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Optimisation of the filling process in counter-gravity casting

M Papanikolaou, P Saxena, E Pagone, K Salonitis and M Jolly

Manufacturing Theme, Cranfield University, College Rd, Cranfield, Bedford MK43 0AL, UK

E-mail: m.papanikolaou@cranfield.ac.uk

Abstract. Metal casting is one of the most energy-intensive manufacturing processes with limited resource efficiency. To solve the problem of high energy consumption, a novel counter-gravity casting process has been earlier introduced. This process also referred to as CRIMSON (Constrained Rapid Induction Melting Single Shot Up-Casting) makes use of melting metal, just enough to fill one mould cavity at a time. The molten metal is subsequently pushed into the mould with the help of a piston, using a counter-gravity controlled method. Although CRIMSON has been proven to be a highly efficient process with the potential to produce high quality final cast products, there is still room for optimisation of the process. The objective of this investigation is to estimate the optimum ingate velocity in order to ensure smooth filling of the mould and eventually reduce turbulence and the likelihood of defects in the final cast product. For this purpose, a computational framework integrating a CFD solver and an optimisation algorithm has been developed. The obtained results suggest that the optimised ingate velocity can contribute towards the smooth filling of the mould and effectively contribute towards the reduction of entrained air and surface defect concentration in the final cast product.

1. Introduction

Sand casting is one of the oldest [1], most widely used and versatile metal forming processes. This process consists of two main stages which involve (a) pouring molten metal into a sand mould, (b) allowing for solidification and (c) removing the cast product by breaking the sand mould. However, producing good quality castings using this method is a not a trivial issue. The mechanical properties of the final product depend on the concentration of defects in the solidified material. One of the most important factors leading to defective castings is turbulence which is responsible for the inclusion of oxide bi-films into the melt [2]. Although turbulence cannot be eliminated, especially in the case of gravity casting, it can be significantly reduced via designing proper running systems and effectively controlling the metal velocity. John Campbell in [3] advocated some running and gating system designs leading to the minimisation of entrainment defects and superior quality castings. More specifically, the author emphasised the importance of placing filters across the runner in order to prevent backflow and promote uniform priming of the runner. Moreover, Campbell distinguished two gating system designs, namely, the Trident Gate and the Vortex Gate which can potentially lead to the elimination of entrainment defects. The potential of the aforementioned gating system designs to reduce entrainment defects was also verified via means of numerical simulations [4].

Counter gravity processes have been developed in order to address the issue of defects entrained in the casting. As indicated by their name, these methods eliminate turbulence arising during the fall of the melt down the sprue. The Constrained Rapid Induction Melting Single Shot Up-Casting method (CRIMSON) developed by Jolly *et al.* [5] is a counter-gravity sand casting method which has been proven to offer energy savings and the potential to minimise the concentration of double oxide films (DOF) and air entrainment in the casting [6]. In CRIMSON, molten metal is pushed into the mould with the help of a piston whose velocity is regulated via a computer-controlled method. Although CRIMSON is a counter-gravity casting method, a small amount of defects might still arise during filling or solidification [7]. Therefore, it of utmost importance to exploit the advantages of this method, such as the controlled filling rate, in order to produce enhanced quality cast products.

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Since the early 1950s the optimisation of casting processes relied mostly on the intuition and experience of the foundry engineers. Later on, water models were used to visualise turbulence in order to geometrically optimise various components of the filling system [8–10]. In the early 1980s the development of numerical models capable of accurately reproducing a wide range of phenomena occurring during casting elucidated the process dynamics and allowed for the optimisation of the process. Nowadays, numerical modelling is widely accepted by foundry engineers as a means to improve quality and increase energy efficiency [11]. The foundations of the numerical modelling of casting processes were laid by Eyres *et al.* [12] back in 1946. Since then, numerical models have been developed for calculating the temperature profiles during solidification [13], identifying the factors leading to shrinkage porosity [14] and micro-porosity formation [15]. More contemporary investigations have been focused on the modification or optimisation of casting processes using numerical modelling. Sun [16] implemented the Taguchi method in order to optimise a set of performance characteristics including filling velocity, shrinkage porosity and product yield of a sand-casting process by identifying the optimal geometrical features of the gating system design. Moreover, in [7] an optimisation framework consisted of an optimiser and a CFD solver was implemented to estimate the optimum dimensions of the feeding system leading to the minimisation of defects.

