

Defect minimisation in vacuum assisted plaster mould investment casting through simulation of high value aluminium alloy components

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Abstract

Vacuum assisted plaster mould investment casting is one of the best available processes to manufacture ultra-high complexity castings for the aerospace and defence sectors. In light of the emerging cross sectoral manufacturing industry digitalisation, process simulation appears as a very important tool to improve casting yield, reduce metallurgical scrap and reduce lead time to new product introduction. Considering the unique aspects and the level of customisation of the process system, this work will present a Computational Fluid Dynamics based simulation tool with bespoke settings (that include thermo-physical properties). Optimal fill and solidification parameters are identified for a representative geometry able to describe a variety of very complex, high value aluminium alloy components through an iterative process.

Keywords: Aluminium, Shaping and Forming, Modelling and Simulation, Solidification

Introduction

Investment casting is a manufacturing process particularly useful to produce components with high precision and complex shape providing the designer with relatively large freedom. Although the process comprises a higher number of steps in comparison with other expendable mould alternatives, its products are near net shape, making it a very good choice for metals that are difficult to machine [1]. The typical main steps of investment casting can be summarised with the following sequence. The starting point is the production of a master pattern (i.e. a replica of the final geometry of the product) that is used to generate a master die filled with wax to produce wax patterns. Then, several of such patterns are arranged around a common sprue to form a so-called “tree”. Furthermore, the “tree” is coated by investment material that is dried and hardened, where particular care is dedicated to the composition of the first layer that needs to be as smooth as possible. Subsequently, the wax patterns are removed by melting, whereas the obtained empty mould is heated at an optimal temperature before pouring liquid metal. Finally, the mould is broken and the castings obtained are separated from the sprue while the small gate stubs are removed by machining [1].

The investment casting process studied in this work uses plaster as investment material and vacuum is generated within the mould before pouring liquid aluminium alloys. The objective

of the study is to identify optimal fill and solidification parameters to minimise defects for a representative geometry using Computational Fluid Dynamics (CFD) simulations.

Although previous studies in this field can be identified, it can be observed that there is no previous literature covering the entire research aim considered. In particular, Kan *et al.* simulated numerically vacuum casting of Al-6061 quantifying the faster casting times under vacuum versus atmospheric conditions (0.95 s versus 1.2 s for the case considered). Furthermore, higher mould temperatures and an 8% increase in the heat transfer rate were reported during the vacuum casting process [2]. Although useful, this work does not consider plaster moulds. Ahmad *et al.* [3] used numerical simulations to improve the quality of products modelling the flow of resin into a five-axis impeller mould considering a vacuum casting process. Key parameters such as fluid temperature, flow rate and filling time are considered reporting the relevant optimal values obtained. However, also in this case, the material of the mould is not plaster and there is no comparison with atmospheric pressure processes. Tang *et al.* [4] developed a method to optimize the process parameters that have an impact on the quality of silicone rubber micro-mould cavities produced for vacuum casting. The authors show that the optimised parameters result in higher quality mould cavities quantified using dimensional analysis and white light interferometry. In particular, miniature gears with dimensional deviations of less than 3% in comparison with the benchmark product are reported. Zhang and Hu [5] combined a response surface method with an artificial fish swarm algorithm to optimise the filling process of a vacuum casting process improving the dimensional accuracy of castings. Suprpto *et al.* [6] developed a method to identify the location and the moment during a vacuum casting process when porosities are formed in aluminium alloys. Output parameters include morphological characteristics, number and size of pores. The authors combine optical emission spectroscopy tests and fluid mechanic parameters and principles (e.g., Reynolds and Niyama numbers, Archimedes' principle, ...) pointing out that further experiments are recommended for validation purposes. Analysis of results recommend a limit of 0.15 cm³ of hydrogen dissolved per 100 g of liquid metal as well as to minimise the presence of impurities with particular attention to copper compounds. Jin *et al.* [7] propose an improved design (with a novel overflow system) of a die for vacuum casting considering two geometries. Results show that the proposed design prevents premature freezing of the metal (i.e., "cold runs") and reduce turbulence of liquid metal. However, also in this case, there is no comparison with a comparable non-vacuum process. On the other hand, Chaus *et al.* [8] compared the micro-structure and properties of steel using gravity and vacuum casting reporting the surface roughness and impurity content alongside hardness and bending strength. Furthermore, it is reported that vacuum casting reduces the concentration of oxygen and hydrogen in the liquid metal by a factor of two and leads to better finishing and mechanical properties. Kuo *et al.* [9] used experimental design methods combined with the Vacuum Differential Pressure Casting (VDPC) technique to improve the tensile strength of castings with a focus on the production of the moulds. The mould cavity temperature is identified as the primary parameter (with an optimal cavity temperature of 35 °C) followed by the mixing time (with 40 s as optimal), differential pressure time (best at 8 s) and mixing chamber inlet valve angle (optimal at 60°). Ignaszak and Wojciechowski [10] validated plaster casting simulations of jewellery against experiments showing accurate prediction of the shrinkage porosity location. Lun Sin *et al.* [11] studied the reaction of molten magnesium alloys with plaster moulds under vacuum casting conditions using thermodynamics principles. The casting temperature do not appear to affect the mould-metal reactivity within typical temperature ranges, while particles from the rough

