CONFORMAL COOLING CHANNEL SHAPE OPTIMISATION FOR HIGH-PRESSURE ALUMINIUM DIE-CASTING TOOLS USING THE ADJOINT METHOD

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ABSTRACT

Additive manufacturing (AM) has reshaped the design process for high pressure die casting tools by enabling a large design space and tolerances for the embedded cooling channels. Traditional straight cooling passages have been replaced by conformal cooling designs that are adapted to the complex mould surface topology. The primary design principle for high pressure aluminium die-casting (HPADC) cooling channels is to provide uniform cooling across the contact interface, as defects like part warpage and shortened tooling life are caused by an excessive thermal gradient. The extreme operational conditions for HPADC mean that achieving more uniform cooling is a challenge of increasing importance. Studies using the adjoint method to optimise cooling channels can be found applied to the injection moulding process for polymers [1], however its application to the cooling of HPADC tools has received limited attention to date. To develop and examine the effect of optimisation for internal cooling channel designs in HPADC, this study has focused on comparing two different approaches that use the adjoint method to achieve a more uniform interface temperature for an industrial casting tool. A steady conjugate heat transfer model was implemented with two decoupled parts representing the aluminium cast and the steel mould to obtain a well-converged initial result. Two different shape optimisation strategies: the adjoint point-set, and the surface method, were applied separately to the primal solution, with the same objective function targeting a minimised surface temperature standard deviation. The temperature distribution across the mould cast interface was compared between the two optimised cooling designs and the original layout. Results from applying both adjoint methods to the cooling channel have shown improvement in temperature uniformity. The adjoint point-sets approach focuses on small tuning of surfaces with limited space, whereas adjoint surface method generate more aggressive deformation with various curvature while maintain lower computational cost. Surface deformation results of the cooling channels using the different approaches also show the benefits and limitations for each case, which will be useful when we consider more complex geometries in future research. Assumptions and limitations for each adjoint method, and the outlook for upcoming studies will also be evaluated and discussed in this work.

1. INTRODUCTION

Prior to the emergence of additive manufacturing (AM) technology, traditional mould cooling systems were constrained by conventional straight-pipe layouts imposed through the use of computer numerical control (CNC) drills. This restriction has been removed through the development of AM methods such as selective laser sintering (SLS). HPADC processes operate under more challenging conditions than those forming polymers. Even with an embedded conformal cooling design, the casting process creates a high thermal gradient throughout the casting cycle. Conformal pipe layouts can increase the tool lifetime and improve the cast quality [2]. Uneven cooling at the contact interface between the molten aluminium and the mould can result in poor finished part quality, and even mould cavity fracture after short number of cycles. Therefore, the development of an optimisation approach to obtain a conformally cooled design for HPADC, that yields high surface uniformity whilst meeting the manufacturing and operational constraints is of considerable interest to tool manufacturers.

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Developed by Lion and Pironneau [3, 4], the adjoint method is a powerful numerical approach to calculate a pre-defined mesh sensitivity for targeted objective functions with specified parameters, which can then be used to deform the shape of the geometry. The adjoint shape optimisation method was initially used for aeronautical applications, and whilst it has since been applied in plastic injection moulding tools to provide conformal cooling design [5], its application in HPADC, especially with conformal cooling layouts, has received limited attention. In this work the optimisation of a HPADC insert with an embedded conformal cooling design has been conducted using the adjoint method. Two different shape deformation approaches will be demonstrated, for an objective function that minimises the thermal gradient at the surface cavity of the mould.

The adjoint point-set method introduces control points to the volume mesh, which is then morphed according to the calculated sensitivity result. New position of the control points will be determined based on the cost function that are linked to the mesh deformation. The concept of introducing secondary control points has been visited by researchers before in aerodynamic optimisation [6] and has been brought to practise in a more recent CFD study [7]. More commonly seen, the adjoint surface method applies the displacement directly to the surface mesh of the morph region, in this case all cooling pipes.

Each optimisation method has its strengths and weaknesses, and it is important to investigate the relative benefits by comparing the results of each optimisation strategy when applied to the appropriate design geometries. The complete moulding tool usually consists of multiple inserts, cooling a thermal mass with a complex shape; therefore, the optimum function is chosen to achieve more uniform temperature throughout the entire cast tool interface. Hence optimisation of a particular insert in isolation will not be accurate for a real industrial application. However, for the purposes of this study only one insert and its embedded cooling channel will be selected, to demonstrate the approach and to appraise the relative merits of the optimisation approaches.