As elaborated in the previous paragraphs, numerical modelling has been proven to be a powerful tool for the optimisation of casting processes. The objective of this investigation is to exploit the design advantages of the CRIMSON process in order to improve the quality of the casting expressed in terms of entrained air and surface defect concentration. More specifically, an optimisation framework has been developed in order to determine the optimum ingate velocity leading to minimum entrainment defects. The objective function was defined as the weighted sum of the inverse fill fraction, normalised surface defect concentration and normalised air entrainment. The obtained results indicate that, even in counter gravity casting, controlling the metal ingate velocity is crucial for delivering superior quality products.

2. Methodology

2.1. Simulation

The CRIMSON process makes use of a plunger which pushes the molten metal into the cavity of a sand mould. A detailed overview of the process can be found in [17]. In order to simplify the simulation process and reduce the computational cost, the motion of the plunger was replaced by a mass source located at the bottom of the mould as illustrated in figure 1. In order to further reduce the computational cost, only a quarter of the simulation domain was simulated by exploiting symmetry boundary conditions. The steps and requirements for the filling stage are listed below:

- The mass source depicted in figure 1 was activated. The source normal velocity was considered as the first optimisation input variable (v_1).
- When the liquid metal reached the level of Probe 1 the value of the source velocity was changed to v_2. This is the second optimisation input variable.
- When the molten metal reached the level of Probe 2 the simulation was terminated.
- The filling time should be less than 4 s; the simulation was terminated at t=4s even if the liquid metal did not reach the level of Probe 2.

The reason behind the positioning of Probe 1 at the bottom of the tensile bars was that turbulence is expected at this critical point due to the sudden change of the cross section. In other words, it is crucial to control the meniscus velocity right at the point when molten metal enters the tensile bars which are the final cast product. As it will be elaborated in the following subsection, the optimisation objective was to estimate the optimal set of velocity values [v_1, v_2] leading to the minimisation of the objective function.

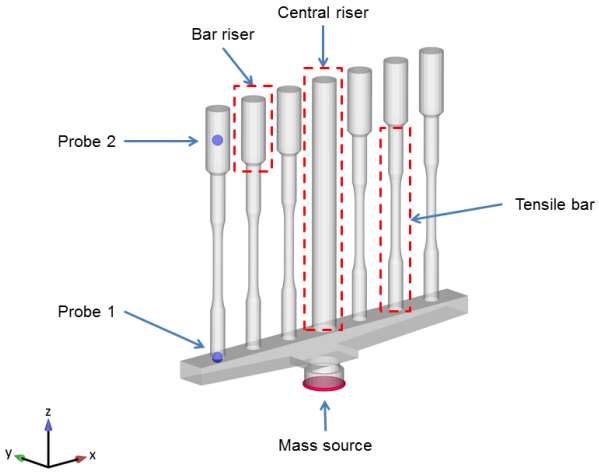

Figure 1. Simulation setup.

The simulated fluid was Aluminium LM-25 while the pouring temperature was set to 680 °C. A solid mesh with orthogonal hexahedra with a cell size equal to 2.5 mm was conformed to the open volume of the simulation domain with an overlap length equal to 1 cm. The cell size was selected so as to have at least 3 cells expanding across the thinner cross section of the mould, which is located at the middle of the tensile bars. Symmetry boundary conditions were applied to all directions with the exception of z_{max}, where a pressure boundary condition was applied. The developed CFD model accounted for surface tension [18] while the RNG k-ε method was used to model turbulence [19]. Surface defect concentration and air entrainment were modelled using the corresponding models [20, 21] of the Flow-3D software [22]. The material properties and simulation parameters used in this study are summarised in table 1 and table 2 respectively.

Table 1. LM-25 properties.

Density [kg/m^3]	2417
Viscosity [kg/(m·s)]	0.00138
Thermal Conductivity [W/(m·K)]	70.15
Surface Tension Coefficient [kg/s^2]	0.8
Latent Heat [J/kg]	$3.58 \cdot 10^5$

Table 2. Simulation parameters.

