

EXPERIMENTAL AND MODELING STUDY OF FLUIDITY IN DUCTILE IRON (GGG40)

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Abstract

Ductile irons (spheroidal graphite cast irons, SGI) are widely used in automotive and energy systems due to their high strength, ductility, and excellent machinability. The casting quality of these alloys largely depends on the flow and filling behavior of the molten metal, namely its fluidity. In this study, the effects of pouring temperature, filling time, and metallurgical quality on the fluidity of GGG40 ductile iron were investigated through both experimental and numerical approaches. Experimental trials were conducted at pouring temperatures of 1350 °C, 1400 °C, and 1450 °C; metallurgical quality levels of 10%, 50%, and 90%; and filling times of 5 s and 10 s. The fluidity lengths were measured and statistically evaluated. The results revealed that increasing the pouring temperature and metallurgical quality significantly improved fluidity, while shorter filling times allowed the molten metal to travel

longer distances before solidification. Modeling studies performed using a commercial casting simulation software showed strong correlation with the experimental data. Microstructural examinations indicated that higher pouring temperatures and improved metallurgical quality led to a more homogeneous distribution of graphite nodules and an increased ferrite fraction in the matrix. The findings provide valuable insights into the influence of process parameters on the fluidity behavior of ductile iron and offer critical design data for enhancing casting quality and productivity in industrial foundry applications.

Keywords: ductile iron (GGG40), fluidity, pouring temperature, filling time, metallurgical quality, numerical modeling, casting simulation

Introduction

Among engineering materials, cast irons play a key role due to their cost-effectiveness, high castability, and favorable mechanical properties. Essentially an iron–carbon alloy, cast iron differs from steel by containing more than 2.11 wt.% carbon (typically between 2.5 and 4.5 wt.%), which provides significant advantages such as a lower melting point and excellent fluidity. The wide range

of applications of these alloys stems from their different microstructural classifications, which depend on the morphology and distribution of carbon within the matrix. The main types of cast iron include gray cast iron with lamellar graphite, white cast iron with a cementite structure, and malleable cast iron obtained through specific heat treatments.^{1,2} Among these, ductile iron (also known as spheroidal graphite iron, SGI) eliminates the brittleness problem typical of conventional cast irons by promoting the precipitation of carbon in a spherical (nodular) form. Consequently, ductile irons exhibit high strength and ductility comparable to steels, making them critically

important for applications in the automotive, machinery, and energy industries.^{3–5}

Achieving the superior mechanical properties of ductile iron requires precise process control during foundry operations. In this context, fluidity is one of the most fundamental casting parameters, describing the ability of molten metal to completely and defect-free fill the mold cavity before solidification occurs.⁶ Fluidity can be defined as the distance molten metal can travel in the mold before solidifying, or its capacity to fill the entire mold cavity.⁷ The fluidity of molten metal is influenced by numerous factors, including alloy composition, mold characteristics, pouring temperature, alloying additions, inoculation treatment, and casting conditions. Insufficient fluidity often leads to critical casting defects such as misruns and cold shuts, particularly in thin-walled or complex-shaped components, thereby reducing productivity and increasing scrap rates. Fundamentally, fluidity is governed by operational parameters such as pouring temperature, chemical composition (especially the carbon equivalent), and heat transfer conditions determined by mold material and section thickness.^{8–10}

Previous studies on thin-wall ductile iron castings have demonstrated that fluidity is strongly governed by the coupled interaction of mold filling and solidification rather than by flow behavior alone.¹¹ In addition, recent investigations have shown that increasing the graphite nodule count is an effective approach to suppress carbide formation and promote a ferritic matrix, even at relatively low silicon contents.¹² Furthermore, fluidity in ductile irons has been reported to be influenced not only by melt flow behavior but also by surface tension effects and oxide film formation during mold filling, particularly in aluminum-alloyed systems.¹³ However, the nodularization treatment applied during the production of ductile iron (through Mg or Ce addition) and its distinctive solidification mechanism exert complex effects on the flow behavior of the alloy compared to conventional gray cast irons. Therefore, determining the influence of varying casting parameters on the fluidity of ductile irons is a crucial engineering requirement for optimizing modern foundry practices.

Although the fluidity of molten metal increases with temperatures above its melting point, excessive superheating may lead to adverse effects such as the loss of alloying elements through various reactions, mold deformation, and grain coarsening. Therefore, determining an optimum pouring temperature is essential. In general, casting is performed at temperatures approximately 100–150 °C above the melting point. The addition of elements that increase the carbon equivalent in cast irons positively affects fluidity.¹⁴ Moreover, inoculation—a critical treatment for improving the flow behavior and final properties of cast irons—minimizes undercooling and increases the number of available nucleation sites for graphite growth.¹⁵

The factors influencing the fluidity behavior of ductile iron have long been a significant topic in the optimization of foundry operations. The literature reports indicate that fluidity is primarily governed by process-specific variables such as pouring temperature and chemical composition. In particular, increasing the pouring temperature raises the superheat level, thereby significantly extending the flow length—an effect frequently confirmed through both experimental studies and numerical modeling.^{16–19} Today, casting processes are optimized at the design stage using advanced simulation software, which enables detailed predictions of mold filling behavior, solidification time, temperature distribution, and potential defect formation. Consequently, the entire process—from mold filling to complete solidification—can be tracked, allowing potential defects to be identified in advance.²⁰

Most existing studies tend to analyze the fluidity of cast irons by isolating individual variables and examining the effect of a single factor under controlled conditions. However, under real foundry environments, fluidity is governed by the simultaneous and interactive influence of multiple parameters, including pouring temperature, filling time, and alloy modification. Therefore, elucidating the combined and quantitative effects of varying casting parameters on the fluidity behavior of ductile iron is essential both for advancing metallurgical understanding and for minimizing casting defects in practice. The primary objective of this study is to address this knowledge gap. In this paper, the effects of key operational variables—namely pouring temperature, filling time, and metallurgical quality—on the fluidity of GGG40 ductile iron were comparatively evaluated through experimental investigations and a commercial numerical modeling software, FlowCast.

