EFFECTS OF PROCESS RELATED VARIATIONS ON FILLABLITY SIMULATION OF THIN-WALLED IN718 STRUCTURES

Mohsin Raza
School of Innovation, Design and Engineering, Mälardalen University, Eskilstuna, Sweden
TPC Components AB, Hallstahammar, Sweden

Roger Svenningsson
Swerea SWECAST AB, Jönköping, Sweden

Mark Irwin
TPC Components AB, Hallstahammar, Sweden

Björn Fägerström
School of Innovation, Design and Engineering, Mälardalen University, Eskilstuna, Sweden

Anders E. W. Jarfors
Materials and Manufacturing, School of Engineering, Jönköping University, Jönköping, Sweden

DOI 10.1007/s40962-017-0189-9

Abstract

Simulation tools have improved significantly and are now capable of accurately predicting mould filling behavior. The quality of prediction is highly dependent on material properties and set-up of boundary conditions for the simulation. In this work material properties were measured and casting conditions were analyzed to accurately replicate the casting process in simulation. The sensitivity of the predictions to minor process variations commonly found in foundries was evaluated by comparing simulation and cast samples. The observed discrepancies between simulation and cast samples were evaluated and discussed in terms of their dependency on process variations. It was concluded that the simulation set-up was capable of reasonable predictions and could replicate the asymmetry of the filling however did not accurately predict the absolute value of the unfilled area. It was discovered that asymmetric flow due to variations in the orientation of the casting mould during filling could have greater influence on the predictions than the actual variation in fill time. The quality of simulation is dependent on equipment and techniques used in the foundry as well as the metallurgical model to simulate the process.

Keywords: *casting, thin-walled, filling, simulation, prediction, inconel*

Introduction

Due to the ability to produce net shape parts that maintain tight dimensional tolerances, investment casting has been widely used to manufacture components used in the hot gas path in gas turbines since 1950's.[1] In the power generation and aerospace industries, the overall weight reduction of engineering systems is much sought after, especially for turbines. Weight reduction of an engineering system can be achieved by using integrated multifunction components or by reducing component weight either by improving component design or using lightweight materials. Increased demands have been put on investment casting foundries by the turbine industry to produce complex thin-walled components.[2] Weight reduction of components is essential to lower fuel consumption and reduce environmental impact.[3] Casting of thin-sections is challenging due to premature solidification in thin-walled sections and long feeding distances often resulting in incomplete filling, cold shuts and shrinkage porosity.[4]

A number of studies have been performed to investigate important aspects of investment casting of thin-walled geometries. Flemings[5] demonstrated that superheat and metal head had greater effect on fluidity than melt viscosity and surface tension for thicker sections. Flemings[5] also concluded that for thin sections surface tension became important, limiting mold filling.

For the nickel base superalloys (IN100 alloy), Chandraseckariah and Seshan[6] concluded that the pouring temperature and mold temperature had greater effect on fluidity than other casting variables, such as, vacuum level and shell thickness.

In an attempt to address the additional challenges imposed by thin-walled castings, Campbell and Oliff[7] established mould filling criteria for thin walled castings. It was shown that at low heat content in a vertical mould set-up fluidity was limited by solidification which they termed flowability, a dynamic aspect, whereas at high heat content of a vertical mould system, fluidity was limited by surface tension which they termed as fillabillity, a static aspect.

Campbell[8] also performed investigations on the effect of capillary repulsion in thin-section moulds and surface tension on the filling pattern in the mould cavity. It was suggested that the surface oxide films formed during filling were pinned to the mould wall blocking the melt flow, resulting in decreased fluidity. These films also caused cold shuts and other internal defects in castings.

Campbell[9] established gating design requirements for thin-walled castings by investigating the effect of different gating methods and their effect on fillability in thin-walled castings. Bottom-gating was concluded superior to top-gated systems and bottom-gating reduced the filling instabilities.

The prediction by simulation has become a vital step in the development of efficient manufacturing processes. The reliability of simulation is significantly dependent upon material properties, metallurgical models as well as accuracy in defining boundary condition.[10] The boundary conditions are influenced by equipment and operation related variations arising from mould handling and melt pouring.[11]

Other parameters such as the mould filling sequence in casting of multi-cavity moulds are related to cluster design and equipment related limitation in process control tolerances. The degree of variation in critical process parameters is also highly dependent on the degree of automation. The relative importance of these process uncertainties on casting quality is not well understood. Although the physical principles governing fill and solidification are well established,[12] it is difficult to account for uncertainties in process parameters when defining boundary conditions for simulations.

As concluded in a related study,[13] there is a lack of literature available that addresses the effect of variation in process parameters on the accuracy of simulation. This suggests a need for further investigation of how to define boundary conditions that more accurately describe the conditions in the foundry.

The aim of this research is to investigate how the uncertainty in variation of foundry parameters can be accounted for when defining initial boundry conditions in order to improve accuracy of simulation. Characterization measurement has been performed on mould and alloy materials to eliminate uncertainties that can potentially be introduced in simulation from inaccurate material data. The discrepancy between experiments and simulations were analyzed and discussed to identify how variation in foundry parameters influence accuracy in simulation of the filling of a thin-walled mould.

Materials and Methods

The initial phase of the experimental work was focused on acquiring accurate thermodynamic data and performing simulations according to an experimental plan, Table 1, using the simulation software, NovaFlow&Solid^{TM}.[14] In order to obtain reliable simulation results thermo-physical properties of the cast alloy and the mould material[15] were introduced into the software.