Mould initial temperature [°C]	25
Pouring temperature [°C]	680
Air temperature [°C]	25
Cell size [mm]	2.5
Total number of cells	59,000

2.2. Optimisation

As mentioned in the previous sections the objective of this investigation is to exploit the advantages offered by the CRIMSON process design in order to investigate its potential to produce further improved results. One of the advantages offered by CRIMSON is that it is a computer-controlled counter-gravity casting method, i.e. the filling velocity can be controlled at all times. In this study the mass source (ingate) velocity values v_1 and v_2 have been used as the optimisation input variables, as discussed in the previous subsection. Linear scalarisation has been used in order to solve this multi-variable and multi-objective problem. The objective function was defined as the sum of weighted individual objective functions:

$$OF = w_1 OF_{ff} + w_2 OF_{ae} + w_3 OF_{sdc} = w_1 \frac{ff_0}{ff} + w_2 \frac{ae}{ae_0} + w_3 \frac{sdc}{sdc_0} \quad (1)$$

where *ff* (dimensionless), the fluid fraction *ae* (dimensionless) the entrained air volume fraction, *sdc* (kg/m^3) the surface defect concentration and w_i is a set of weights with $\sum_{i=1}^{3} w_i = 1$. The individual objective functions were normalised by their corresponding values obtained in the first iteration of the optimiser (ff_0, ae_0 and sdc_0); this was due to their different orders of magnitude between the different objectives. The values of *ff*, *ae* and *sdc* were calculated by averaging their corresponding cell values over the region of the tensile bars (which are the final cast product) at the last timestep of the filling simulation. Among the 3 individual optimisation objective functions the most important is OF_{ff}, i.e. the

tensile bars should be necessarily completely filled. In order to fulfil this requirement, the highest weight was assigned to the specific individual objective (w_1=0.5). Moreover, the values of the initial guess [v_{10}, v_{20}] were selected so as to ensure that the tensile bars are completely filled (ff_0=1). Therefore, although very low ingate velocities led to zero air entrainment and surface defect concentration they were eventually rejected as solutions as they led to incomplete filling (ff<1).

The developed optimisation framework consisted of a commercial CFD software (Flow-3D™) and a python code responsible for the following tasks: (1) post-processing of the CFD results, (2) estimation of the objective function (OF), (3) feeding of the calculated OF value to the optimiser, (4) optimisation and (5) modification of the input file based on the new input variables proposed by the optimiser. The aforementioned process ran in a loop until the value of objective function converged to a minimum. The L-BFGS-B constrained multi-variable optimisation method [23] was used while both input variables (v_1 and v_2) were bounded between 0 and 0.5 m/s.

3. Results

3.1. Filling simulation

In the simulation case presented below the mass source was removed at the end of the filling process and an additional 10 s interval was allowed for equilibration. It has to be noted that the equilibration phase was neglected when performing the optimisation loop as described in the methodology section. This was because the values obtained for the average surface defect concentration and air entrainment volume fraction in the area of the tensile bars with or without the equilibration phase were not significantly different. Moreover, simulating the equilibration phase for each iteration would dramatically increase the computational cost.

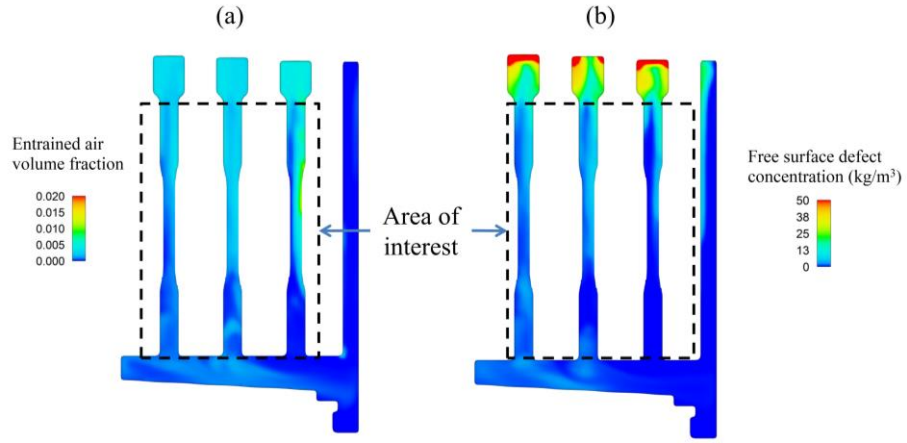

Figure 2. (a) Entrained air volume fraction and (b) free surface defect concentration distribution at the end of the equilibration process.