Materials and Methods

In this study, the fluidity behavior of ferritic ductile iron (GGG40 grade) was investigated under varying casting conditions. For this purpose, a specially designed multi-section fluidity test model was employed to evaluate the influence of different pouring temperatures, filling times, and metallurgical quality levels. The experimental design aimed to quantitatively determine the progression of molten metal within the mold as a function of these parameters. The test model consisted of channels with different section thicknesses and a total length of 450 mm, allowing detailed observation of fluid flow behavior under varying conditions. Figure 1 presents the solid model and dimensions of the designed fluidity test mold used in this study.

In the design shown in Figure 1, the channel length was intentionally set to 450 mm to ensure that complete mold filling would not occur under certain casting conditions, thereby allowing clear observation of flow termination. The channel width was kept constant, while the thickness was

varied at different sections. The purpose of using multiple section thicknesses was to determine the range of conditions under which the molten metal could successfully fill the mold. Accordingly, the section thicknesses were selected between 2 and 10 mm. Since no fluidity-related issues were expected in thicker sections, 10 mm was designated as the upper limit. A model plate was prepared according to the design specifications. The molds were produced using a sodium silicate-based binder and hardened with CO₂ gas. Before each casting, a thin layer of graphite-based release agent was applied to the mold surfaces.

Castings were then carried out using the designed molds to investigate the effects of process parameters on fluidity. The main experimental variables were defined as pouring temperature, filling time, metallurgical quality, and section thickness. In this study, metallurgical quality was defined as a relative parameter representing the effectiveness of nodularization and inoculation treatments and was controlled by varying the type and amount of inoculant and nodularizing alloy. The filling time was defined as the total duration required for the molten metal to completely fill the mold cavity. The experiments were carried out by manual ladle pouring under practical foundry conditions, without imposing a constant mass flow rate or controlled pressure head. The target filling times (approximately 5 s and 10 s) were achieved through controlled pouring practice. In the simulation model, the same pouring temperature and filling

time values were applied, and the inlet boundary condition was defined to reproduce the experimentally observed filling duration. No artificial adjustment of thermal parameters was introduced.

Metallurgical quality levels (10%, 50%, and 90%) were established through controlled variation in nodularization and inoculation practice under industrial foundry conditions. The base melt chemistry was maintained within the GGG40 specification range throughout all experiments. The objective of these adjustments was to modify the effectiveness of graphite nucleation and nodularity rather than to intentionally alter the bulk chemical composition of the melt. Although inoculant additions may theoretically introduce minor variations in Si content, these additions were limited and not intended to produce significant compositional shifts. Therefore, metallurgical quality in this study is treated as a relative microstructural parameter rather than a direct chemical composition variable. Table 1 summarizes the experimental parameters and casting conditions employed to evaluate the fluidity characteristics of the GGG40 ductile iron alloy.

As shown in Table 1, a total of 18 castings were produced using the GGG40 grade ductile iron under three different pouring temperatures, three levels of metallurgical quality, two filling times, and four section thicknesses. The melting process was carried out in an industrial foundry using a 500 kg capacity induction furnace. The melt temperature was continuously monitored using a digital thermocouple pyrometer, and once the target temperature was reached, nodularization and inoculation treatments were applied in a ladle. Subsequently, the molten metal was poured into the molds according to the specified filling times. The chemical composition of the cast alloy is presented in Table 2.

Examination of the chemical composition values presented in Table 2 indicates that the main constituents of the material are iron (Fe), carbon (C), and silicon (Si), along with minor additions of manganese (Mn), magnesium (Mg), and phosphorus (P). These results confirm that the chemical composition of the casting alloy complies with the GGG40 standard specifications. After casting, the samples were allowed to cool to room temperature, then removed from the molds and cleaned. Following the cleaning process, the specimens were examined

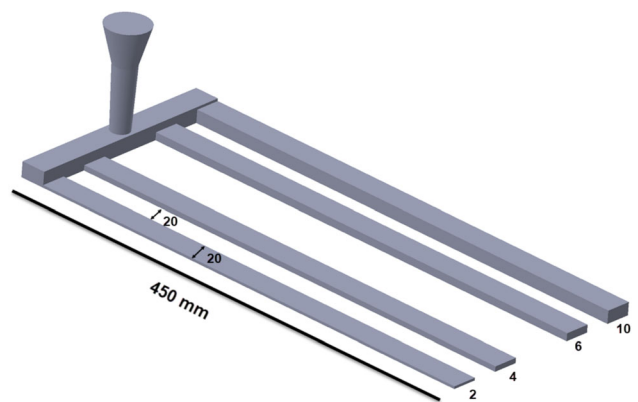


Figure 1. Model view and dimensions of the fluidity test mold.

Table 1. Experimental Parameters and Casting Conditions

Alloy	Ferritic ductile cast iron (GGG40-DIN EN 1563 standard)											
Temperature (°C)	1350				1400				1450			
Metallurgical quality (%)	10	50		90	10	50		90	10	50		90
Filling time (s)	5		10		5		10		5		10	
Section thickness (mm)	2	4	6	10	2	4	6	10	2	4	6	10

Table 2. Chemical Composition of the Alloy (wt.%)

Alloy	Element (%)								
	C	Si	S	P	Mn	Sn	Cu	Cr	Mg
GGG40	3.64	2.42	0.0020	0.023	0.34	0.050	0.024	0.025	0.034

Table 3. Thermophysical Properties of the Alloy Used in the Simulation Database

Alloy	Thermal conductivity (W/mK)	Specific heat (J/kg·K)	Density (kg/m ³)	Casting temperature (°C)	Solidification temperature (°C)	Solidification range (°C)	Latent heat of fusion (J/kg)
CI DI Ferr	41.51	460.24	7176.064	1350-1450	1128.378	41.667	230115.6

macroscopically, and the flow distances of the molten metal in the channels were determined. The fluidity was evaluated by measuring the flow length of the molten metal in the cast specimens after solidification. The measurements were performed using a digital caliper with an accuracy of ± 0.1 mm. For microstructural examinations, specimens were sectioned from the junction between the horizontal runner and the channel in each casting, corresponding to every section thickness. The obtained specimens were prepared according to standard metallographic procedures, including grinding, polishing, and etching with 2% nital solution. Microstructural analyses were performed using a Nikon Eclipse L150A optical microscope equipped with a Clemex digital camera.

