SCIREA Journal of Materials
ISSN: 2995-7028
http://www.scirea.org/journal/Materials
July 1, 2025
Volume 10, Issue 1, February 2025
https://doi.org/10.54647/materials430289

Numerical modeling and simulation of mold filling and solidification process of BS100 Grade A6 alloy in sand casting of excavator bucket coupling parts

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Abstract

Carbon steel bucket couplings are widely used in the construction and mining industries due to their quality and versatility. These couplings are manufactured using sand casting techniques to meet international standards. This casting technique has significant shrinkage defects during solidification and needs to be improved. In this study, JSCast simulation software was used to analyze the mold filling and solidification process of BS100 Grade A6 alloy during sand casting of excavator bucket couplings. The simulation provides important insights into the thermal and flow dynamics, allowing prediction and prevention of potential casting defects. The mold filling simulation demonstrated a steady and efficient flow of molten metal into the mold cavity, achieving full filling within 16.12 seconds. The temperature distribution throughout the filling process remained almost uniform, with minor cooling observed in the thinner and peripheral regions. There were no major flow defects such as airlocks, freeze-ups, or misruns, indicating that the runner system was well designed to promote smooth and complete filling. Solidification simulations showed a solidification

pattern that progressed inward from the mold wall toward the core. The thinner sections solidified earlier, while the risers held the molten metal for a longer time—up to 676.17 seconds—allowing for effective shrinkage zones. The delayed solidification of the shrinkage beans relative to the casting was confirmed by the solidification fraction curve, confirming their role in reducing the risk of internal shrinkage and porosity.

Keywords

Numerical modeling, Jscast, sand casting, mold filling, solidification, excavator bucket coupling, BS100 Grade A6.

1. Introduction

Sand casting is a widely used manufacturing process for producing metal components, suitable for both ferrous and non-ferrous materials [1,2]. This method offers several advantages, including excellent dimensional accuracy, ease of pattern development, faster production rates, and reduced solidification time compared to die casting. Key process parameters in sand casting include venting, gating system design, nozzle and riser configuration, and the specification of dimensional and pattern tolerances. These parameters play a crucial role in determining the quality of the final casting. Additionally, the bonding mechanism of the mold material is influenced by several factors such as physical and mechanical properties, crystal structure, and bonding compounds [2-6]. The quality and mechanical performance of the cast specimen are heavily dependent on the proper selection of both process parameters and input materials. In this context, a comprehensive literature review is essential to evaluate and predict the hardness of the specimen. This is particularly important for analyzing the mold filling behavior of ***BS100 Grade A6*** alloy in the sand casting of excavator bucket coupling parts, with the ultimate goal of enhancing product quality [7].

Modeling and simulation have become indispensable tools in modern sand casting, allowing engineers and designers to analyze and optimize the casting process before experimental production. These tools facilitate the determination of die channel dimensions, gate system geometry, and riser locations based on the casting geometry and the thermal and flow properties of the alloy. Advanced simulation software such as JSCast, MAGMASOFT, ProCAST, and ANSYS Fluent use numerical methods—such as finite element and finite volume techniques—to simulate fluid flow, heat transfer, and solidification in casting processes. These simulations help predict mold filling, cooling rates, turbulence, shrinkage porosity, and other defect-related phenomena that are critical to achieving high-quality castings (Kumar & Rao, 2017; Liu et al., 2019) [8]. For example, Liu et al. (2019) [9] demonstrated that optimizing the sprue system through ProCAST significantly reduced air entrapment and porosity in aluminum alloy castings. Similarly, Kumar and Rao (2017) [10] demonstrated that the use of curved gates and multiple inlet gates improved flow uniformity and reduced turbulence-related defects in steel castings. Through simulation, JSCast allows users to adjust parameters such as pouring temperature, gate geometry, and mold venting to ensure uniform and complete mold filling. For example, a study by Singh et al. (2020) [11] demonstrated that changing the gate location and size in JSCast significantly improved mold filling uniformity for a complex cast iron component.