The entrained air volume fraction and surface defect concentration distribution at the end of the equilibration process are illustrated in figure 2. By comparing figure 2(a) and figure 2(b) it is evident that there are some significant similarities and discrepancies between the two distributions. Although both profiles are similar, surface defect concentration appears to sharply increase in the vicinity of the risers in contrast to the entrained air volume fraction which remains relatively constant. Similarly to entrained air, surface defects arise at the fluid free surface and subsequently diffuse into the bulk. However, in contrast to air entrainment, surface defect concentration depends on the exposure time of the free surface. As a result, its value continuously increases during the equilibration phase. However, due to the fact that the fluid velocity becomes almost negligible as equilibration proceeds defects cannot be diffused and are confined to the vicinity of the risers.

3.2. Optimisation

Linear scalarisation was used to minimise the objective function of equation (1). The fill fraction (ff), air entrainment (ae) and surface defect concentration (sdc) were evaluated at the last timestep of the filling simulation in the area of the tensile bars as illustrated in figure 2. It has to be noted that runs

performed with a higher resolution mesh did not affect the average values of air entrainment and surface defect concentration. Two sets of weight distributions (*wd)* have been tested. For both cases the weight assigned to the fill fraction objective function (OF_{ff}) was equal to 0.5 as this is the most important of all optimisation objectives. In the first case, reduced air entrainment was considered more important than surface defect concentration (w_2=0.4 and w_3=0.1) while in the second one the inverse scenario was examined (w_2=0.1 and w_3=0.4).

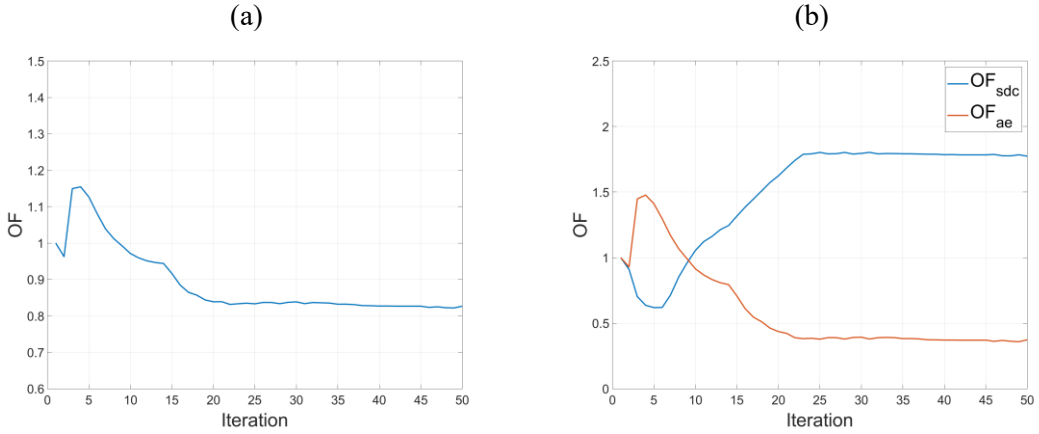

Figure 3. (a) Total and (b) individual objective functions versus number of iterations for wd_1.