surface of the casting form a reaction layer between the plaster mould and the casting. Władysiak and Pawlak [12] studied the crystallization and cooling process of a silicon-aluminium alloy in a plaster mould using Topological Data Analysis (TDA), parametrising the study with the casting temperature. The work shows that a casting temperature in the range of 725 to 800 °C prolongs the crystallization time and that 725 °C is the optimum for filling the mould and dimensional accuracy. Bogdanoff *et al.* [13] presents a numerical procedure (based on CFD) to approximate the yield strength of A380 with plaster mould casting of A356.0 and A360.2. A yield strength of 140 MPa and 210 MPa (respectively) is predicted after heat treatment. Brevick *et al.* [14] investigated the effect of different levels of silica sand and carbon fibre additions on the properties of plaster moulds and related aluminium alloy castings. Analysis of statistical data showed the relationship between wet and dry strength of plaster moulds with sand and carbon fibre content. An addition of 30% silica sand did not appear to reduce the strength of the plaster and it has the potential to reduce cost. Instead, since the addition of 0.5% carbon fibre significantly increased the strength of the plaster, the authors suggest adding both silica sand and carbon fibre to plaster moulds to significantly enhance their hardness.

Studies in the literature on the optimisation of casting parameters to minimise defects are not much focused on plaster mould vacuum investment casting. For example, Ahirrao and Marlapalle investigated the effect of several parameters (including pressure and die temperature) to minimise surface roughness and wear resistance of aluminium alloys with simulation but their study was conducted considering a high pressure die casting process [15].

As it can be observed by this literature survey, although parts of the themes involved in this work have been studied extensively in the literature, not much has been investigated to minimise defects in plaster mould vacuum investment casting of aluminium alloys through CFD simulations.

Methods

A geometry representative of a family of products of interest (Figure 1) have been investigated with CFD simulations using the commercial tool Flow-3D [16] where aluminium alloy A356 is the casting material.

The accuracy of insights gleamed from CFD simulations is governed by the accuracy and attention to detail in simulations setup. Broadly, the stages of this setup will include establishing the relevant physical models (with associated parameters), defining the properties of the materials present in the system, configuring a suitable meshing and applying physical boundary conditions with extremity limits. The decision of which outputs to monitor and at which frequency is a final consideration.

Second only to meshing, over-prescribing physical models has a significant impact on simulation run time. It is important that the aim of the simulations is clearly defined and only models in association with such aim are initiated. In this case, reducing the number of active models was not possible as all were relevant, however alternative time-saving options are available in such situations. Therefore, the simulation was split into two halves – filling and solidification – in which flow effects were excluded in the latter part. With no flow effects, there was no need to solve the full momentum equations, presuming stationary fluid on which

solidification calculations are made. In the initial (filling) simulation, the air entrainment, gravity, heat transfer and viscosity and turbulence models were activated whereas only the heat transfer and gravity models were active in the second (solidification) simulation in addition to activating the solidification model calculation. It is worth noting that during the second simulation, the solver for the heat transfer model was switched from explicit to implicit. Implicit solvers bypass the stability restrictions that are placed on explicit solvers allowing them to operate with a larger time step, ideal when working with computational demanding studies. Such solvers are not always recommended, requiring a case-by-case sensitivity assessment ahead of the full study to confirm that it provides accurate results.

The properties of materials, or at least sufficiently comparable materials, are generally present in literature sources and provide adequate good accuracy in situations where exact material properties cannot be measured. Wu *et al.* [17] and Rahmanian and Wang [18] present data on the thermal conductivity and specific heat capacity of plaster as a function of temperature which have been employed in this study; the region of interest is between room temperature and 400 °C.