2. Materials and Methods

In applications involving ***BS100 Grade A6 alloy***, used in high-strength components such as excavator bucket couplings, the role of simulation becomes even more critical. This alloy exhibits high hardness and wear resistance, which makes it susceptible to casting issues like incomplete mold filling, cold shuts, and hot tearing if not properly designed. Modeling software can simulate the alloy's behavior during solidification to identify and correct these issues before tooling is manufactured. Prediction of Solidification Time: The amount of heat that must be removed from a casting to cause it to solidify is directly proportional to the amount of superheating and the amount of metal in the casting, or the casting volume. Conversely, the ability to remove heat from a casting is directly related to the amount of exposed surface area through which the heat can be extracted and the insulating value of the mould. These observations are reflected in ***Chvorinov's rule*** [12], which states that ts, the total solidification time, can be computed by:

$$t_s = C_m \left({}^{V}\!/_{A} \right)^n \tag{1}$$

where n is *1.5 to 2.0*; V is the volume of the casting; A is the surface area; and C_m is the mould constant, which depends on the characteristics of the metal being cast (its density, heat capacity, and heat of fusion), the mould material (its density, thermal conductivity, and heat capacity), the mould thickness, and the amount of superheat. Thus, based on the solidification time calculated according to ***Chvorinov's rule***, the shape of the casting being a bucket joint and the properties of ***BS100 Grade A6*** alloy in the sand mold, the preliminary fill time of metal into the mold is approximately *18 s*, the inlet velocity is approximately *68 cm/s* and the inlet area is $12.5\ cm^2$.

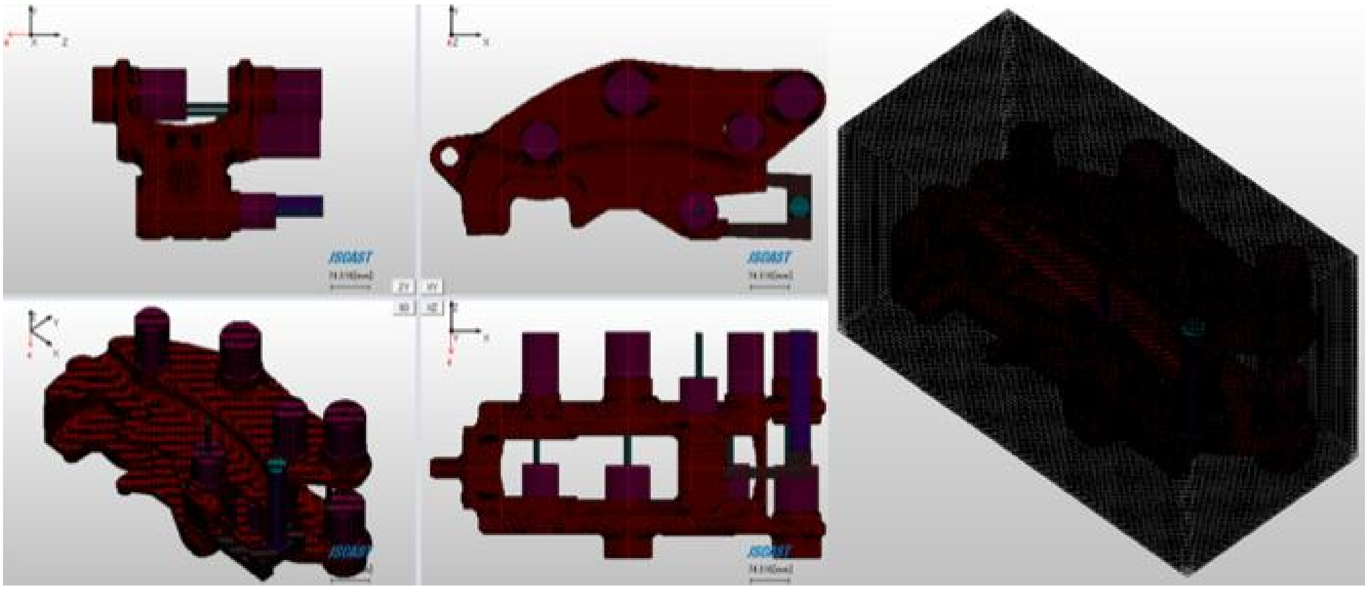

Figure 1. *Geometry, element of the Casting and Sand Mold.*

Carbon steel ***Grade A6*** is one British steel casting material, which is a popular carbon-manganese steel material in casting purpose. ***BS 3100 Grade A6*** Casting Chemical Requirements (***Table 2***) and Mechanical Property [7]:

Tensile Strength: *690-850MPa* min,

Yield Strength: *495MPa* min

Elongation: *13.0%* min

Hardness values for Castings: *201-255HB*.