A test geometry resembling a segment of a turbine hub was designed with varying thickness as shown in Figure 1a. The variation in thickness was intended to restrict the melt

Table 1. Experimental Plan to Evaluate the Effect of Parameter Variation

Trial #	Filling system	Cast temp. (°C)	Pour time (s)
1	Bottom-gated	1475	12
2	Bottom-gated	1530	12
3*	Bottom-gated	1530	18
4**	Bottom-gated	1475	18
5	Top-gated	1450	8,0
6	Top-gated	1500	8,0
7	Top-gated	1500	12
8	Top-gated	1450	12

* Extra insulation applied around the down sprue

** Misalignment in mould holder (in casting chamber) corrected to zero level

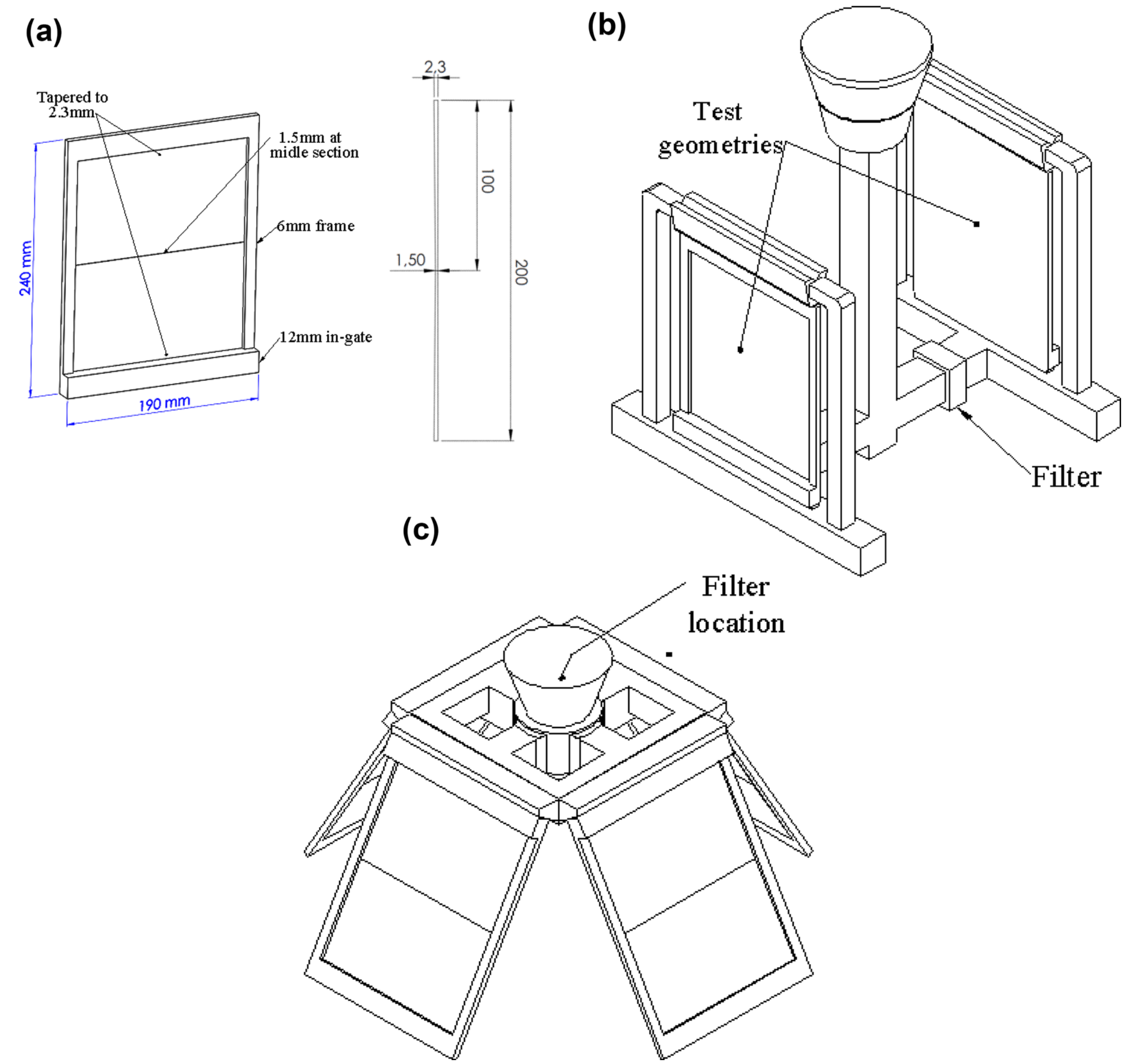

Figure 1. (a) Test geometry with varying wall thickness, (b) bottom-gated mould filling system, (c) top-gated mould filling system.

flow in order to achieve a certain degree of unfilled area so that it could be used as a reference for comparison between simulations and castings. The gating systems were designed to replicate industry standard multi-component gating systems which are typically used in investment casting process and are shown in Figure 1b, c.

A standard ceramic mould was prepared consisting of three different material layers.

- First prime coat (0.15 mm) applied using water based colloidal silica slurry containing $CoAlO_3$ and $ZrSiO_4$ (325Mesh) as additives and Al_2O_3 (90 FEPA Grit) as stucco.
- Second prime coat (0.30 mm) applied using a water based colloidal silica slurry containing $ZrSiO_4$ (200 mesh) and stuccoed with Al_2O_3 (54 FEPA Grit).
- Backup coat (8 mm) applied using a water based colloidal silica slurry containing fused silica, SiO_2 (270 mesh) and stuccoed with $AlSiO_3$ (16/30 mesh).

The thermo-physical properties of the mould material used in this study were taken from the literature.[15] The moulds were insulated using a fiber blanket consisting of 48% Al_2O_3 and 52% SiO_2, with a density of 96 kg/m^3 and thermal conductivity of 0.62 W/(mK) at 1000 °C.[16]

Aerospace grade IN718 according to AMS5383[17] was used in the experimental work. Table 2 shows the composition of the alloy, measured using a XRF MagiX FAST 2460 spectrometer.