Definition of a suitable mesh is not a simple task, requiring a balance between resolution of complex geometries and simulation stability as well as run time. Flow-3D allows for multiple overlapping meshes to be generated to allow for local mesh refinement around areas of interest that helps in alleviating this dilemma. Figure 2 shows the grid lines of the mesh constructed around the casting geometry for this study. The mesh features a “global” mesh covering the whole domain with three additional mesh planes, visible in the left and centre panels of the figure, which grant local enhancement to resolution to the casting component. Mesh sizes are 0.0025 m and 0.0003 m in the case of global and mesh planes respectively.

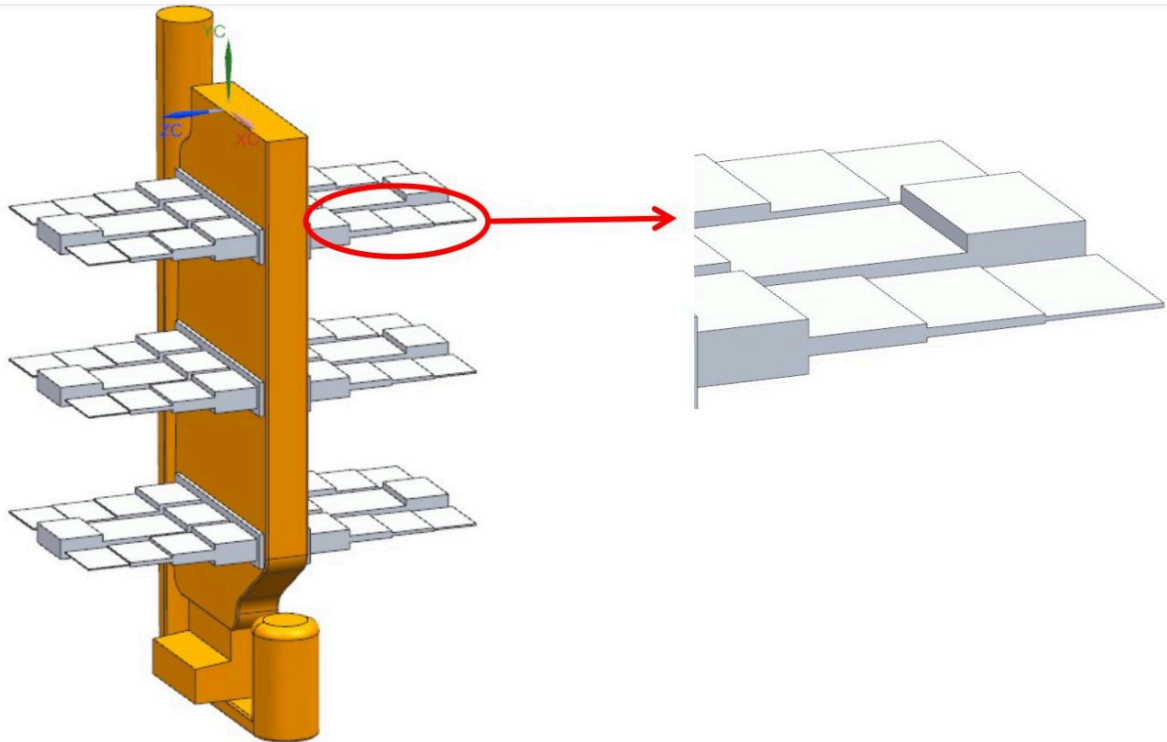


Fig. 1 – Representation of the computational domain of the CFD simulations.