As shown in figure 3(a) the optimiser has converged within 25 iterations while the objective function has been reduced by almost 18% at the end of the run. Since air entrainment has been assigned with a higher weight than surface defect concentration, the minimisation of OF_{ae} has been prioritised over OF_{sdc} and its value has been minimised as illustrated in figure 3(b). However, there is a cost for that: OF_{sdc} increased. This behaviour can be explained by observing figure 4 which illustrates the evolution of the velocity values selected until the final solution has been reached. It is clear that the reason for the penalty imposed on OF_{sdc} is due to the convergence to lower velocity values compared to the initial guess (v_{10}= v_{20}=0.21 m/s). Lower velocities lead to decreased turbulence but on the other hand increase the duration of the exposure of the moving free surface to air as well as the free surface defect concentration (OF_{sdc}) in the final casting. The solution obtained suggests using a lower ingate velocity during the first part of the filling process (while the fluid level is below the location of Probe 1) and a higher velocity for the rest of the filling process. This is because of the fact that the area of the free surface is much larger when being below Probe 1.

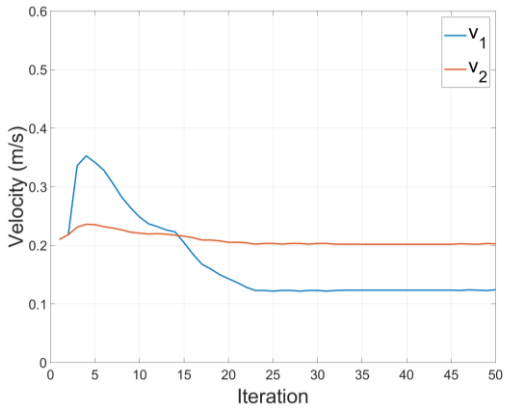

Figure 4. Input variables versus number of iterations (wd_1).

The trends observed above are inversed for the second weight distribution (wd_2) as expected. Although the total objective function has converged within the first 30 iterations as shown in figure 5(a), this time OF_{sdc} has been prioritised over OF_{ae} due to its higher weight. Similarly to wd_1, the penalty for this change is higher air entrainment, as shown in figure 5(b).

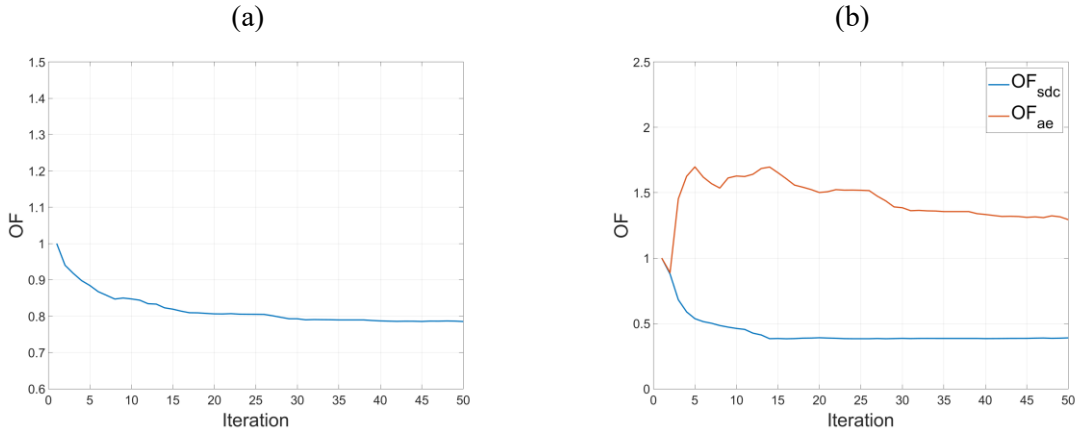

Figure 5. (a) Total and (b) individual objective functions versus number of iterations for wd_2

As shown in figure 6, in this case the obtained solution suggests using higher velocities than the ones of the initial guess in order to decrease the filling time and consequently the diffusion of surface defects to the bulk. More specifically, the proposed ingate velocity for the first filling stage v_1 is almost double the corresponding initial guess v_{10}. This is because the longer exposure of the free surface to the air the more the surface defect concentration. The proposed velocity values would be even higher if there wasn't the constraint imposed by the air entrainment criterion. This is evident by observing the curve for v_1 in figure 6. Between the 10th and 14th iteration the optimiser attempts to further increase the value of v_1. However, the value of OF_{ae} at the corresponding iteration increases sharply as shown in figure 5; this is the reason why v_1 is maintained to a lower and steady level. The same principles apply for v_2 which is maintained at lower levels due to the fact that the surface defect criterion is more dominant during the first filling stage to the increased free surface area.