In JSCAST, using the solidification formula [13]:

$$T_i = T_{\mathrm{solidus}} + (T_{\mathrm{liquidus}} - T_{\mathrm{solidus}}) \times (1 - F_s)^n \quad (2)$$

Where n is *2* (empirical constant), we can calculate the temperature T_i for different solid fractions (F_s) ranging from *0* to *1* (*Table 1*). The solidification process is non-linear, and the rate of temperature change slows as the solid fraction increases.

The *3D* geometric model of the casting is created using solidwork software and meshed in JSCAST. JSCAST software also has the function of automatically designing the mold according to the casting model. The total elements is *4,874,553* with minimum size is *0.1*.

This geometric model and mesh are described in *Figure 1*. The thermal properties of casting and sand mold and ductile carbon steel ***BS3100 grade A6*** properties is mentioned in ***Table 3 and 4***. [11]

Table 1. *Calculated Temperatures for Steel at Different Solid Fractions.*

Solid Fraction (Fs)	Temperature Ti (°C)
0.0	1526.0
0.2	1509.8
0.4	1493.6
0.6	1477.4
0.8	1461.2
1.0	1480.0

Table 2. *Chemical composition of Carbon Steel **BS3100 Grade A6***

Element	Weight
Carbon [%]	0.18-0.25max
Manganese [%]	1.20-1.60
Silicon [%]	0.60 max
Sulfur [%]	0.050 max
Phosphorus [%]	0.050 max

Table 3. *Thermal Properties of Casting and Sand Mold.*

Thermal-physical properties	BS100 Grade A6 alloy	Sand Mold
Densty [kg.m^{-3}]	7900	1500
Specific heat [J.kg^{-1}.K^{-1}]	800	800
Conductivity [W.m^{-1}.K^{-1}]	400	8.4
Solidus temp. [K]	1753	
Liquidus temp. [K]	1799	
Initial temp. [K]	1873	293
Latent heat [J.kg^{-1}]	209200	

Table 4. *Ductile Carbon Steel **BS3100 Grade A6** Properties.*

Nucleation	Value
Diff.coeff.of C in Gamma [m]	2.0×10^{-8}
Densty: Liquid [kg.m^{-3}]	7900
Densty: Gamma [kg.m^{-3}]	7200
Densty: Graphite [kg.m^{-3}]	2200
Eutectic Conc. of C [J.kg^{-1}]	200
Initial R: Graphite [m]	1.0×10^{-6}
Initial P: Graphite + Gamma [m]	1.5×10^{-6}

3. Results and Discussions

3.1. Mold Filling Behavior Using JSCast

Numerical simulation of the sand casting process was performed using JSCast software to evaluate both the mold filling behavior and solidification dynamics of the BS100 Grade A6 alloy composition. The objectives were to predict potential casting defects, evaluate thermal behavior, and ensure optimal process conditions for the production of excavator bucket coupling components. The results of the Mold Filling Simulation shown in Figure 2, performed using JSCast software for the BS100 Grade A6 alloy composition, illustrate the progressive filling behavior over time, providing valuable insight into the flow dynamics and potential casting quality issues.