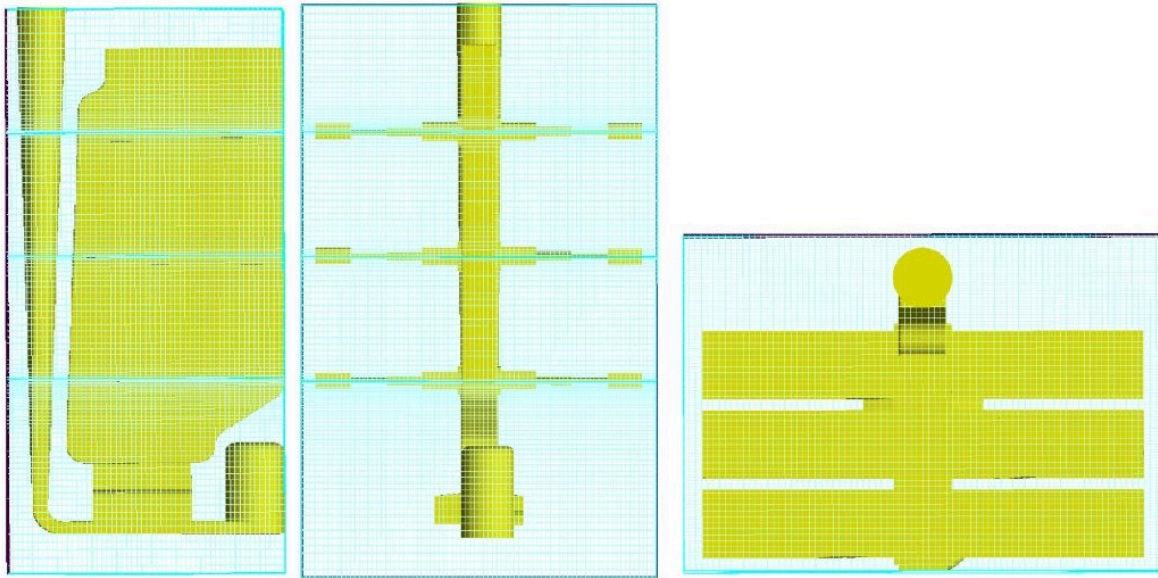


Fig. 2 - Three axis view of component mesh construction.

Boundary conditions are applied to the outer faces of the global mesh block at the edge of the domain, meaning six boundaries in total given the cubic nature of the mesh space. To replicate conditions inside the vacuum chamber, in which air enters and leaves through a single valve, all boundaries except one were set to wall conditions with the final being set to a pressure boundary condition. Wall conditions apply a no slip and zero velocity criteria at the boundary, preventing fluid from entering or leaving the domain although temperature and pressure information as initial or functions of time can be defined. The pressure condition at the final boundary facilities user specified temperature and pressure as a function of time as well as allowing fluid to flow out of the domain.

Results and discussion

During the filling of metal castings, the factors considered in this study to separate a sound casting from a sub-standard one are fluid velocity, fluid temperature and evolution of air entrainment due to turbulent flow. Jin *et al.* [7] show that fluid velocities in excess of 0.5 m/s has a detrimental effect on filling and final casting quality. The predicted velocity profile in the computational domain at the final time step of the simulation (Figure 3) shows that fluid flow throughout the running system has a velocity consistently in excess of 0.5 m/s which diminishes at the in-gate as fluid enters the main casting with the exception of a narrow vertical patch of excess velocity in the main body above the in-gate. It is believed this was a result of fluid inertia during filling.

The final distribution of temperature in the casting at the final time step of the filling simulation (Figure 4) show that portions of the fluid furthest from the down sprue at 435 °C have begun solidifying (considering a melting temperature of the metal of 620 °C). Unlike the opposite side of the casting which was in proximity to the still hot alloy in the down sprue

maintaining fluid temperature, this portion of the casting faces only the outside air leading to this accelerated cooling. Similarly, the horizontal aspects of the casting at the centre (right hand panel of the figure) retain heat due to close contact with surrounding elevated temperature material, whereas alloy on the periphery see relatively more rapid cooling. This pattern of solidification towards the centre of the casting has the potential to give rise to porosity in the casting. However, further investigations will be needed to determine the approximate position and extent of this porosity (as reported below). Importantly, as solidification has only just been initiated, the choice to divide the simulation into two parts with solidification modelling only in the second half is justifiable.

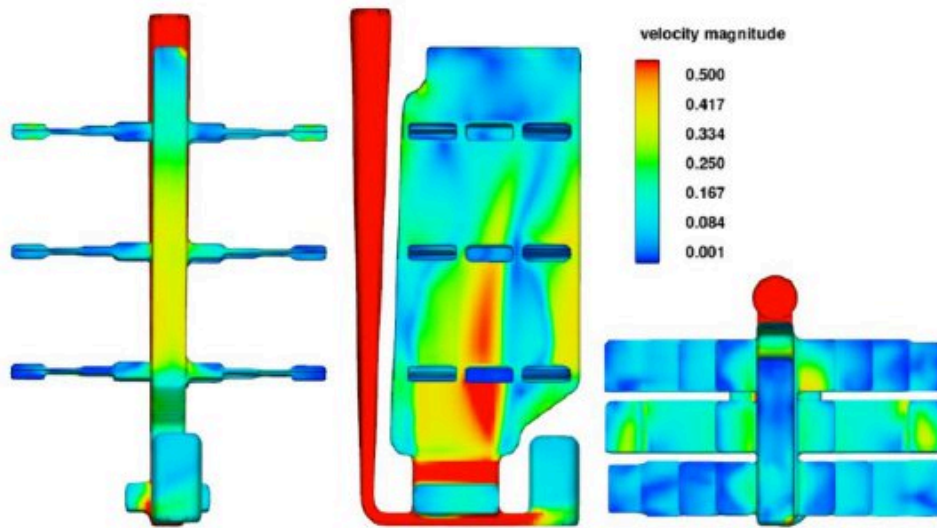


Fig. 3 - Fluid velocity (in m/s) contour plot of casting at final time step from three orthogonal orientations.