The captured images were evaluated using the Clemex Vision Lite image analysis software, through which parameters such as the number of graphite nodules, nodularity ratio, and phase fractions were quantitatively determined. Graphite morphology (nodularity and nodule size) was quantitatively evaluated by digital image analysis in accordance with the ISO 945-4 image analysis approach (alternatively ASTM E2567). For each experimental condition, metallographic analyses were performed on a minimum of three specimens, and five randomly selected, non-overlapping fields of view (FOV) were analyzed per specimen. All micrographs were acquired at 100 $\times$ magnification. Image segmentation was performed using grayscale thresholding followed by morphological filtering. To eliminate polishing artifacts and non-graphitic features, a minimum graphite particle size corresponding to an equivalent circle diameter of ≥ 5 μ m was applied. Graphite particles satisfying the shape criteria defined by the standard were classified as nodules. Based on this analysis, nodularity and average nodule size were evaluated to support the microstructural observations presented in this study.

In the modeling studies, the solid models were created in SolidWorks, converted into STL format, and imported into the casting simulation environment. The simulations were performed using a commercial casting flow and solidification modeling software. The experimental parameters—pouring temperature, filling time, and metallurgical quality—were numerically defined in the modeling setup to ensure consistency between experimental and computational conditions. The modeling process began with importing the geometry and defining the material properties. The mesh structure was subsequently generated, consisting of approximately 20 million elements, with at least three cubic elements across the thinnest section of the model. The thermal and physical properties of both the ductile iron alloy and the mold material were assigned in the software. Table 3 presents the thermophysical properties of the CIDI Ferr alloy available in the database of a commercial simulation software.

The modeling studies were carried out based on the actual casting and filling conditions observed during experiments. In the numerical simulations, the filling rate was not defined as a fixed input parameter. Instead, the mold filling process was controlled by prescribing the filling time and pouring conditions, consistent with the experimental setup. Based on these inputs, the flow behavior and instantaneous filling rate were internally calculated by the commercial simulation software during the simulation. To determine the influence of varying casting parameters, different CLF (Critical Fraction of Liquid) values were employed in the simulations, and the results were compared with those obtained from real castings. In addition, the flow lengths of the molten metal within the mold were measured in the simulation software and compared with the experimental fluidity distances. Consequently, the modeling outcomes showed strong agreement with the experimental data, confirming that the fluid flow behavior and progression

Table 4. Fluidity Lengths of Molten Metal Under Different Casting Conditions (mm)

Experimental Conditions		Fluidity length vs. section thickness (mm)			
		2 mm	4 mm	6 mm	10 mm
1	1350–10–5	23	125	290	450
2	1350–10–10	37	122	195	450
3	1350–50–5	36	181	212	450
4	1350–50–10	24	217	355	450
5	1350–90–5	30	270	386	450
6	1350–90–10	54	220	322	450
7	1400–10–5	56	433	450	450
8	1400–10–10	48	424	450	450
9	1400–50–5	54	442	450	450
10	1400–50–10	58	438	450	450
11	1400–90–5	72	450	450	450
12	1400–90–10	65	450	450	450
13	1450–10–5	81	450	450	450
14	1450–10–10	74	446	450	450
15	1450–50–5	87	450	450	450
16	1450–50–10	84	450	450	450
17	1450–90–5	93	450	450	450
18	1450–90–10	82	450	450	450

distances of the molten metal in ductile iron castings can be accurately predicted under different process conditions.

Experimental Results and Evaluation

Fluidity Model, Casting Experiment Results, and Evaluation

After casting, the specimens were removed from the molds and initially examined macroscopically to confirm casting integrity before proceeding with detailed analyses. To evaluate the fluidity characteristics, the flow lengths of the molten metal were measured for different section thicknesses. For each casting condition, the distance traveled by the molten metal within the mold cavity was determined according to the section thickness, and the results are presented in Table 4.

Examination of the results presented in Table 4 reveals that the flow lengths of the molten metal vary significantly under different casting conditions, depending on section thickness. In all casting experiments, the channels with a section thickness of 10 mm were found to be completely filled under every condition. However, in thinner sections, the flow distance of the molten metal exhibited notable variation depending on factors such as pouring temperature, filling time, metallurgical quality, and section thickness. When the experimental parameters are

evaluated, the pouring temperature appears to be the most influential factor affecting the flow length. As the temperature increased, the fluidity improved and the molten metal advanced further within the mold for all section thicknesses. Another critical parameter influencing fluidity is the filling time. Under shorter filling time conditions (i.e., faster pouring), the molten metal was observed to flow a longer distance before solidification occurred. In the present study, the filling conditions were controlled by manually adjusting the ladle pouring rate, without using a choke or flow-restricting element in the gating system. Moreover, improvements in metallurgical quality were also found to slightly enhance the flow distance, thereby contributing positively to the alloy's fluidity behavior. In this study, metallurgical quality is defined as a relative parameter related to the effectiveness of nodularization and inoculation treatments and is assessed through microstructural characteristics such as graphite nodularity and morphology. Figure 2 presents representative images of the cast samples produced at a pouring temperature of 1350 °C under various experimental conditions.

Figure 2 shows the fluidity specimens obtained from experiments performed at a pouring temperature of 1350 °C with different filling times (5 s and 10 s) and metallurgical quality levels of 10%, 50%, and 90%. It was observed that the flow length of molten metal within the mold decreased with increasing filling time. At a filling time of 5 seconds, the molten metal exhibited a more

