind riser together with external chills is designed as a coordinated feeding system, and the transfer of shrinkage defects from the casting body to the riser is evaluated through comparison between the initial and optimized schemes.

2. Process design

2.1. Structural and material analysis

The bucket tooth consists of a working tip and a clamping connection section, with overall dimensions of approximately 370 mm × 77 mm × 84 mm and a casting mass of about 9.1 kg. As shown in Figure. 1, it is a small but geometrically complex cast steel part. The working zone must be free from cracks, shrinkage defects, and slag inclusions, while the mounting holes and local planar surfaces require adequate dimensional accuracy and surface quality. ZG30CrMnSi is selected as the casting material because it offers high strength, sufficient toughness, and good wear resistance. Since cast steel is susceptible to oxidation and volumetric contraction during pouring and solidification, the key task of process design is to establish directional solidification and effective feeding.

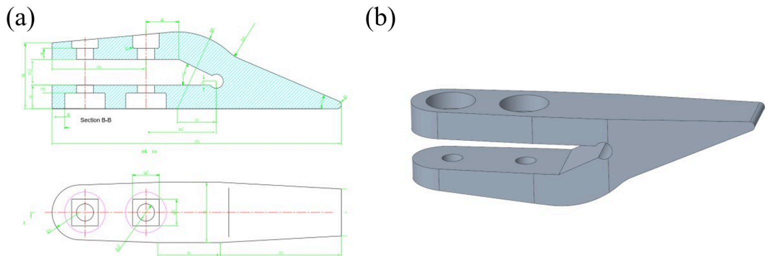

Figure 1. Two-dimensional drawing and three-dimensional model of the bucket tooth

2.2. Molding material and gating system design

Considering the size of the bucket tooth, its small-batch production mode, and the requirement for good surface quality, resin self-setting sand is used for manual molding. Compared with conventional clay sand, it provides higher mold strength and lower defect sensitivity. A zircon-based alcohol coating is further adopted to improve refractoriness and reduce metal penetration. A horizontal pouring posture is selected, and the gating system is arranged on the parting surface to

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balance molding convenience and riser placement. According to the empirical formula for cast steel, the pouring time is calculated as 4.8 s and the choke area as 4.41 cm2. The resulting layout is shown in Figure. 2.

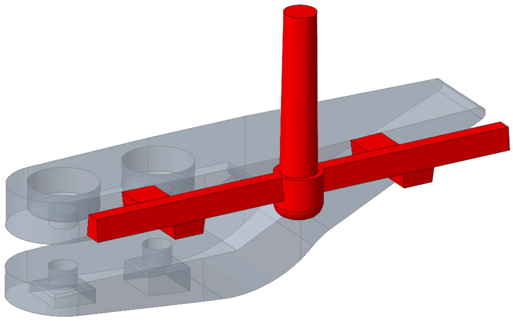

Figure 2. Gating system layout of the bucket tooth

2.3. Modulus analysis and identification of the final solidification region

Modulus analysis is first carried out to identify hot spots before simulation. The modulus is defined as M = V / A, where V is the local heat-storage volume and A is the effective heat-dissipation area. A larger modulus indicates slower cooling and a higher probability of becoming the final solidification region. The bucket tooth is divided into seven representative regions, as shown in Figure. 3. Region 7 has the largest modulus, 1.22 cm, while Region 1 has a modulus of 0.61 cm, indicating a large thermal imbalance. This result identifies Region 7 as the main shrinkage-sensitive zone.

The value of modulus analysis in the present work lies in its role as a bridge between geometric intuition and thermal assessment. Instead of treating the component as a single body, the region-based approach makes it possible to compare local heat-storage capacity among the tooth tip, the transition zone, and the mounting section. The contrast between Region 7 and Region 1 shows that the tooth side cannot be expected to solidify uniformly with the thinner sections near the mounting features. This result is especially important because it defines the process objective before simulation starts: the final solidification position should not remain inside the casting body, but should be shifted toward an external feeding reservoir. In this sense, modulus analysis provides the first quantitative criterion for evaluating whether the later feeding design is reasonable.

(a) (b)

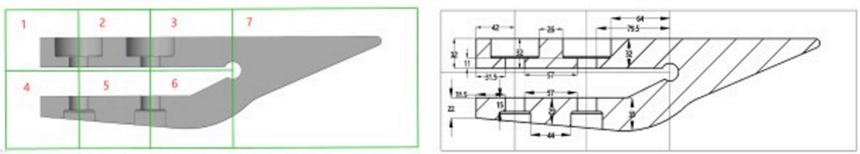

Figure 3. Region partition and modulus-analysis basis for the bucket tooth

2.4. Simulation model and parameters

The three-dimensional model is imported into AnyCasting and discretized with a uniform mesh. Figure 4 presents the global and local mesh views. The simulation parameters are summarized in Table 1, including casting material, molding sand, cooling condition, pouring time, pouring temperature, and casting method. The same parameter set is used for both the initial and optimized schemes, ensuring direct comparability.