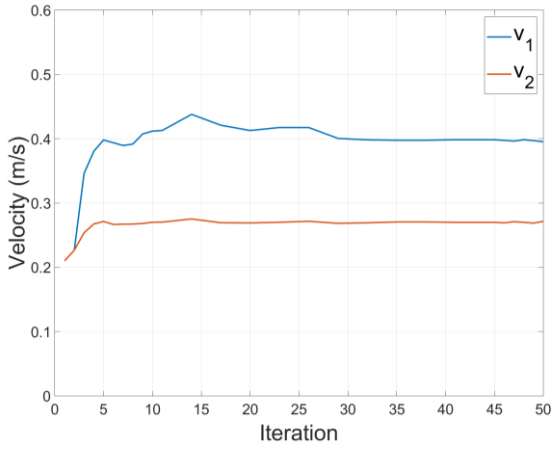

Figure 6. Input variables versus number of iterations (wd_2).

Table 3. Final solution for the 2 sets of weight distributions.

w_1 (OF_{ff})	w_2 (OF_{ae})	w_3 (OF_{sdc})	v_1 (m/s)	v_2 (m/s)
0.5	0.4	0.1	0.12	0.20
0.5	0.1	0.4	0.4	0.27

Table 3 summarises the effect of the weight distributions on the final solutions proposed by the optimiser. It is clear that low velocity values are selected when air entrainment is more significant as an optimisation criterion compared to surface defect concentration while the velocity values gradually

increase as the importance of criteria is inversed. Moreover, it can be observed that v_1 has a larger variation than v_2. This is because the metal top surface area is larger during the first filling stage and it is more likely that surface turbulence, affecting both air entrainment and surface defect concentration, might arise at this stage compared to the second one. Thus, controlling the ingate velocity while the melt top surface is below the level of Probe 1 has a greater effect on the final result than controlling v_2.

In both cases examined in this investigation, the weight distribution between surface defect concentration and air entrainment is imbalanced. This results in two distinct solutions due to the prioritisation of one of two conflicting objectives each time. However, a good casting is defined based on the specifications set by the foundry engineers in reality. In the case where bubble damage or gas porosity have been identified as the major defects to be avoided, the air entrainment criterion should be prioritised. On the other hand, if the focus is laid on the elimination of potential sites for crack nucleation and propagation the surface defect concentration criterion should be assigned with a higher weight. If both of the aforementioned scenarios are likely and equally important both the two criteria should be assigned with equal weight (w_2=w_3=0.25); the developed framework allows the free allocation of weights to each criterion examined.

4. Conclusions and future work

In this investigation a computational framework for the optimisation of the Constrained Rapid Induction Melting Single Shot Up-Casting (CRIMSON) method has been developed. The proposed framework was consisted of an optimisation algorithm plugged to a commercial CFD software while the optimisation objective was the minimisation of entrained air and surface defects in the final cast product by controlling the ingate velocity during filling. Two scenarios with different weight distributions assigned to the individual optimisation objectives were examined. In the first scenario, air entrainment was considered more significant than surface defect concentration while in the second one the inverse case was examined. The L-BFGS-B constrained multi-variable optimisation method was used to solve this multi-variable and multi-objective optimisation problem. Linear scalarisation was also used for the estimation of the total objective function. The main conclusions drawn from this study are listed below:

- Very low ingate velocities lead to smooth filling but on the other hand increase surface defect concentration and the risk of incomplete filling and premature solidification.
- For all weight distributions examined the optimisation algorithm was capable of reducing the value of the total objective function by at least 15%. The design advantage of the CRIMSON process to control the ingate velocity can lead to superior quality castings.
- The optimisation algorithm was capable of converging to the minimum value of the objective function within the first 30 iterations.
- The velocity value during the first filling stage has more dominant effects on the quality of the final cast product than its corresponding value during the second stage. In a more general context, it is of utmost significance to control the filling velocity when the metal surface area is large. This is due to the fact that the majority of defects might arise at this point in time.