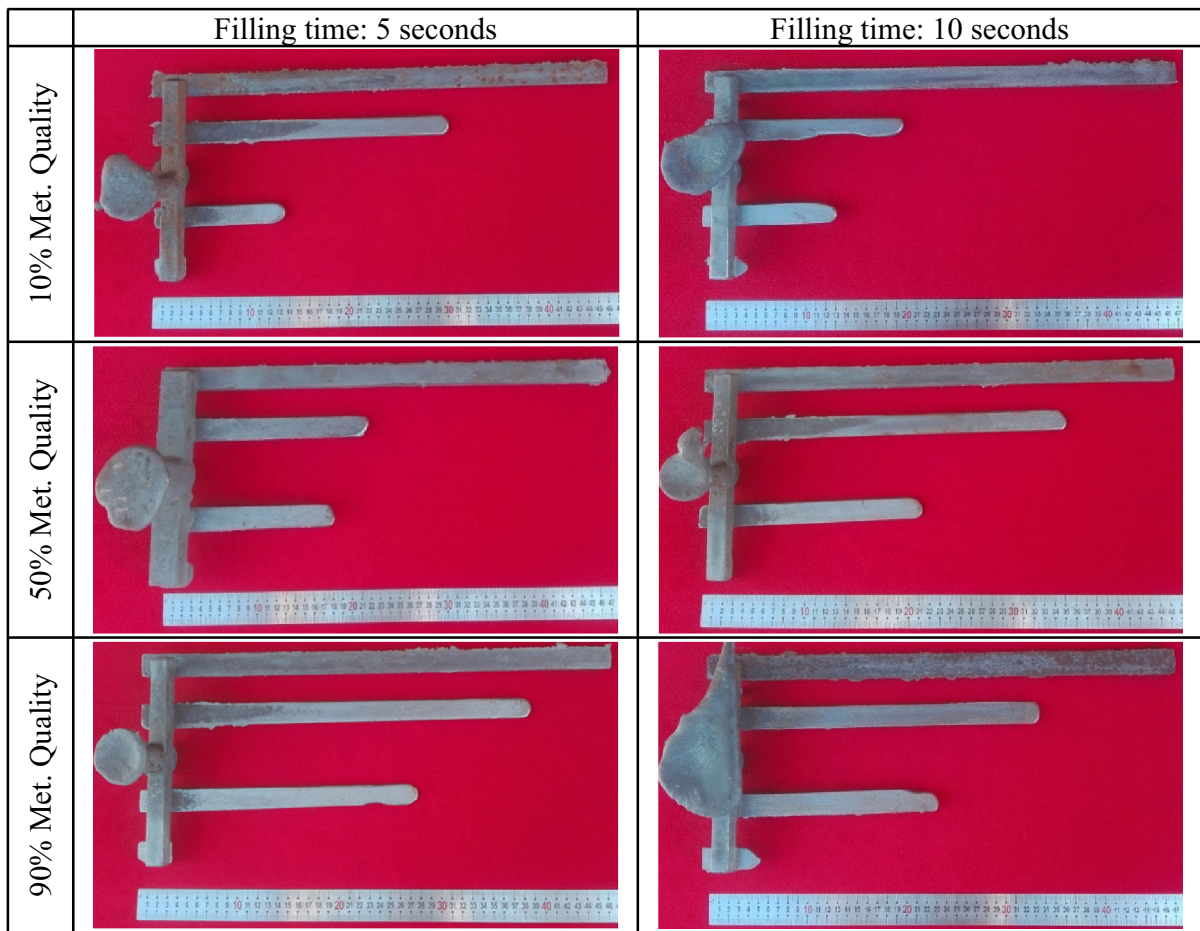


Figure 2. Fluidity test specimens obtained from casting experiments performed at 1350 °C.

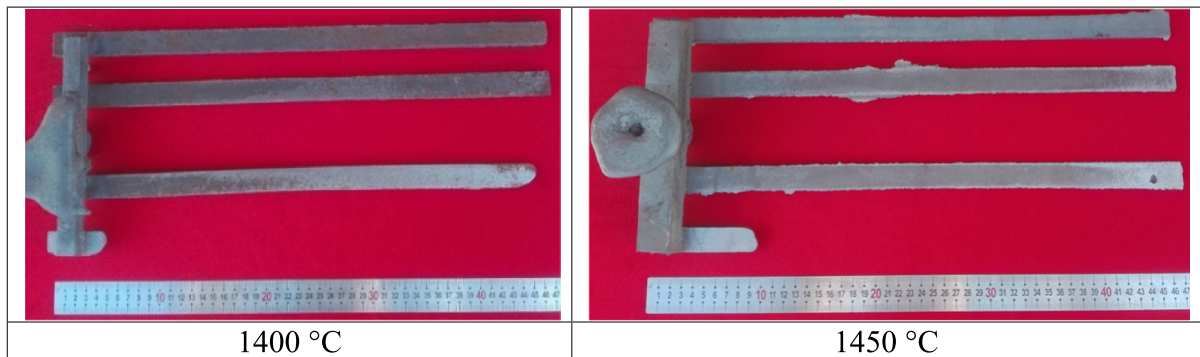


Figure 3. Fluidity samples at a metallurgical quality level of 50% with a filling time of 10 s.

homogeneous flow pattern with fewer interruptions caused by premature solidification. In contrast, at a filling time of 10 seconds, the flow length was shorter, and early solidification occurred particularly in thin-walled sections. This behavior can be explained by increased heat loss during prolonged contact between the molten metal and the mold at slower filling rates, leading to reduced fluidity over shorter distances. This observation is consistent with

previous findings on thin-wall ductile iron castings, which showed that flow interruption is primarily governed by the coupled interaction of mold filling and early solidification rather than by melt flow behavior alone.¹¹ The results clearly demonstrate that shorter filling times (i.e., faster pouring) have a direct and positive effect on fluidity. At low metallurgical quality (10%), incomplete mold filling and interrupted flow paths due to early solidification were

Table 5. Simulation Results Under Various Modeling Parameters

	Modeling conditions	CLF value (%)	Simulated filling time (s)	Filling ratio (%)
1	1350–10–5	10	3.33	66.57
2	1350–10–10	10	5.99	59.93
3	1350–50–5	50	3.39	67.67
4	1350–50–10	50	6.54	65.46
5	1350–90–5	90	3.52	70.32
6	1350–90–10	90	6.71	67.03
7	1400–10–5	10	3.99	79.96
8	1400–10–10	10	7.37	73.67
9	1400–50–5	50	4.17	83.39
10	1400–50–10	50	7.53	75.24
11	1400–90–5	90	4.23	84.59
12	1400–90–10	90	7.62	76.13
13	1450–10–5	10	4.45	89.11
14	1450–10–10	10	8.64	86.41
15	1450–50–5	50	4.46	89.22
16	1450–50–10	50	8.65	86.45
17	1450–90–5	90	4.47	89.39
18	1450–90–10	90	8.73	87.23

observed. At medium quality (50%), the flow became more stable, and the molten metal advanced further in thinner sections. At high quality (90%), enhanced inoculation and nodularization conditions improved melt fluidity, resulting in the highest flow lengths. Here, metallurgical quality refers to a comparative parameter related to the effectiveness of nodularization and inoculation treatments and is quantified based on microstructural indicators such as graphite nodularity and morphology. To assess the effect of pouring temperature, Figure 3 presents the casting specimens produced at 1400 °C and 1450 °C under conditions of 50% metallurgical quality and a 10 s filling time.