Specific heat and heat of fusion were measured by differential scanning calorimetry using a NETZSCH DSC 404 C instrument. The heating rate was 0.2 K/s. The measurements

Table 2. Measured Composition of IN718 (wt%) and Standard[17]

Element	Value	Standard	
		Min.	Max.
C	0.059	–	0.08
Si	0.02	–	0.035
Mn	0.04	–	0.035
P	0.006	–	0.015
S	0.002	–	0.015
Al	0.46	0.40	0.80
B	0.003	–	0.006
Co	0.28	–	1.00
Cr	17.88	17.00	21.00
Cu	0.02	–	0.30
Mo	3.00	2.80	3.30
Nb	5.01	4.70	5.50
Ni	51.45	50.00	55.00
Ti	0.92	0.65	1.15
Fe	20.75	Remainder	

were carried out between 25 and 1375 °C in the presence of Argon as a purge gas to ensure efficient heat transfer for improved sensitivity. The samples had a cylindrical geometry, with dimensions of 6.1 mm × 21.65 mm. The liquidus and solidus temperature of studied sample was 1228 and 1345 °C respectively.

Linear thermal expansion was measured using a NETZSCH DIL 402 C on 12 mm long and 6 mm diameter rods, taken from cylindrical samples after machining and polishing. The temperature range was 20–1200 °C. The heating and cooling rate was approximately 0.2 K/s. Purge helium gas at 50 ml/min rate was used. Density at different temperature was derived from thermal expansion data.

The thermal diffusivity, α, of IN718 alloy was measured using a Laser-Flash Netzsch LFA 427 over the range of 25–1200 °C. The test sample was 12.5 mm long and 4 mm in diameter. Based on the measured thermal diffusivity together with the density, ρ, thermal expansion and the specific heat measurements, thermal conductivity, λ, was calculated as

$$\lambda(T) = \alpha(T)\rho(T)cp(T)$$

Temperature drop in the mould cavity during transport from the pre-heat furnace was measured in three different conditions, i.e. uninsulated, with one layer of insulation and with two layers of insulation. A "K" type thermocouple was used to determine the temperature inside mould cavity. The results from this experiment were used to define boundary conditions, i.e. mould temperature, filter temperature and insulation temperature.

The pouring rate was estimated from in situ experiments by measuring melt stream diameter variation over time during the tilt pouring sequence. This was done by analyzing video recordings of the pour and using image analysis software ImageJ™ [18] to estimate the melt stream diameter. The estimated diameter was then used in the simulation software to describe the area of impact in the pouring basin and to reversely calculate the mass flow during pouring. The average rate of pour was determined to be 1.8 kg/s for both the bottom and the top-gated systems. The pouring parameters were adjusted to replicate the foundry conditions, i.e. tilt-pouring-over-lip resulting in a non-vertical angle of incidence for the melt jet, based on the point of impact and pouring height. The volume inside mould and the surrounding environment were defined as vacuum in the simulation model to replicate vacuum casting conditions. Under low pressure conditions, the conductive/convective heat transfer through the air gap is negligible and heat transfer occurs mainly through direct contact between the mould and metal.[19] The contact area between the melt and the mould depends on surface roughness of the mould. The roughness of the solidifying surface is estimated to be 3 microns based on observation of roughness of cast surfaces. The roughness of the mould material however, is estimated to be substantially higher, 44 microns. Based on these observations it is assumed in the simulation that 5% of solidifying melt surface is in contact with the mould which gives an average interface heat transfer coefficient (IHTC) value of 10 kW/m^2/°C. A constant value of IHTC was used in simulations as the variation in thermal conductivity of the mould is fairly small at the temperature ranges where metal solidifies. Similar IHTC value has been reported in the literature.[20]

Sensitivity analysis for mesh size and parameters related to fluid flow through the mesh was performed in order to choose an appropriate mesh size as well as threshold values for melt flow. A mesh size of 1 mm was used throughout the geometry and an order of millions of elements were used in simulation of both the top-gated and bottom gated systems. A mesh size coarser than 1 mm resulted in over predicted filling. A mesh size finer than 1 mm increased the simulation time significantly making it impractical for the foundry. The fluidity threshold, above which the Navier–Stokes equations are applicable was set to 70%. The percolation threshold was set to 50% below which melt flow is absent without plastic deformation. Here it should be noted that, in simulation Darcy's law applies between the fluidity threshold and the percolation threshold. An increase in fraction solid at the melt free surface was used as an indicator for flow stop.

The extent of variation in process parameters such as cast temperature and pouring rate is known from empirical observation from the foundry. These values have been used in performing a simulation campaign, as described in

Table 1, which has been carried out in order to investigate the sensitivity of simulated results to variation in these parameters. Top and bottom-gated runner systems were compared in order to evaluate the accuracy of simulation for each system.

The second phase of this study focused on performing casting trials according to the experimental plan, as described in Table 1 and using test geometries shown in Figure 1, as well as analyzing and comparing casting to the simulated results. Casting experiments were performed in order to identify typical variations in foundry parameters such as handling time, pouring time and rate, melt and mould temperature and filling sequence in the multi cavity mould. The impact of these variations was determined by comparing the casting results with simulations.

In order to measure the unfilled area, Images were taken using a Leica DFC295 digital microscope camera and the percentage of unfilled area was calculated using GIMP™ [21] Image analyses software. The unfilled area for simulated results was also determined using GIMP™.

Results and Discussion

Thermo-physical properties of IN718 are presented in Figure 2a–d. Thermal heat capacity C_p measurements over a temperature range of 25–1200 °C are presented in Figure 2a. Thermal diffusivity measurements in a temperature range of 25–1200 °C are presented in Figure 2b. Figure 2c shows density change over a temperature range between 100 and 1200 °C. Figure 2d shows thermal conductivity in the temperature range between 25 and 1200 °C.