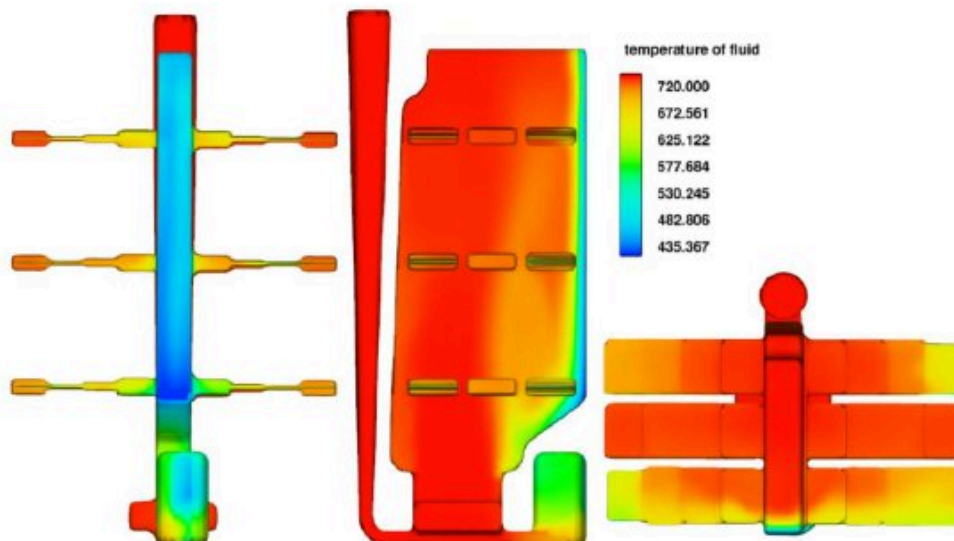


Fig. 4 - Fluid temperature (in °C) contour plot of casting at final time step from three orthogonal orientations.

As would be expected, the volume fraction of air entrained (Figure 5) has been forced to the extremities of the casting by the inbound fluid flow. In fact, there is a bubble trap at the end of the horizontal runner bar and at the tips of the horizontal elements of the computational domain. An additional explanation for this that could be presented is as a result of the thinning cross section of the casting towards the tips of these horizontal elements and, therefore, the alloy has difficulty reaching the extremity. This is considered the more likely scenario as a maximum porosity of 17.9% is higher than would be expected for a vacuum casting.

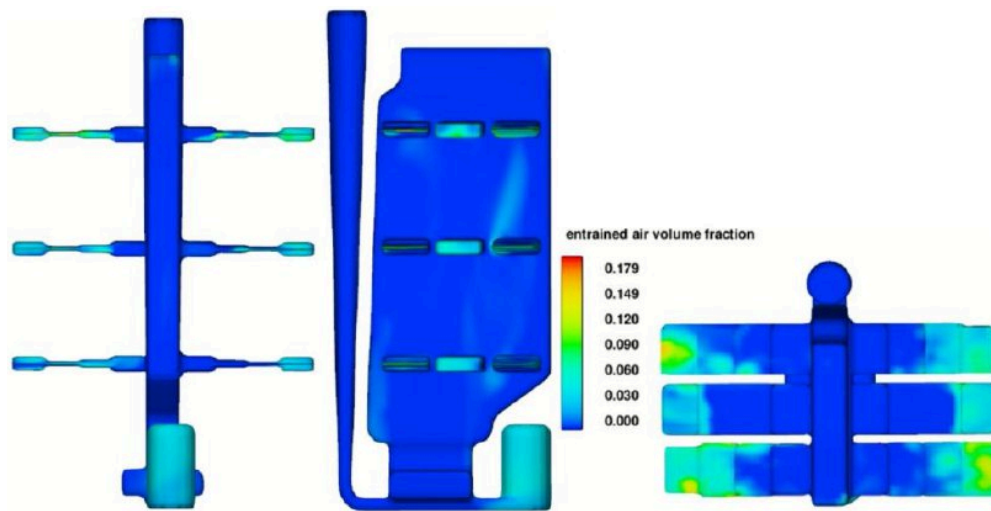


Fig. 5 - Fluid air entrainment contour plot of casting at final time step from three orthogonal orientations.