In the images presented in Figure 3, it can be observed that the channels with section thicknesses of 6 mm and 10 mm were completely filled with molten metal, whereas the 2 mm and 4 mm channels were not fully filled. When comparing the castings performed at different pouring temperatures under conditions of 50% metallurgical quality and a 10-second filling time, it is evident that pouring temperature is the most influential parameter affecting fluidity. To better interpret the relative influence of pouring temperature and metallurgical quality, superheat was evaluated as the difference between pouring temperature and the estimated liquidus temperature (Pour Temp—TLiq). Based on the nominal GGG40 base chemistry (C $\approx$ 3.6 wt.%, Si $\approx$ 2.4 wt.%), the liquidus temperature was estimated to be approximately 1145–1155 °C using established empirical relations. Accordingly, the calculated superheat values were approximately 200 °C at 1350 °C,

250 °C at 1400 °C, and 300 °C at 1450 °C. These differences in superheat are significantly larger than the variations attributed to metallurgical quality levels, indicating that temperature is the dominant parameter governing fluidity. The base chemistry was maintained within the GGG40 specification range, and no intentional modification of the TLiq–TSol interval was introduced between experimental conditions. Furthermore, the estimated TLiq values are consistent with the solidification temperature range defined in the simulation database. As the pouring temperature increased, the flow length of the molten metal also increased. This behavior can be attributed to the higher metal temperature providing a longer solidification time, allowing the molten metal to travel further within the mold cavity before solidifying. In this study, it was observed that the flow length of molten metal increased significantly with rising pouring temperature across all section thicknesses, whereas complete mold filling became more difficult in thinner sections (2–4 mm) due to early solidification. This trend is consistent with previous findings reporting that, in thin-wall ductile iron castings, increased heat loss within the mold and rapid temperature drop of the molten metal can interrupt the flow continuity.⁹ Moreover, shortening the filling time (i.e., faster filling) enhanced the fluidity by allowing the molten metal to advance a longer distance before solidification occurred, an effect also confirmed by numerical–experimental studies investigating mold filling dynamics under variable pouring rates.^{10,21} The improvement in fluidity with increasing metallurgical quality is consistent with prior studies reporting that enhanced

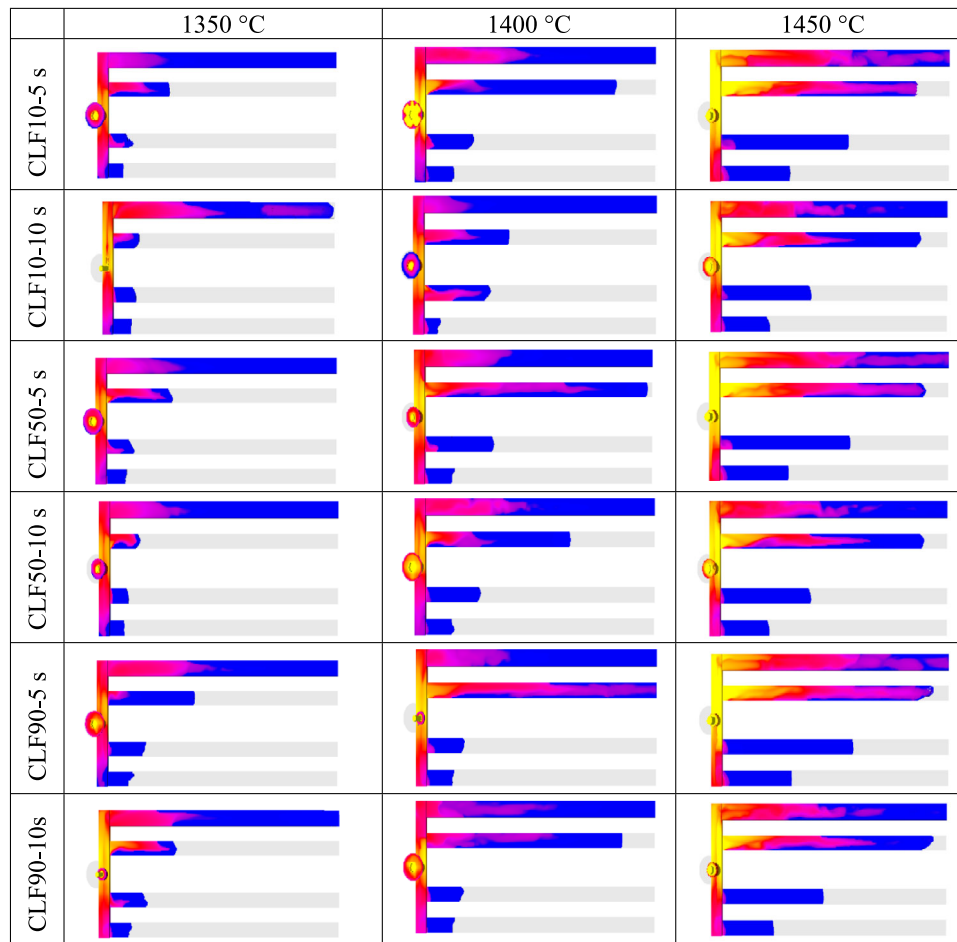


Figure 4. Filling simulation results obtained from the numerical casting simulations.

inoculation and nodularization efficiency, associated with higher graphite nodularity, improves the filling behavior of thin sections. In the present study, metallurgical quality levels corresponded to measurable differences in graphite nodularity and morphology, supporting this trend.^{22–24} Conversely, oxidation and inclusions in the molten metal may decrease fluidity, thereby increasing the likelihood of misruns and cold shuts—an issue extensively discussed in the literature.²⁵ It should be noted that manual ladle pouring may introduce transient variations in runner filling, which can influence oxidation and inclusion formation. In the present study, this effect was minimized by applying a consistent pouring practice by the same operator for all experiments; nevertheless, its potential contribution to fluidity variations is acknowledged. The strong correlation between the flow lengths and filling patterns obtained from the numerical simulations and those measured experimentally is consistent with validation studies confirming the reliability of combined flow–solidification numerical approaches.²⁶ Overall, the concurrent optimization of pouring temperature and filling time, together with effective inoculation and nodularization control, appears to be a key strategy for minimizing misruns and cold-shut defects, particularly in thin-wall ductile iron (KGDD) castings.^{22,27}

Fluidity Experiment Modeling Results and Evaluation

The modeling studies were conducted to numerically simulate the actual casting experiments under conditions consistent with the physical trials. In the fluidity modeling process, the filling time parameter was initially defined based on the real casting durations observed during experiments. Accordingly, the filling times were set to 5 s and 10 s to correspond to the experimental pouring conditions. Depending on the mold filling rate and pouring temperature, the total casting duration ranged between 3 and 5 s and 6–10 s. Furthermore, to evaluate the influence of varying casting conditions on metallurgical quality, different CLF (Critical Liquid Fraction) values were applied within the simulation software. The results obtained for each CLF value were then matched with those from the experimental castings to ensure consistency between numerical and real casting behaviors. This approach enabled verification of the correlation between simulated and experimental flow patterns and filling times. Table 5 presents the filling durations and corresponding filling percentages obtained at different CLF values.