At Time 0.0 s (0 Filling), the mold cavity is completely empty and new molten metal has begun to enter. At 0.44 s (9% Fill), rapid metal entry is observed, mainly filling the upper part of the mold, characterized by a uniform temperature distribution near 1600 °C, indicating minimal initial heat loss. As the filling progresses to 3.03 s (19% Fill), the flow front begins to spread out laterally, showing signs of directional flow and increased surface contact area, especially in the thinner sections. Temperatures remain high throughout the molten metal, but thermal gradients begin to appear, indicating heat loss to the mold walls. At 6.23 s (39% Fill), more complex flow paths appear, especially near complex geometric features. Areas near the inner corners and thinner wall regions begin to cool more rapidly, which is evident by the change in color gradients. The simulation shows signs of potential turbulence and instability of the flow front, which can cause air entrapment or freezing if not properly managed. By 9.43 seconds (Fill 59%), the majority of the main cavity has been filled, with continued progression into narrower regions. The flow pattern remains coherent, but some regions show noticeable cooling, dropping below 1575 °C. These cooler regions could become problematic if the delay in filling continues, potentially leading to incomplete fusion or premature solidification. At 12.62 seconds (Fill 79%), the simulation shows that molten metal is reaching deeper regions of the mold, including the risers and isolated cavities. The color map shows increased thermal variation, with localized cooling regions that could correspond to areas prone to shrinkage if not properly fed.

By 15.95 s (99% Fill) and finally 16.12 s (100% Fill), the mold was completely filled. The metal temperature ranged from 1584.8 °C to 1600.0 °C at the end of filling. Notably, the lowest temperatures were observed near the ends of the mold, especially in the thin-walled regions. However, the overall temperature distribution remained within an acceptable range, indicating that solidification would proceed relatively uniformly if the gating and riser systems were optimized..