Table 1. Simulation parameters used in AnyCasting

Parameter	Value
Casting material	ZG30CrMnSi
Molding sand	Resin self-setting sand
Heat exchange coefficient between air and sand mold	Database default
Flask cooling condition	Air cooling
Pouring time	4.8 s
Pouring temperature	1550 °C
Casting method	Gravity sand casting

The simulation settings for the initial scheme and the optimized scheme were kept exactly the same on purpose, so that any change in the defect distribution could be linked to the process modifications themselves, not to shifts in the boundary conditions. Getting that consistency right is especially useful in feeding studies, because differences in pouring temperature or cooling conditions can easily hide the real effect of the riser and chill design. The mesh shown in Figure 4 also gives a way to think about how reliable the results are: a global mesh does a good enough job of catching the overall filling path, while the local mesh view confirms that the representation of the geometry around the feeding system and the critical section transitions is adequate for thermal and defect analysis.

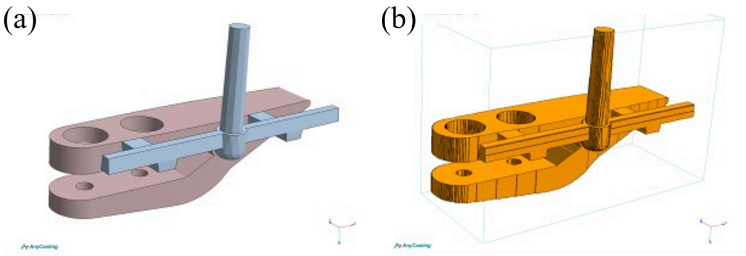

Figure 4. Mesh layout used in the AnyCasting simulation

3. Simulation analysis and discussion

3.1. Initial scheme analysis

The initial process scheme is simulated under gravity sand-casting conditions with a pouring time of 4.8 s, a pouring temperature of 1550 °C, and air cooling of the flask. The results are shown in Figure. 5. The filling result indicates relatively continuous metal flow through the sprue, runner, and ingates, without obvious large-scale splashing or severe erosion, suggesting that the designed gating system can meet the basic filling requirement. However, the solidification and defect-prediction results show that the thick tooth region remains at elevated temperature for a longer period. The final solidification location is consistent with Region 7 identified by modulus analysis, and shrinkage defects are mainly concentrated in this region and adjacent thick sections. Therefore, the initial process cannot provide sufficient feeding for the casting body.

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The initial scheme is therefore adequate from the viewpoint of flow continuity, but inadequate from the viewpoint of solidification control. This distinction is important: a stable filling pattern does not automatically guarantee a sound casting. Figure 5 shows that the melt can still enter the cavity in an orderly manner while the thermal field remains unfavorable for feeding. As the thick tooth section cools more slowly than its neighboring regions, isolated liquid pockets are more likely to persist there, eventually turning into shrinkage defects once the surrounding metal has already solidified. The agreement between the defect predictor and the modulus-based hot-spot location confirms that the process problem is not primarily a filling instability, but an insufficiently controlled feeding condition during the late stage of solidification.

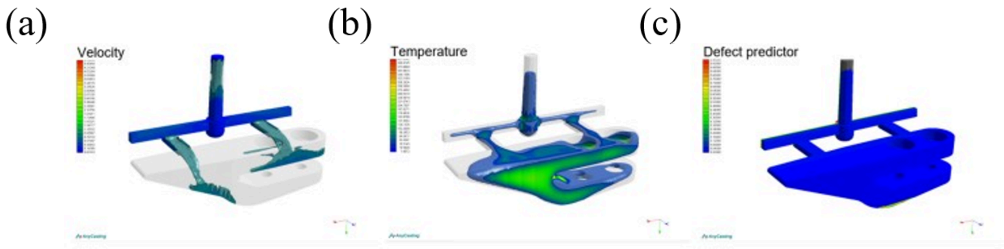

Figure 5. Filling, solidification, and defect prediction of the initial scheme

3.2. Optimized scheme and discussion

A blind riser with an obround shape was designed to feed the final solidification zone, so that the predicted shrinkage defects could be eliminated. Starting from the modulus of Region 7, which was 1.22 cm, the required riser modulus worked out to 1.46 cm once a modulus enlargement factor of 1.2 had been applied. In places where the riser alone could not deliver enough feed metal, external chills were brought in; about 226 g of chill mass went to Region 1 and roughly 163 g to Region 5. An 8 mm vent hole was also put into the setup to make it easier for gases to escape during pouring. After the design changes, the process was simulated again. What Fig. 6 shows is that the optimized scheme kept filling stable, built a more favourable thermal gradient while solidification was proceeding, and managed to shift shrinkage defects out of the casting body into the riser, a result that points to the combined riser-chill arrangement being able to set up effective directional solidification and feeding.