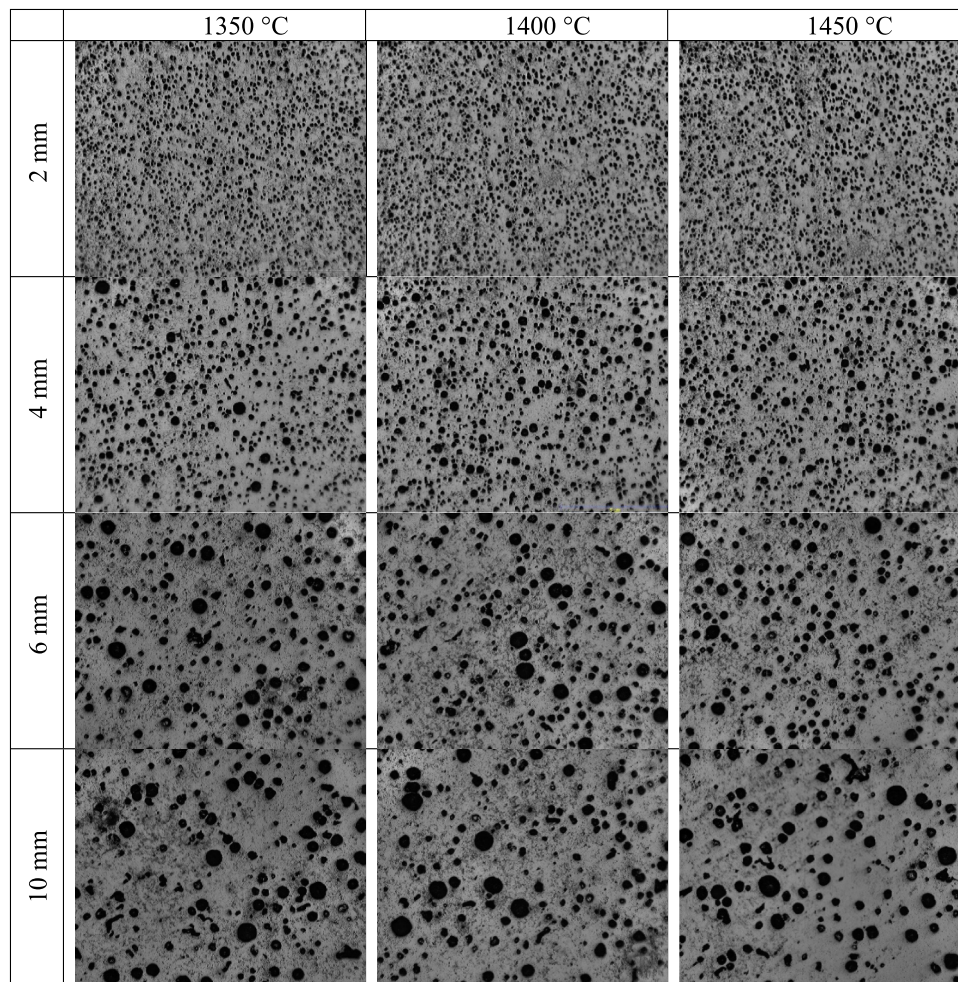


Figure 5. Optical micrographs of samples cast at different pouring temperatures.

Table 5 presents the results obtained from modeling studies conducted under various casting conditions, indicating the points at which the molten metal lost its fluidity and ceased to flow within the mold. Examination of the filling ratios reveals that fluidity was significantly affected by the changing process parameters. It was observed that faster mold filling allowed the molten metal to travel longer distances before solidification occurred. In all simulations, when other parameters were kept constant, the filling rate was found to have a distinct effect on fluidity—shorter filling times resulted in higher filling ratios and improved flow continuity. Moreover, an increase in pouring temperature led to a noticeable improvement in fluidity characteristics and a higher percentage of mold filling. The greatest flow length and fluidity were achieved at a pouring temperature of 1450 °C. The influence of metallurgical quality was evaluated in the simulations by varying the CLF (Critical Liquid Fraction) values. As the CLF ratio increased, the flow length also increased, confirming that improved metallurgical quality positively influenced the fluidity behavior. In conclusion, when all parameters were evaluated together, the pouring temperature was identified

as the most influential factor on fluidity, followed by the metal filling rate and metallurgical quality. Within the scope of the modeling studies, the flow behavior of the molten metal within the mold cavity and its progression through different section thicknesses were analyzed using a commercial casting simulation software. The simulations were conducted by considering key process parameters such as pouring temperature, filling time, and metallurgical quality. Figure 4 presents the filling simulation results obtained under various combinations of pouring temperatures, filling durations, and metallurgical quality levels. In the simulations, the filling time was not defined as a fixed input parameter; instead, it was controlled indirectly by prescribing the experimental pouring conditions, and the resulting filling time was calculated by the simulation software.