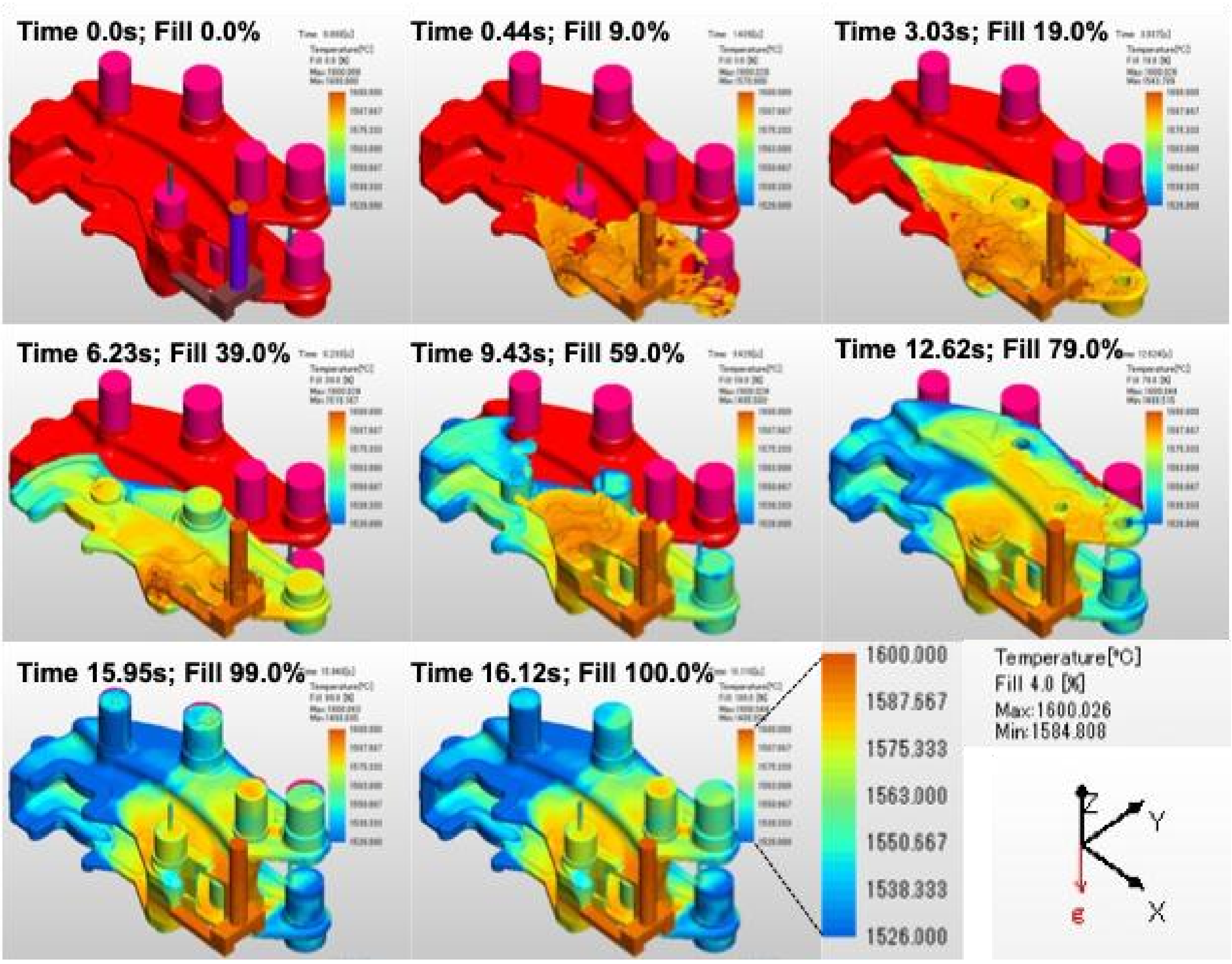

Figure 2. *Mold Filling Behavior Using JSCast*

3.2. Heat Transfer and Solidification Modeling

In sand casting, the solidification stage plays a pivotal role in determining the final microstructure and mechanical properties of the cast component. Accurate prediction of solidification behavior is essential for controlling shrinkage, porosity, and the distribution of hardness across the part. This is especially critical when working with high-strength alloys such as ***BS100 Grade A6***, which are used in heavy-duty applications where uniform mechanical performance is mandatory. Simulation tools like JSCast enable designers to model the entire thermal history of the casting, including heat extraction through the mold, temperature gradients, and solidification fronts. These thermal simulations are grounded in transient heat conduction equations that account for latent heat release and alloy-specific thermal properties. When properly calibrated, they allow for the visualization of how and where solidification initiates and terminates within the mold. Simulation of thermal gradients also informs the optimal placement of risers and chills. When the mold lacks sufficient thermal control, isolated hot spots may persist, leading to hot tearing or internal voids. Through predictive modeling, JSCast helps preempt such defects by adjusting parameters such as pouring temperature, mold material conductivity, and external cooling aids. Overall, heat transfer and solidification modeling are vital for ensuring uniformity in the mechanical properties of BS100 Grade A6 castings. These simulations reduce reliance on trial casting, shorten development cycles, and ensure the structural integrity of critical components like excavator bucket couplings.