In the authors' opinion there is still room for optimisation of the CRIMSON process. CRIMSON offers the advantage of controlling the plunger velocity during the whole filling process with a high resolution, making the potential of defect free castings feasible. Therefore, future research should be directed towards using smooth ingate velocity profiles and avoid the use of steps in order to further reduce turbulence during filling.

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References

[1] Weiss D 2018 Advances in the Sand Casting of Aluminium Alloys *Fundamentals of Aluminium Metallurgy* (Elsevier) 159–71
[2] Campbell J 2015 *Complete Casting Handbook: Metal Casting Processes, Techniques and Design* (Butterworth-Heinemann)
[3] Campbell J 2018 *Mini Casting Handbook.* (Aspect Design)
[4] Papanikolaou M, Pagone E, Jolly M and Salonitis K 2020 Numerical Simulation and Evaluation of Campbell Running and Gating Systems *Metals (Basel).* **10** 68
[5] Dai X, Jolly M R and Zeng B 2011 The capability enhancement of aluminium casting process by application of the novel CRIMSON method *Shape Cast. John Wiley Sons, Inc* 265–72
[6] Salonitis K, Jolly M R, Zeng B and Mehrabi H 2016 Improvements in energy consumption and environmental impact by novel single shot melting process for casting *J. Clean. Prod.* **137** 1532–42
[7] Papanikolaou M, Pagone E, Georgarakis K, Rogers K, Jolly M and Salonitis K 2018 Design optimisation of the feeding system of a novel counter-gravity casting process *Metals* **8** 817
[8] Swift R E, Jackson J H and Eastwood L W 1949 A study of principles of gating *AFS Trans.* **57** 76–88
[9] Grube K R and Kura J G 1955 Principles applicable to vertical gating *Trans AFS* **63** 35–48
[10] Hsu F Y and Lin H J 2009 A diffusing runner for gravity casting *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* **40** 833–42
[11] Yu K-O 2001 Modeling for casting and solidification processing (CRC Press)
[12] Eyres N R, Hartree D R, Ingham J, Sarjant R J and Wagstaff J B 1946 The calculation of variable heat flow in solids *Philos. Trans. R. Soc. London. Ser. A, Math. Phys. Sci.* **240** 1–57
[13] Sulaiman S and Hamouda A M S 2004 Modelling and experimental investigation of solidification process in sand casting *J. Mater. Process. Technol.* **155**–**156** 1723–6
[14] Gunasegaram D R, Farnsworth D J and Nguyen T T 2009 Identification of critical factors affecting shrinkage porosity in permanent mold casting using numerical simulations based on design of experiments *J. Mater. Process. Technol.* **209** 1209–19
[15] Lee P D, Chirazi A and See D 2001 Modeling microporosity in aluminum-silicon alloys: A review *J. Light Met.* **1** 15–30
[16] Sun Z, Hu H and Chen X 2008 Numerical optimization of gating system parameters for a magnesium alloy casting with multiple performance characteristics *J. Mater. Process. Technol.* **199** 256–64
[17] Papanikolaou M, Pagone E, Salonitis K, Jolly M and Makatsoris C 2018 A Computational Framework Towards Energy Efficient Casting Processes *International Conference on Sustainable Design and Manufacturing* pp 263–76
[18] C.W. Hirt *Modeling Surface Tension*
[19] Prasad V.Tota 2009 Turbulent Flow Over a Backward-Facing Step Using the RNG k- ε Model *Flow Sci.* 1–15
[20] C.W. Hirt 2012 *Modeling Turbulent Entrainment of Air at a Free Surface* (Flow Science, Inc.: Santa Fe, NM, USA)
[21] Barkhudarov M R and Hirt C W 1998 Tracking defects *1st international Aluminium casting technology symposium*
[22] Anon 2019 *FLOW-3D® Version 12.0 [Computer software]* (Santa Fe, NM: Flow Science, Inc.)
[23] Zhu C, Byrd R H, Lu P and Nocedal J 1997 Algorithm 778: L-BFGS-B: Fortran subroutines for large-scale bound-constrained optimization *ACM Trans. Math. Softw.* **23** 550–60

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