As shown in Figure 4, increasing the pouring temperature significantly enhanced both the fluidity and the flow length of the molten metal within the mold. With higher temperatures, the viscosity of the melt decreased, allowing the molten metal to travel longer distances before solidification

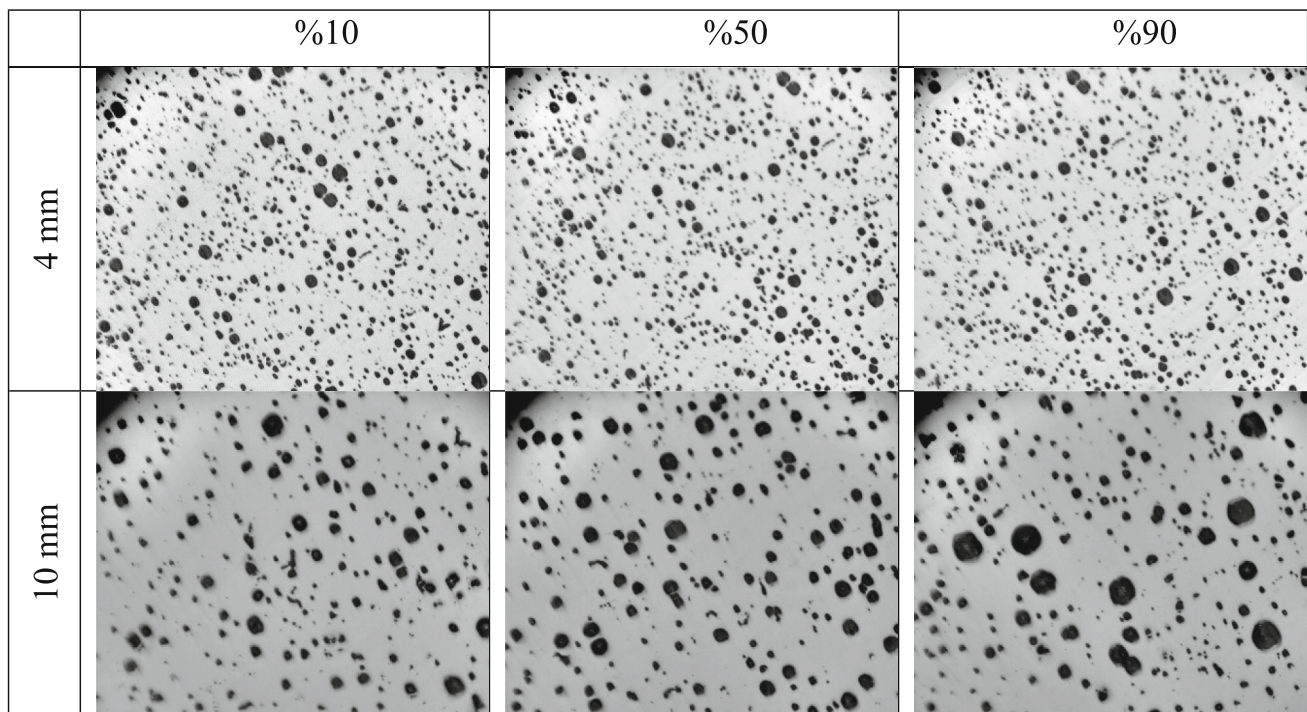


Figure 6. Microstructural images obtained under different metallurgical quality conditions.

occurred. This trend was consistently observed in both the simulation results and the experimental castings. In all runners, the flow length increased with greater section thickness and higher pouring temperature. Furthermore, increasing the filling rate and improving the metallurgical quality also had a positive influence on fluidity, leading to a more continuous and uniform filling behavior of the molten metal inside the mold.

The metallurgical quality value varies between 0 and 100 depending on foundry practices and the amount of inoculant used. In the present study, the CLF value was found to range between 10 and 90 depending on the type and quantity of inoculant applied. Adjustment of the CLF (Critical Fraction of Liquid) parameter can improve agreement between simulation and experimental results under plant-specific conditions; however, pouring temperature (superheat) and section thickness remain the primary factors governing fluidity. Similarly, in the literature on aluminum alloys, alloying additions modeled through CLF variations have been shown to produce trends consistent with experimental fluidity behavior.²⁰ A general correlation was observed between the experimental and simulated results. In both methods, increasing the pouring temperature, filling rate, and metallurgical quality had a positive effect on fluidity, allowing the molten metal to travel longer distances in thinner sections. However, certain numerical discrepancies were identified between modeling and experimental data. These deviations are believed to result from limited precision in input parameters, incomplete definition of the thermophysical properties of the alloy, or differences in the pouring point configuration

between the simulation and the actual casting. Notably, while complete filling was achieved in 6 mm and 10 mm channels during the real casting trials, only partial filling was observed in the simulations, representing the most distinct example of this divergence. This discrepancy in the 6 mm section is interpreted as occurring within a transitional regime between complete and incomplete filling, where small variations in thermal conditions (effective superheat) or flow boundary conditions may significantly influence the predicted outcome. Several previous studies have also emphasized that accurate definition of material properties and mold geometry consistent with actual casting conditions is critical for reliable simulation outcomes.^{28–32} Calibration of the CLF parameter improves the agreement between simulation and experimental results; however, temperature (superheat) and section thickness remain the primary controlling factors affecting fluidity.

Microstructural Characterization and Evaluation

Within the scope of the study, the effect of pouring temperature on the microstructure was investigated under constant metallurgical quality (50%) and a filling time of 10 s. Samples obtained from castings performed at different temperatures were examined, and microstructural images taken at 100× magnification from various cross-sectional regions are presented in Figure 5.

As shown in Figure 5, increasing the section thickness resulted in a noticeable increase in the average diameter of the graphite nodules. The variation in pouring temperature