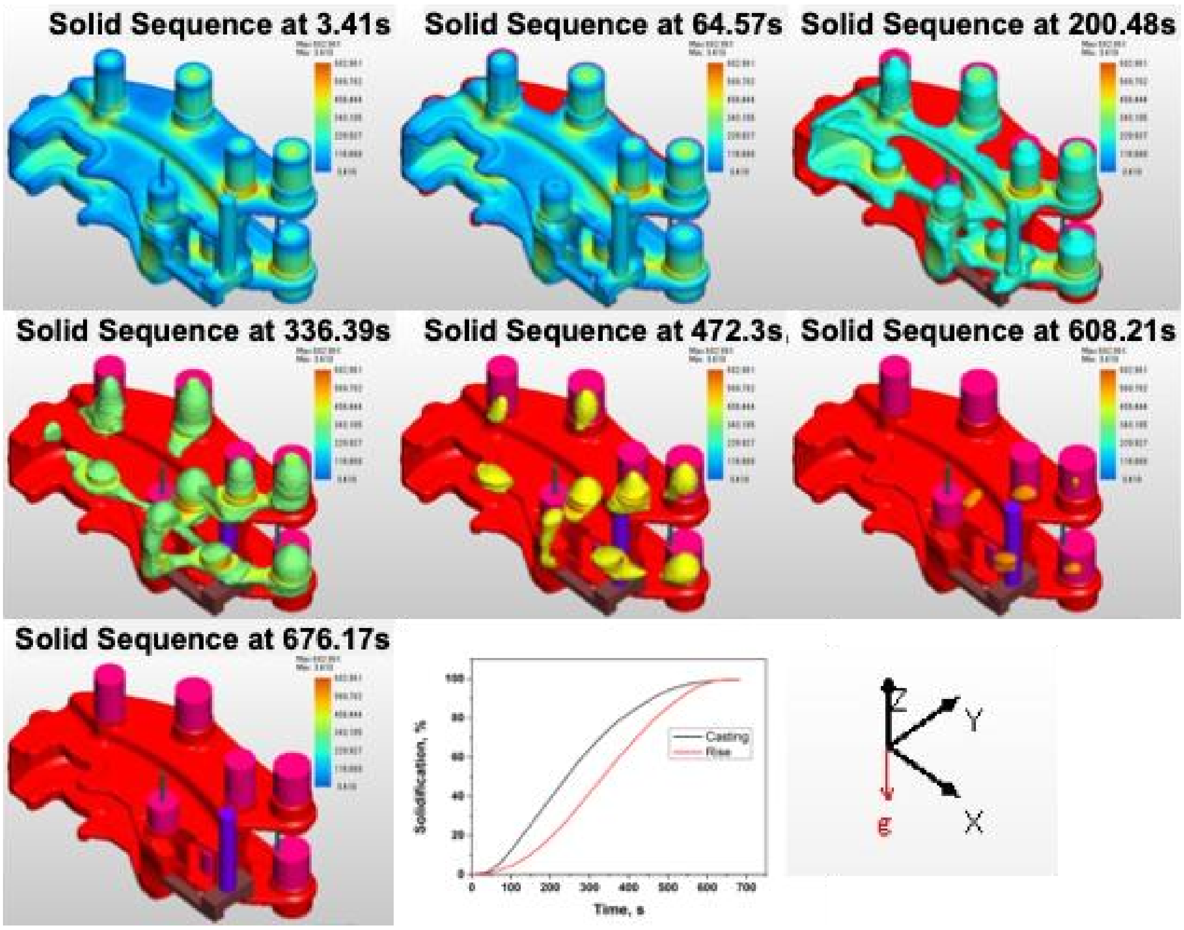

Figure 3. *The solidification simulation of the BS100 Grade A6 alloy casting*

The results of the simulation of the solidification of the BS100 Grade A6 alloy casting after full filling are shown in Figure 3.

At 3.41 seconds, the casting has just begun to solidify, with simulation results showing that only a small portion near the outer edges has begun to cool. The entire geometry remains largely liquid, indicated by the blue color on the temperature scale, with minimal solidification. By 64.57 seconds, solidification has progressed significantly through the thinner parts of the part. These regions, which are more exposed to the mold surface and have a smaller thermal mass, begin to solidify earlier. However, the core and larger cross sections remain largely liquid, indicating a well-controlled temperature gradient from the walls to the interior, driving solidification in a directional manner. At 200.48 seconds, a significant volume of the casting has turned solid. The Simulation results begin to show important features such as temperature gradients and potential hot spots. The central mass is still solidifying, while the risers and some peripheral regions are still liquid, indicating that the feed lines are still active and functional. By 336.39 s and 472.30 s, most of the casting is solid, except for the regions connected to the risers. These results indicate that the risers are effectively delaying solidification in their vicinity to provide molten metal to compensate for shrinkage, which is ideal. The thermal behavior during this period is critical to determining the adequacy of the hot-head design. At 608.21 s and 676.17 s, solidification is nearly complete. The last regions to solidify are located at the hot-head bases, consistent with good hot-head functionality. The red color in these images confirms complete solidification, with only minimal temperature gradients remaining.

The solidification curve, which plots the percent solidification over time for both the casting and the hotend, supports these visual observations. The hotends show a slow solidification curve compared to the main casting, confirming that the hotends remain molten longer to provide for the solidified casting. This slow solidification is characteristic of efficient hotend design and contributes to the reduction of porosity and shrinkage defects..

4. Conclusions

The simulation results confirm that the mold design, gating system, and and riser placement are effective for casting a BS100 Grade A6 alloy bucket coupling. The pouring phase of the liquid metal into the mold shows smooth, uninterrupted metal flow with favorable heat distribution, while the solidification sequence confirms successful solidification promotion with proper direction and feed of the risers. These findings highlight the importance of integrated simulation in optimizing casting quality, reducing defects, and improving process efficiency prior to physical testing. Further refinement could focus on minimizing cooling temperature differences in thin-walled regions and validating the simulation results through experimental casting tests.

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