The material properties for the mould material were taken from a previous study[15] as shown in Figure 3.

When comparing casting results with simulations, an asymmetric fill can be seen for the bottom-gated system, as

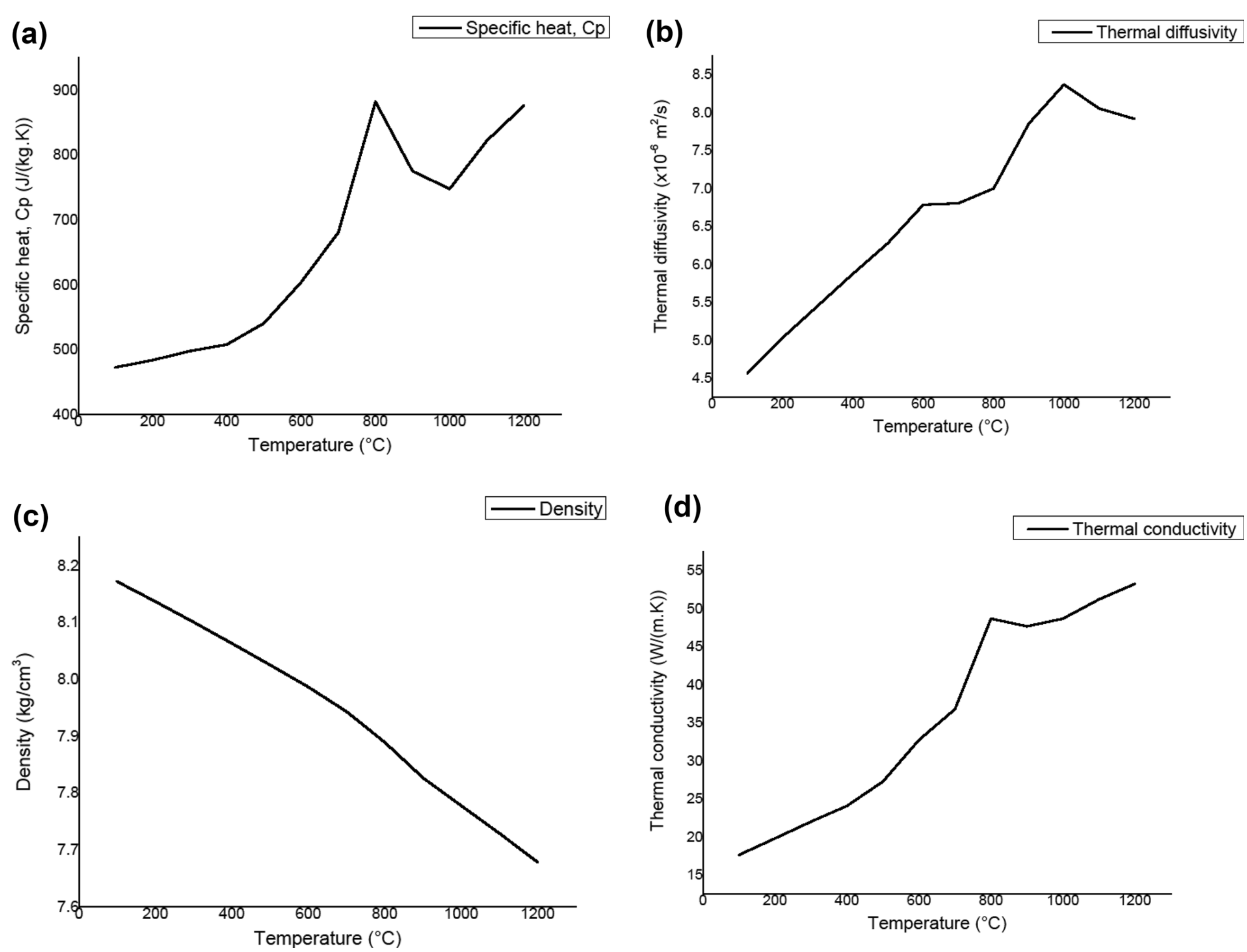

Figure 2. Thermo-physical properties of the alloy IN718™, (a) measured specific heat of the alloy, (b) measured thermal diffusivity of the alloy, (c) density from measured linear thermal expansion data of the alloy, (d) calculated thermal conductivity of the alloy.