Table 6. Microstructural Image Analysis Results Section Thicknesses

Casting conditions	2 mm			4 mm			6 mm			10 mm		
	Nodularity (%)	Nodule diameter (μm)	Graphite area Percentage (%)	Nodularity (%)	Nodule diameter (μm)	Graphite area percentage (%)	Nodularity (%)	Nodule diameter (μm)	Graphite area percentage (%)	Nodularity (%)	Nodule diameter (μm)	Graphite area percentage (%)
1350–10–5	82.7	28.5	11.6	81.2	34.4	11.3	80.9	48.2	10.2	81.3	66.2	9.7
1350–10–10	83.1	28.6	11.4	81.4	36.5	11.2	81.2	47.4	10.1	81.5	67.2	10.2
1350–50–5	85.2	28.3	11.8	84.2	38.7	10.4	83.8	48.6	10.3	84.1	66.2	10.4
1350–50–10	85.9	27.9	11.7	83.9	37.9	10.6	83.9	49.9	10.4	84.1	69.2	10.1
1350–90–5	86.4	28.2	11.3	85.3	38.4	10.7	85.1	48.1	10.2	85.1	66.1	10.1
1350–90–10	86.8	27.4	10.8	85.6	39.1	10.2	85.4	48.7	10.5	85.3	67.5	10.3
1400–10–5	82.1	27.8	10.5	80.8	36.8	11.2	80.6	47.5	10.4	80.9	67.6	10.8
1400–10–10	82.4	28.2	10.9	81.3	38.1	11.8	81.1	48.3	10.6	81.5	68.6	10.9
1400–50–5	85.1	28.1	11.4	84.1	38.4	11.3	83.7	49.7	10.1	84.5	69.4	11.1
1400–50–10	84.8	28.2	11.8	84.2	38.5	11.7	84.1	49.1	10.8	84.1	69.9	11.1
1400–90–5	89.4	28.1	11.6	86.2	39.3	10.4	85.7	47.4	11.3	86.4	68.5	11.4
1400–90–10	89.4	27.8	11.1	85.9	39.8	10.5	85.8	48.7	11.4	85.6	68.6	11.6
1450–10–5	81.0	27.1	11.5	81.8	37.6	10.7	81.4	47.8	10.1	82.1	66.5	11.2
1450–10–10	81.2	27.4	11.3	81.5	37.9	11.4	81.6	47.2	11.1	81.6	66.1	11.5
1450–50–5	85.1	28.3	11.7	83.2	40.2	10.8	82.1	46.4	10.7	84.1	68.9	11.0
1450–50–10	84.8	27.9	12.1	83.3	38.9	10.1	82.7	48.3	10.5	83.9	68.4	9.5
1450–90–5	87.4	26.8	11.9	86.8	36.2	10.6	85.4	47.4	10.4	87.1	69.3	9.8
1450–90–10	87.5	27.2	11.6	85.4	39.4	10.2	85.2	49.1	11.2	86.6	69.1	10.3

produced only minor changes in the microstructure, whereas section thickness was found to have a more dominant influence on structural evolution. Another remarkable observation was the deterioration of graphite sphericity with increasing section thickness. The variation in the average diameter of graphite nodules was more pronounced in thicker sections compared to thinner ones. This behavior can be attributed to the reduced cooling rate in thicker regions, allowing graphite particles to grow for a longer duration during solidification. To investigate the effect of metallurgical quality on the microstructure, castings were performed at a pouring temperature of 1350 °C with a filling time of 5 s. Samples corresponding to metallurgical quality levels of 10%, 50%, and 90% were analyzed. Representative microstructural images obtained from 4 and 10 mm section thicknesses at 100× magnification are presented in Figure 6.

As shown in Figure 6, changes in section thickness resulted in observable variations in microstructure, whereas differences in metallurgical quality were associated with changes in the size and sphericity of the graphite nodules. With increasing metallurgical quality, the graphite particles became more spherical, and the most homogeneous structure was achieved under the 90% metallurgical quality condition for all section thicknesses. The evaluation of the filling rate indicated that the pouring speed had no significant influence on the microstructure. Based on image analysis of the micrographs, parameters such as nodularity (%), average nodule diameter, and the area fraction of graphite nodules were measured. Table 6 presents the measurement results obtained for each section under the corresponding experimental conditions.

The values presented in Table 6 represent average results obtained from image analysis measurements for each condition. As shown in Table 6, the sphericity (nodularity) ratios observed in the microstructure were above 80%, which is considered acceptable for ductile cast irons. Variations in experimental parameters did not lead to pronounced differences in nodularity values, and the distribution of these values appeared relatively uniform. A slight increase in nodularity was observed with the improvement of metallurgical quality; however, this difference remained limited due to the short solidification times and the relatively small variation in section thickness among samples. In contrast, the graphite nodule diameters showed a clear dependence on section thickness. The average nodule diameter was approximately 28 µm in 2 mm sections, 37 µm in 4 mm sections, 48 µm in 6 mm sections, and around 68 µm in 10 mm sections. This trend can be attributed to the inverse relationship between cooling rate and section thickness, where slower cooling in thicker sections promotes the growth of larger graphite nodules. These findings are in strong agreement with recent studies reporting that higher cooling rates in thinner sections promote finer graphite nodules and higher nodularity,

while thicker sections exhibit coarser graphite morphologies due to reduced undercooling and slower solidification kinetics.^{33–37} The observed increase in graphite nodularity and refinement of graphite size with improved metallurgical quality is consistent with the findings of Almanza et al.,¹² who reported that higher nodule counts significantly reduce carbide formation in thin-wall ductile iron sections. For instance, previous studies have demonstrated that the mean nodule diameter in GGG40 castings increases with section thickness, mainly due to extended diffusion times during eutectic solidification. Similarly, reported that optimized inoculation and controlled cooling can stabilize graphite morphology, maintaining nodularity above 80% even at varying wall thicknesses. Thus, the results of the present study align well with existing literature, confirming that microstructural refinement in ductile irons is strongly governed by the interplay between section thickness, cooling rate, and metallurgical quality.

Conclusions

In this study, the effects of pouring temperature, filling time, and metallurgical quality on the fluidity behavior of GGG40 ductile cast iron were investigated through experimental trials and numerical simulations. The main conclusions are summarized as follows:

- Pouring temperature was identified as the most influential parameter governing fluidity. Increasing temperature significantly enhanced flow length in all section thicknesses. Full filling (450 mm) was consistently achieved in 10 mm channels, whereas 2 mm sections remained limited due to rapid solidification.
- Section thickness strongly influenced both fluidity and microstructural evolution. Thicker sections exhibited improved flow length and larger graphite nodules due to reduced cooling rates.
- Shorter filling times (faster pouring) improved fluidity by allowing molten metal to travel longer distances before solidification.
- Numerical simulations showed good agreement with experimental results. Temperature and section thickness were confirmed as the dominant factors, while metallurgical quality had a secondary but measurable influence on fluidity.
- Increasing metallurgical quality slightly improved flow length and promoted higher graphite nodularity and more uniform microstructures.
- Adjustment of the CLF (Critical Liquid Fraction) parameter improved the agreement between simulation and experimental results; however, it represents a secondary modeling parameter rather than a primary controlling factor.
- Overall, proper control of pouring temperature, filling time, and metallurgical quality is essential

for optimizing fluidity and minimizing casting defects in thin-walled GGG40 components.

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Conflict of interest The authors declare that they have no conflict of interest related to this study.

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