With the mould filled, discussion can turn to the behaviour of the casting during solidification. The solidification process as modelled was completed in 233 seconds, during which consideration of the fluid temperature and evolving porosity were selected. Considering the final temperature distribution in the computational domain at the end of solidification (Figure 6), the outer most portion of the casting has almost reached room temperature with a rather steep gradient across the component to approximately 290 °C on the opposite face. A key feature of merit is that there are no isolated hot spots present in the casting that would otherwise lead to solidification defects.

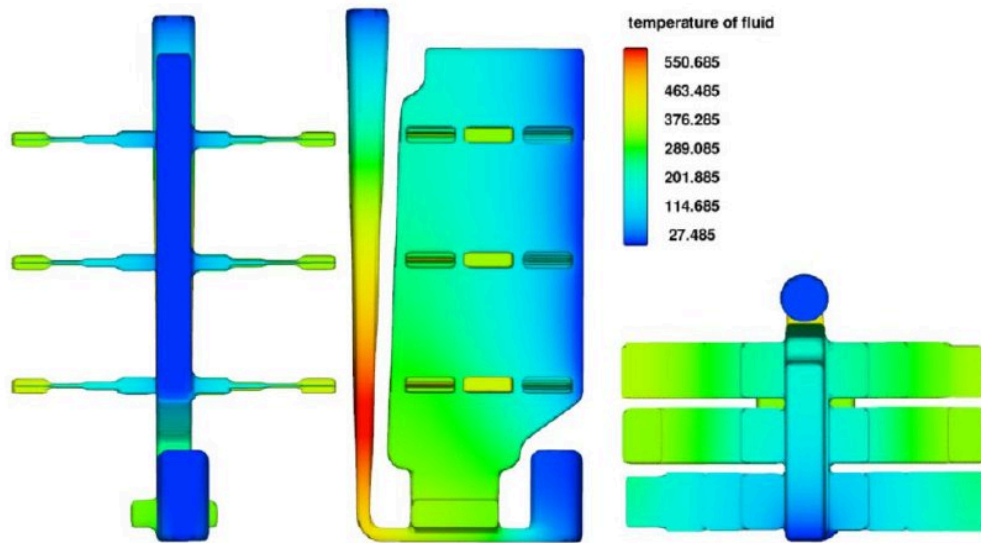


Fig. 6 - Final temperature (in °C) distribution at the conclusion of solidification from three orthogonal orientations.

Micro-porosity in the casting is the final element for discussion and, arguably, the most relevant as it relates directly to quality and operational performance in the context of this case. For components of this type, manufacturers typically do not allow more than 5% porosity, beyond which a casting would be rejected. As can be seen in Figure 7, a maximum of 3.52% micro-porosity is predicted – a value comfortably below the maximum tolerable. It is interesting that there is a difference between the predicted 3.52% micro-porosity and 17.9% entrained air suggesting that not all entrained air is contributing to micro-porosity. However, comparing the presented distributions of air entrainment and porosity there is significant overlap, implying air entrainment is a contributor to the porosity observed.

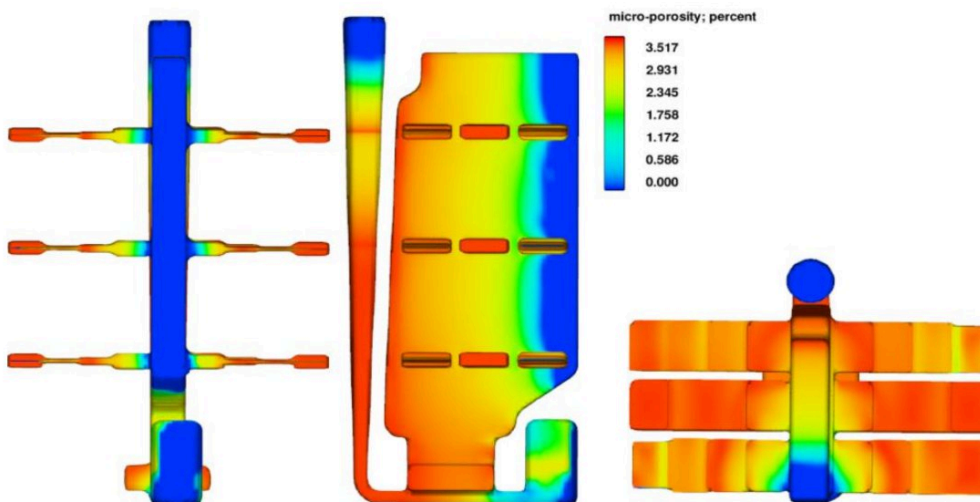


Fig. 7 - Micro-porosity map of casting at the conclusion of solidification from three orthogonal orientations.