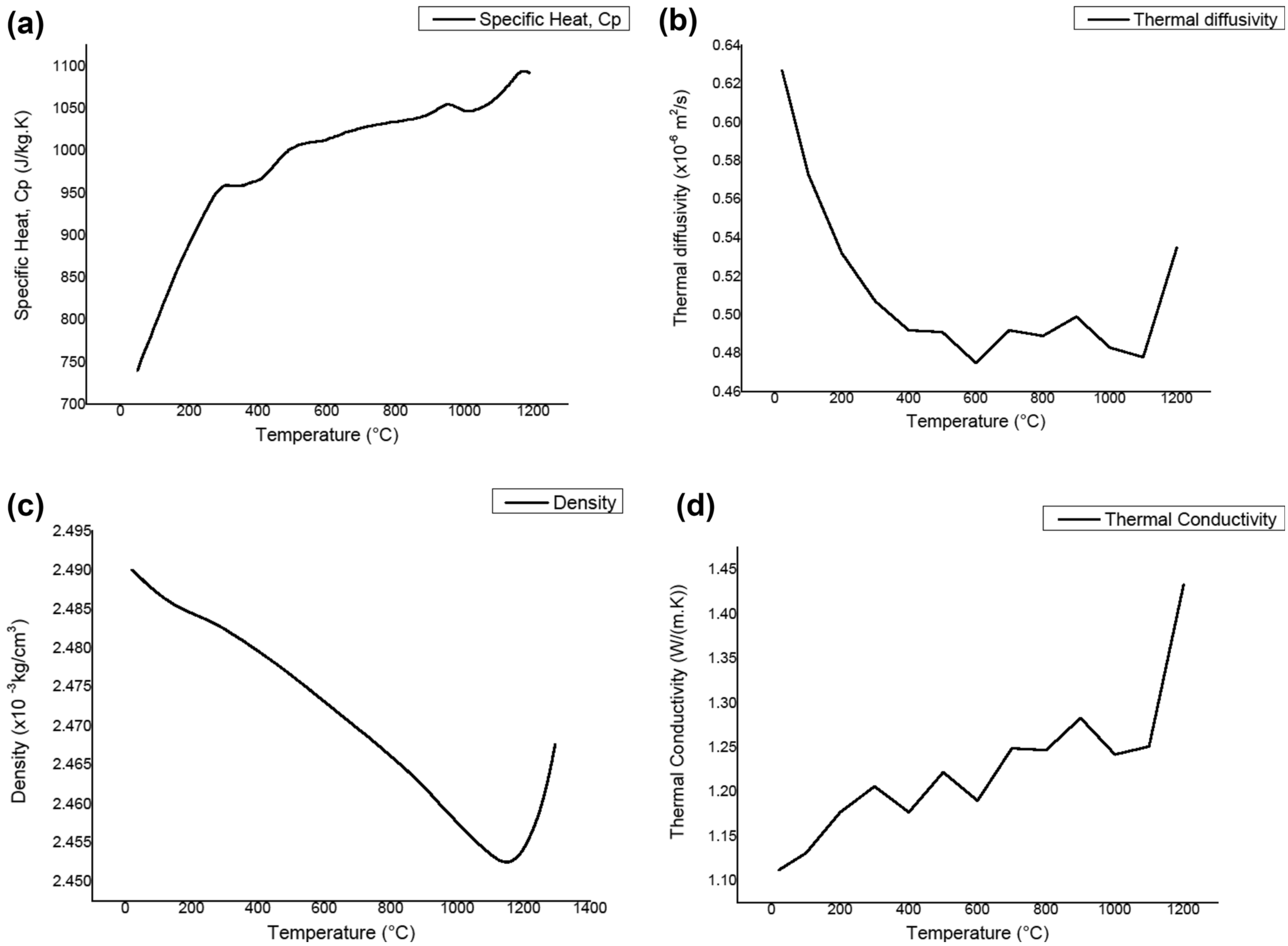

Figure 3. Thermo-physical properties of the mould material used in simulation, (a) specific heat of the mould material measured at different temperatures, (b) thermal diffusivity of the mould material measured at different temperatures, (c) density of the mould material measured at different temperatures, (d) calculated thermal conductivity of the mould material at different temperatures. [15]

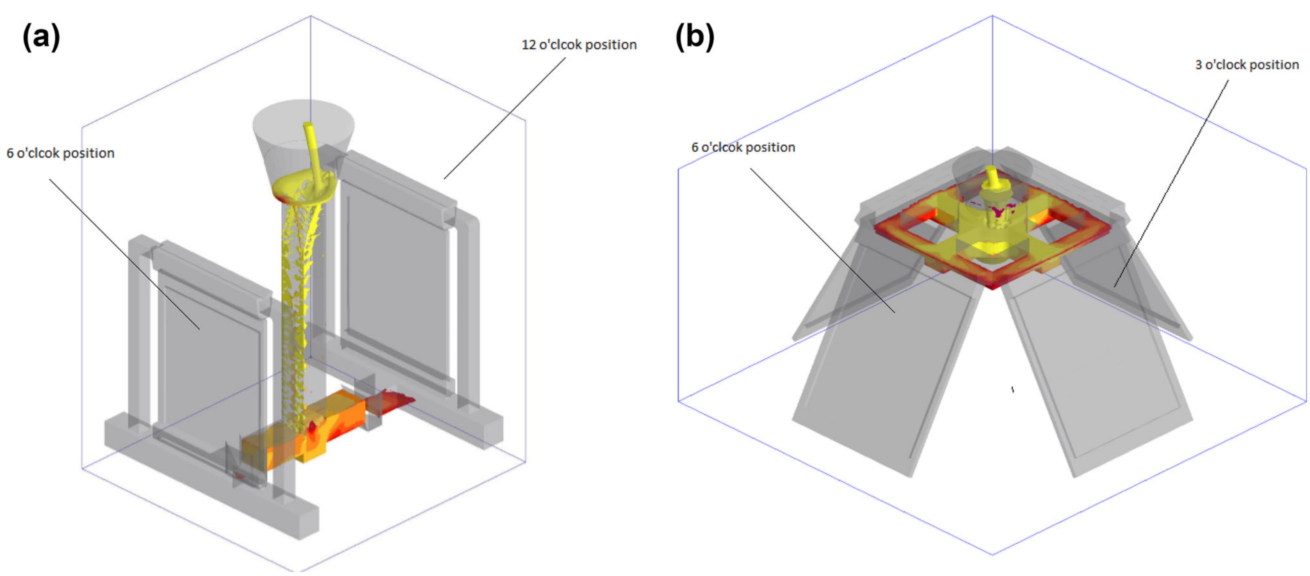

Figure 4. Asymmetric flow in the mould. (a) Bottom-gated mould. (b) Top-gated mould.