The riser and the chills actually take on complementary functions: the blind riser works as the main liquid reservoir sitting above the critical hot spot, whereas the chills hold back local heat accumulation in secondary hot spots and cut down the time during which those spots linger in a semi-liquid state. This kind of coordination is necessary because the bucket tooth contains more than one thermally sensitive region. If the riser had been used on its own, secondary hot spots could have stayed active outside the main feeding path; if only chills had been applied, the region most prone to shrinkage would still have lacked an adequate supply of liquid metal. In effect, what the optimized result brings about is not just a reduction in defects but a controlled reorganization of the solidification sequence, steering it toward the feeding system.

Looked at from a thermal angle, the optimized process amounts to a redistribution of thermal dominance within the casting system. In the initial design, the strongest hot spot was sitting inside the casting body itself, and that encouraged internal shrinkage to form. After optimization, it was the feeding system that became the favoured thermal reservoir. The shift can be picked up in the defect predictor and, at the same time, matches the physical demand for directional solidification. In process-design language, the real achievement of the riser-chill strategy is its ability to turn a

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defect-prone internal hot spot into a controlled external feeding zone, raising soundness without upsetting the overall filling behaviour.

What also became clear from comparing the initial and the optimized schemes is that the core difficulty was never about whether the cavity could be filled; it lay in whether the final solidification path could be directed toward the feeding system. The contrast in modulus between Region 7 and Region 1 helps explain why the thick tooth section ends up as the dominant hot spot. At the same time, the riser supplies the main feeding channel while the chills pull heat faster out of secondary hot spots. Their joint action accounts for the observed movement of defects from the casting body into the riser. That means the effectiveness of the optimized scheme does not come only from adding more feed volume but from reshaping the thermal hierarchy and keeping a continuous feeding path open during the last stage of solidification.

These findings carry some practical weight for process development. In that context, simulation turns out to be valuable not merely as a tool for spotting defects but as a way of judging whether a proposed feeding system really reroutes the solidification sequence in the direction that was intended. In the case discussed here, the optimized result shows that the end of solidification has been redirected away from the casting body and toward the feeding system, and that is the basic requirement for controlling shrinkage properly. This way of reading the results links numerical outputs directly to process decisions and gives a clearer footing for picking a final process scheme.

A broader methodological point also surfaces from this study. The bucket tooth is far from being an extremely large casting, but the shifts in local section create a distinct hierarchy of hot spots. Because of that, the quality of the process cannot be judged merely by the overall size of the casting or by whether filling looks stable; the local thermal behaviour has to be examined explicitly. Putting modulus analysis and numerical simulation together supplies a repeatable framework in which thermal risk is first ranked analytically and then checked numerically. That approach is especially useful for small and medium cast steel parts, where process development has to remain cost-effective while still making sure that internal quality is good enough.

Taken as a whole, the optimized scheme can be seen as a process design that deliberately ties together thermal control and feeding control. The riser pins down where the final liquid reservoir is maintained, while the chills make certain that competing regions do not hang on to too much heat. Such a coordinated strategy improves not only the control of defects but also the predictability and robustness of the final solidification sequence. Even though the conclusions rest on process calculations and simulations rather than on destructive checks, the methodology that has been put forward is well suited to process screening and can be carried over to other compact cast steel components that have non-uniform section thicknesses and localized hot spots.

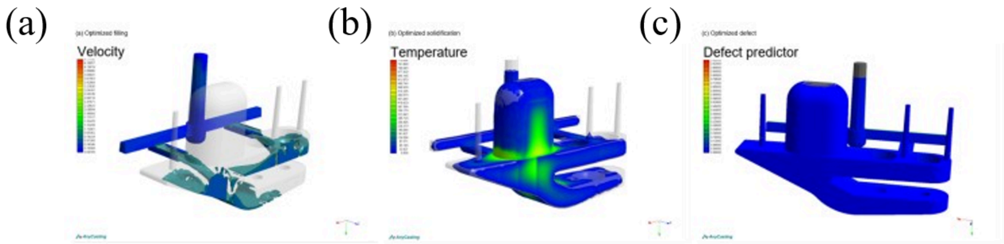

Figure 6. Filling, solidification, and defect prediction of the optimized scheme

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4. Conclusions

This work investigated the feeding-process optimization of a cast steel bucket tooth by combining process design, modulus analysis, and AnyCasting simulation. The results show that the designed semi-closed gating system can satisfy the basic filling requirement, whereas modulus analysis identifies Region 7 as the final solidification zone and the main shrinkage-sensitive region. A coordinated feeding scheme using an obround blind riser and external chills is then established and verified by simulation. After optimization, the thermal gradient becomes more favorable, and shrinkage defects are transferred from the casting body to the riser. The proposed design route improves the targeting and interpretability of feeding-process optimization and provides a practical reference for similar cast steel components.

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