Given the importance placed on porosity in this casting due to the direct impact on component serviceability, this has been selected as the target parameter for an optimization assessment. Three parameters with the greatest influence on porosity have been selected: mould temperature, in-gate fluid temperature and in-gate fluid velocity. A L9 orthogonal experimental design was constructed by selecting three levels for each of these parameters, as shown in Table 1. It should be noted that at least three levels are needed to appropriately identify non-linear patterns. An orthogonal test method has similarities with Taguchi methods [18] although there is a conceptual difference. Whilst the Taguchi method studies the stability of the entire system under a selection of different environment, the orthogonal method studies the responsiveness of target output parameters to the input control factors in the system.

Table 1 - Details of three levels used in optimization study.

Parameter	Level 1	Level 2	Level 3
Mould temperature (°C)	350	400	450
In-gate fluid temperature (°C)	670	720	770
In-gate fluid velocity (m/s)	0.5	1	1.5

Running these nine simulations according to a Design of Experiment (DoE) approach yields nine values of porosity from which conclusions can be drawn. The parameters used in each simulation run are detailed in Table 2, with the final porosity predicted by each simulation at the final time step (i.e., the end of solidification) displayed in a comparative histogram plot in Figure 8.

Table 2 - Details of the parameter configuration used in each run.

Simulation Run	Mould temperature (°C)	In-gate fluid velocity (m/s)	In-gate fluid temperature (°C)
1	Level 1: 350	Level 1: 0.5	Level 1: 670
2	Level 1: 350	Level 2: 1.0	Level 2: 720
3	Level 1: 350	Level 3: 1.5	Level 3: 770
4	Level 2: 400	Level 1: 0.5	Level 2: 720
5	Level 2: 400	Level 2: 1.0	Level 3: 770
6	Level 2: 400	Level 3: 1.5	Level 1: 670
7	Level 3: 450	Level 1: 0.5	Level 3: 770
8	Level 3: 450	Level 2: 1.0	Level 1: 670
9	Level 3: 450	Level 3: 1.5	Level 2: 720

It should be noted that this configuration of input parameters represents the second iteration of the investigation. The original selection of parameters was identified for extreme difference analysis upon the conclusion of which the best options were selected for further scrutiny. The

micro-porosity predictions presented here were lower than those predicted in the original investigation, illustrating the success of this approach.

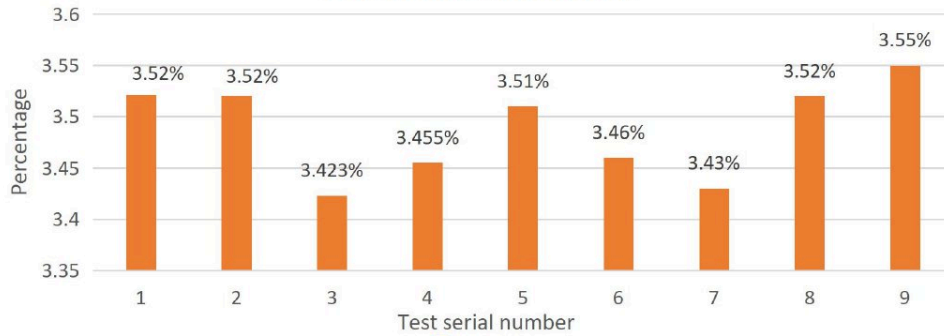


Fig. 8 - Histogram of percentage porosity predicted in the nine numerical trials.

From this collection of porosity results, further assessments can be made to identify not only the most optimal setting for each parameter, but a measure of their relative importance. Considering each parameter in turn, taking the average of the porosity results corresponding to each level in turn (all three L1s, L2s and L3s), 9 mean values corresponding to each level of each parameter can be obtained and have been denoted as M values. Plotting the three M values for each parameter (Figure 9) the corresponding optimal value can be readily identified. As the goal is minimisation of porosity, the minimum M value for each parameter is sought. Hence, predictions suggest optimal values of 400 °C, 0.5 m/s and 770 °C for the mould temperature, fluid velocity and fluid temperature, respectively. These results are aligned with expectations based on the observation that a higher fluid temperature extends the onset of solidification and, hence, the formation of dendritic structure whilst filling is still occurring in thin sections. It is well known that a lower fluid velocity is beneficial in terms of lowering casting defects, however an interesting observation is that it appears that there is a predicted reduction in micro-porosity when velocity is increased to 1.5 m/s. This would need further investigation to explain in full depth. Finally, the mould temperature must be high enough to ensure there is no premature solidification but not so high the excess heat is trapped within the system to fuel long-term porosity growth. The most optimal configuration, defined by the lowest M value, was a mould temperature of 400 °C, a fluid in-gate velocity of 0.5 m/s and an in-gate fluid temperature of 770 °C. It should be noted that the values of the input parameters were selected based on industry input. A broader range in these parameters could be investigated at a higher order orthogonal test to deepen understanding of the process beyond industry expectations; this however is a subject for further work.