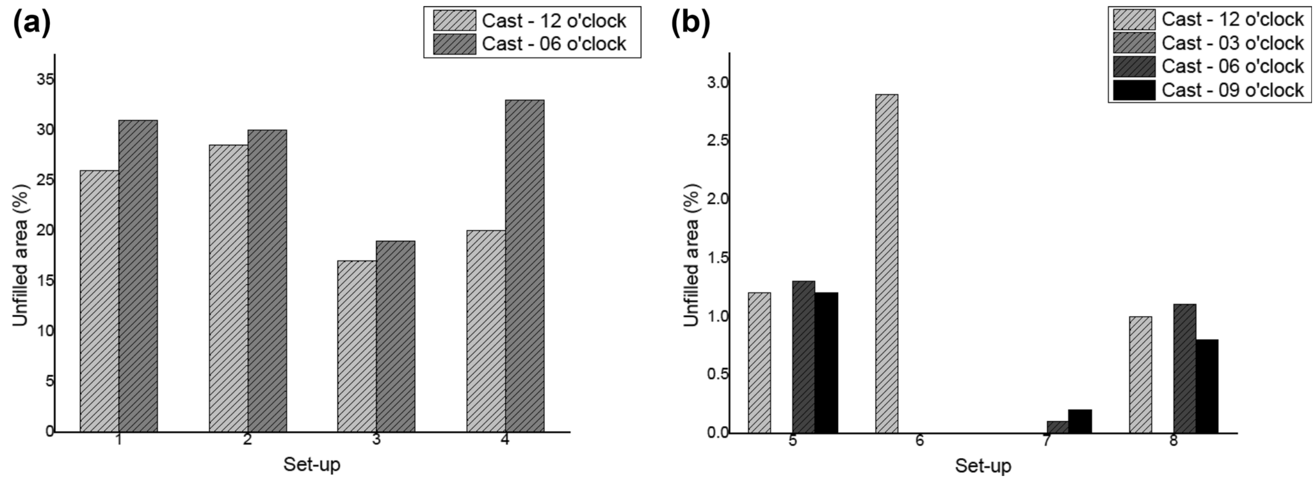

Figure 5. (a) Unfilled area for bottom-gated gating system from casting trials, (b) unfilled area for top-gated system from casting trials.

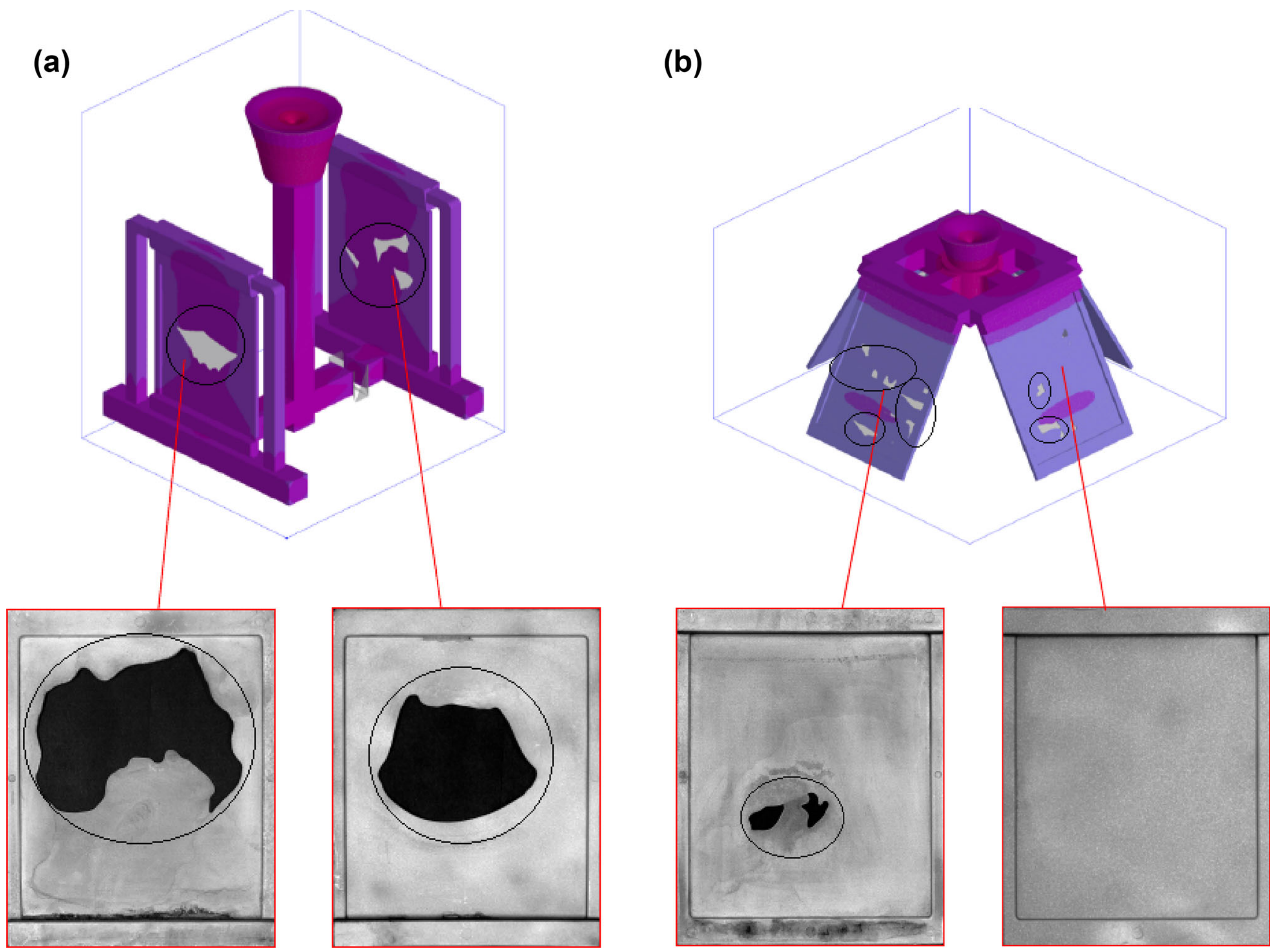

Figure 6. Comparison of extent of unfilled area predicted by simulation and observed empirically in casting trials, unfilled area is shown white in simulated geometries and black in cast geometries, (a) set-up 4, for the 6 and 12 o'clock position, (b) set-up 5, for the 6 and 3 o'clock position.

shown in Figures 4a and 5a. Here the term *asymmetric* refers to different fill patterns seen in cavities in the same mould. It can be clearly seen in Figure 4a that the filling of the 12 o'clock position is initiated before filling of the 6 o'clock position. As a result of the non-symmetric lip pouring used in the simulations, the 12 o'clock part is more completely filled than the 6 o'clock part. A similar asymmetry in fill pattern was found in the actual castings, as seen in Figures 5a and 6a.

The top-gated system also showed asymmetric filling but in general with a higher degree of filling compared to the bottom-gated system, as shown in Figures 4b, 5b and 6b. This was valid for both the simulations and the casting experiments, although asymmetry in simulations is not as apparent for the top-gated system relative to the bottom-gated system, as can be seen Figure 4b. The asymmetry of flow is, however in agreement with previous work by Renukananda and Ravi.[22]

A higher temperature in set-up 3 and an additional layer of insulation applied on the downsprue, as described in Table 1 (see footnotes), reduced temperature loss during mould filling. The extra insulation resulted in a reduced unfilled area demonstrating the importance of minimizing temperature loss during filling of thin sections, as is also reported in previous work.[7] It should be noted that longer time of contact between the melt and the downsprue as well as extra insulation results in the mould being heated through, as can be deduced using Einstein relation to estimate the diffusion length.[23] The results are in agreement with a previous work.[24]

In general the cavity located at the 12 o'clock position in the bottom-gated set-up was filled to a greater extent than the cavity in the 6 o'clock position, as can been seen Figure 5a. However, a significant difference in the castings in the 12 o'clock and 6 o'clock positions is observed in set-up 4 where misalignment in hanging was adjusted, as described in the footnotes of Table 1. It should be noted that mould misalignment is a common problem in foundries, where repeated contact with a hot mould can cause deformation of mould holding fixtures in the casting oven. The correction in misalignment of the mould holder made before filling in set-up 4 increased asymmetry in filling, as compared to set-ups 1–3. In set-ups 1–3 the effect of asymmetric fill was overshadowed due the misalignment and thus altering the flow pattern of the tilt-pouring. The misalignment caused a slight uphill fill for the mould cavity for 12 o'clock position and at the same time the asymmetric pour resulted in faster filling of the runner to the 6 o'clock position. Removing this misalignment amplified the effect of the asymmetric pouring, as shown in set-up 4, Figure 5a. The increase in asymmetry in set-up 4 was in accordance with simulation results. It suggests that filling asymmetry can be altered if the position of the mould hanging in the casting chamber is adjusted accordingly.

It is worthwhile to note that both downsprue insulation and the asymmetric pouring have greater influence on extent of filled area than an increase in the filling time from 12 to 18 s for set-up 1 and 2 compared to set-ups 3 and 4. The effect of melt temperature also seems to be less significant and appears to be dominated by temperature loss in the downspure. This is illustrated by the effect of the extra insulation applied in set-up 3, as shown in Figure 5a. Although uneven flow in a multi-cavity system has been previously reported in literature,[22] the effects of misalignment and asymmetry of filling have not been reported previously.

The results from the casting trials for the top-gated system are shown in Figure 5b. Compared to the bottom-gated system, the fill time was much shorter and the extent of unfilled area was accordingly significantly lower. The temperature in the mould drops continuously after removal from pre-heating oven. A greater extent of fill was observed in the top-gated system since there was less heat loss during the fill. The observed effect of fill time on unfilled area is in agreement with previous work.[25] In the top-gated system the parts cast at the 6 o'clock position tended to fill first. The influence of the melt temperature seems important as the unfilled area was lower for the higher melt temperature in set-ups 6 and 7 as compared to the lower melt temperature in set-ups 5 and 8. The effect of melt temperature on extent of fill is in agreement with previous work.[26] A shorter fill time at a higher casting temperature results in extending the period of time in which the melt can feed the mould cavity.[27] It should be noted that for set-up 6 which has the shortest fill time, the casting at the 12 o'clock position deviates from this pattern. This can be attributed to a reported interruption in melt pouring which resulted in a non-continuous melt flow during the last phase of mould filling.

Figure 6 shows typical simulation results for both bottom-gated (set-up 4) and top-gated (set-up 5) systems. Comparing flow and unfilled area in simulated and cast results, asymmetry is observed in both the simulation and cast samples. The location of the unfilled areas predicted in the simulation is consistent with that observed in the cast samples. Figure 6a shows a comparison of the parts cast at the 12 o'clock and 6 o'clock positions for set-up 4. Figure 6b shows a similar comparison of unfilled area for set-up 5 in parts cast at the 6 o'clock and 3 o'clock positions.

For both the bottom-gated and top-gated systems there are deviations in the actual prediction of unfilled area but the tendency in asymmetry and location of the unfilled area are qualitatively captured.

The discrepancy in the prediction of the unfilled area had a systematic deviation both in top and bottom-gated systems, as shown in Figure 7a, b. For the bottom-gated system the extent of unfilled area estimated by the simulation was lower than that observed in cast samples, while the opposite was true for the top-gated system. The fill times were shorter for the top-gated system and longer for the bottom-