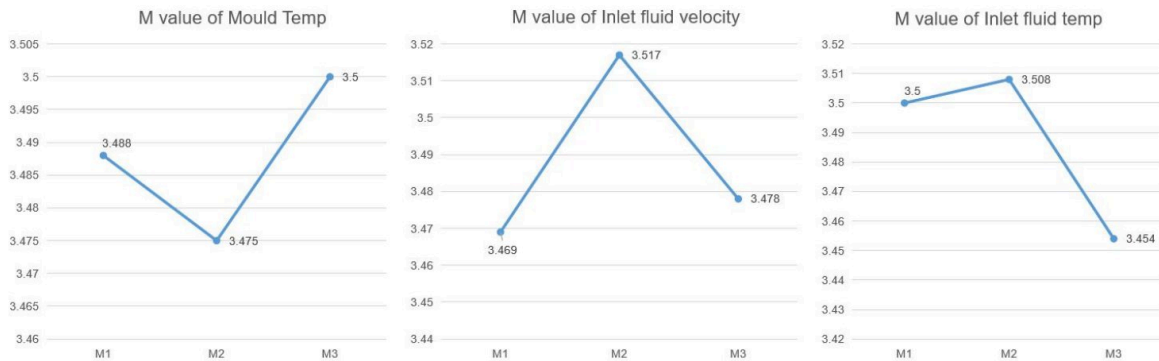


Fig. 9 - *M-value plots for each input parameter of the design of experiment.*

As a final observation from this data, by considering the difference between the greatest and lowest value of the M values in each case, the relative importance of each parameter can be assessed. This relative importance will be denoted as the R value with R_1 , R_2 and R_3 representing the relative importance of the mould temperature, fluid velocity and fluid temperature respectively. Making the calculation from this data set yields $R_1 = 0.025$, $R_2 = 0.048$ and $R_3 = 0.054$. The higher the R value, the greater the impact of that parameter, so this investigation reveals fluid temperature as the driving factor of the three investigated with fluid velocity and mould temperature taking second and third place.

There are of course limitations to such simulations. Optimization has suggested that a reduction in the filling rate would be beneficial, however such a reduction would increase the filling time and hence the possibility of premature solidification and surface oxide formation. Equally, simulation models are not necessarily comprehensive. Depending on the number of models active and the extent of underpinning assumptions, aspects of the physical phenomena may not be fully captured.

Results obtained in this optimization study would readily lend themselves to a further optimization investigation on macro-shrinkage, air entrainment or volume fraction.

Conclusion and further work

This work presented a numerical study to minimise porosity formation in vacuum assisted plaster mould investment casting of aluminium alloy A356. A scientific literature survey revealed several studies on the broad topic but not many relevant, specific studies. A geometry designed to represent a family of products of interest has been modelled in the calculation domain of Computational Fluid Dynamics (CFD) simulations. The case considered showed a local maximum of 3.52% micro-porosity, a value well below the typical 5% threshold used in the industry to scrap high-value components. Results suggested also that not all entrained air is contributing to micro-porosity. A further optimisation based on a 9-level orthogonal Design of Experiment (DoE) based on mould temperature, in-gate fluid temperature and in-gate fluid velocity has been carried out identifying optimal process parameter values. Furthermore, in-gate fluid temperature resulted the most important parameter to affect porosity whereas the mould temperature the least important.

Future development aspects of this work can be summarised in the following areas.

- Further investigate the predicted reduction in micro-porosity when in-gate fluid velocity is increased to 1.5 m/s.
- A broader range of the inputs parameters considered in the DoE could investigate the design space beyond stringent industry expectations.
- Investigate a reduction of the filling rate (that has a beneficial effect towards micro-porosity) to identify cases of cold-runs or surface oxide formation.
- Further optimisation of macro-shrinkage, air entrainment or volume fraction.

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