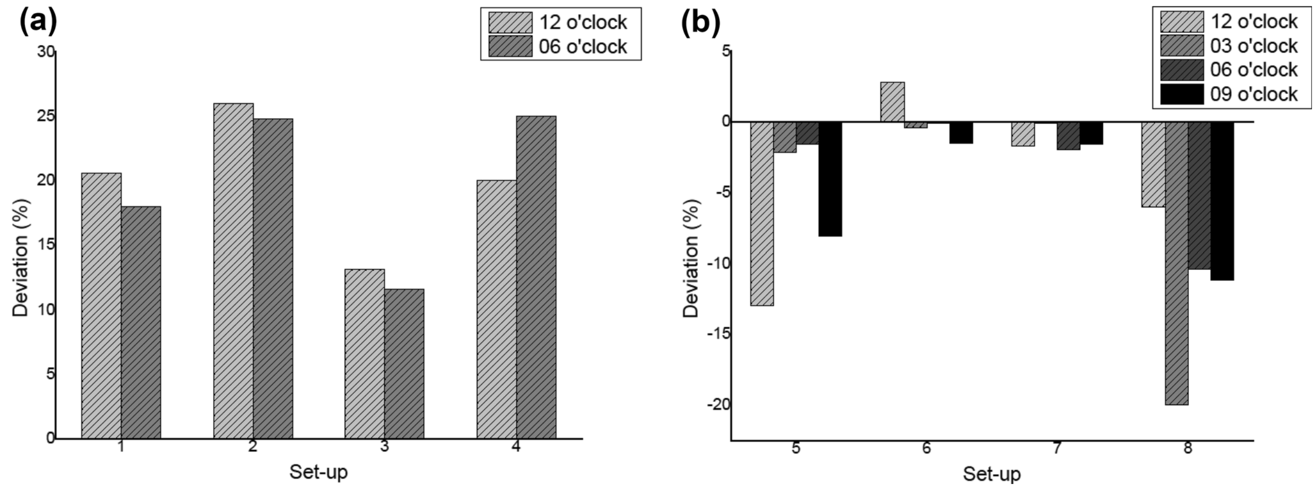

Figure 7. Deviation in % filled area in cast samples compared to that predicted by simulation (a) % deviation in filled area of cast sample compared to filled area in simulated geometry in bottom-gated system (b) % deviation in filled area of cast sample compared to filled area in simulated geometry in top-gated system.

gated system. The mode of filling and tendency for surface break up where the flow goes from continuous to intermittent can be estimated by the Weber number

$$\mathrm{We} = \frac{\rho r v^2}{\gamma}$$

where ρ is density, r is hydraulic diameter (or wetted perimeter), and γ is surface tension. Turbulent breakup of the surface during filling will occur when We > 100.[28] For the current case this is approximately at a fill speed of 0.3 m/s, the critical value. The predicted value of We for the top-gated and bottom-gated system were 0.25 m/s and 0.2 m/s respectively. For the bottom-gated system, the value is well below the critical value. For the top-gated system We is closer to the value threshold for turbulent flow. The uncertainty here resides in the surface tension and wetting between the mould and fill front. The wetting angles of the melt in the mould cavity were estimated by examining the edges of the casting around the unfilled area. The wetting angles for the parts in the 6 o'clock positions in set-ups 4 and 5 were determined to be 145° and 163°, respectively indicating a non-wetting system. The edge radius was also well rounded and smooth for both cases suggesting limited surface turbulence as suggested by the Weber number analysis. The non-wetting characteristics forced the fill front to be well defined and fill the complete cross section of the part. The well-defined front reduces the amount of formation of solid films at surface of the flowing melt stream thus reducing the friction between melt and mold wall.[8]

The under-prediction of the unfilled areas for the bottom-gated system suggests that the heat transfer between the mould and the molten metal was slightly underestimated by the settings used in simulation. On the other hand for shorter fill times for the top-gated system the extent of unfilled area was overestimated suggesting an over estimation of the heat transfer. The actual conditions for the two cases were not significantly different and the discrepancy can be attributed to the effect of surface tension.[7] Indications of scattered shrinkage in the x-ray images of cast samples from top-gated system suggests unzipping type of melt propagation [29] due to effect of surface tension.

Shorter fill times, and therefore a higher mould temperature in the cavity as well as unzipping type of melt propagation were the main reasons for the significantly reduced amounts of unfilled area for the top-gated system as compared to the bottom-gated system. This supports the conclusion that for gravity casting of thin-walled structures, surface tension cannot be neglected, as suggested by the fillability theory developed by Campbell and Oliff.[7]

Conclusion

Most of the previous work on predictive simulation has focused on using correct material data. In the current study empirically measured thermo-physical properties of the mould material and the alloy were used in the simulation to achieve maximum accuracy.

Setting initial conditions and boundary conditions such as mass flow rate during filling and heat transfer between the metal and the mold have a critical impact on both casting results and quality of prediction. Inverse techniques have been applied in previous studies to define initial boundary conditions by e.g. Anglada et al.[13] but these do not consider the effects of variation in point of impact of the pouring stream nor misorientations of the cavity. In the current study, it was shown that to predict the extent of fill in a multi-cavity investment casting mould it was essential to replicate the actual pouring conditions to capture the asymmetry of the flow pattern. Furthermore, the influence of a small misalignment of the mould relative to the melt stream was shown to be extremely important as concluded by the significant effect that correction of misalignment of the mould relative to the melt stream had on extent of filling. Effects of misalignment are often overlooked in simulation and are a potential source of error. This in turn can lead to bad decisions in gating design when interpreting the results and devising a corrective action.

This work has been focused on simulation methods for predicting filling. Although in this study the best fill was achieved in the top-gated system, it should be noted that it is generally reported in the literature that bottom-gated systems produce castings with lower defect densities.[30]

The state of the art simulation software today uses the *volume of fluid* algorithm which assumes all fill fronts are diffuse and the effect of surface tension is normally not captured. In the current study it was shown that for thin-walled sections this is important as the ability to fill thin sections is heavily influenced by the surface tension which is consistent with previously established fillability concept.[7]

Funding

The work has been supported by the Strategic Innovation Programs for Lightweight and Metallic Materials. The programs are funded by VINNOVA, Formas and the Swedish Energy Agency. Authors also thankfully acknowledge the financial support of the Innofacture program at Mälardalen University funded through KK-Stiftelsen.

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