2. METHODOLOGY

The adjoint method is essentially implemented for both optimisation strategies, such gradient based approach predicts the influence of the different input parameters or quantities of interest. In this study, the sensitivity of the defined objective cost function (surface temperature standard deviation) with respect to the input parameter (temperature T) of the correspond boundary (contact interface on the mould side). To calculate the gradient of the minimise objective function $J(U,T)$ at the discrete grid points U, base solution U_0 is linearised to provide smooth grid deformation in the design variables modify the surface geometry which can be fully expressed as:

$$\frac{dJ}{dT} = \frac{\partial J}{\partial U}\frac{dU}{dT} + \frac{\partial J}{\partial T} \quad (1)$$

In this study, two different adjoint shape optimisation approaches have been examined by comparing the mould/cast interface temperature uniformity achieved from both resulting optimal designs. The commercial finite volume computational fluid dynamics (CFD) software STAR-CCM+® was used, and the adjoint model was implemented to examine the baseline design of a conformal pipe embedded in an insert as shown in Figure 1. The simulation was carried out under the steady condition of an isothermal mould surface throughout the solidification period. Previous work has shown that the tool interface temperature reaches 400°C – 450°C [8] immediately after metal injection, dropping by 30°C by the end of the solidification process [9]. This change in the temperature mainly depends on the solidus, liquidus temperatures of the aluminium alloy composition in addition to the cast thickness. Prior to this study, a separate model for water flow inside the coolant pipe with a 5.5L/min flow rate was set up, the convection heat transfer coefficient around the internal cooling walls were monitored. This value has then been extracted from the model and mapped onto the pipe region for use during the optimisation. This has allowed the computational cost of the simulation to be reduced dramatically.

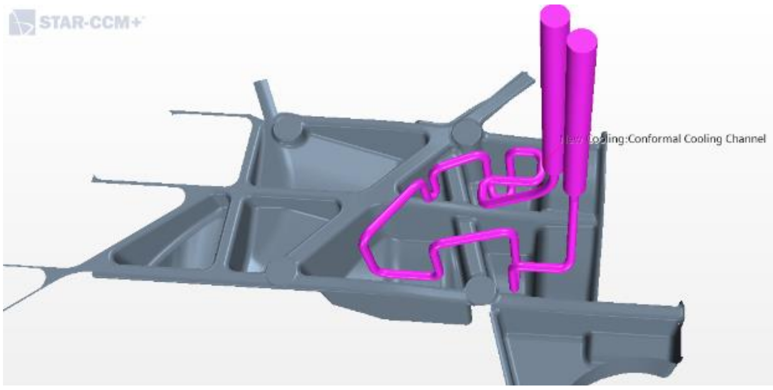


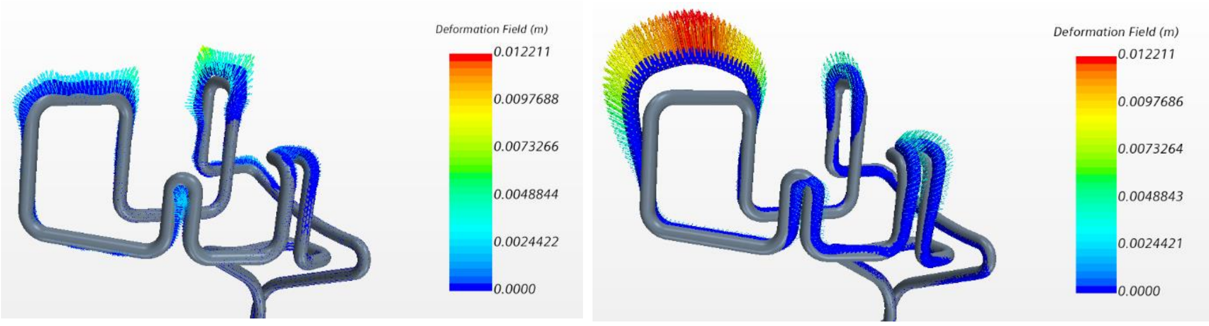
Figure 1: Geometry of part of the industrial HPADC insert conformal cooling channel with mould/cast interface

Two individual parts were considered in this steady simulation, a solid steel mould (with a subtracted conformal cooling region) and the complete Aluminium cast with heat generation. All internal cooling passages were configured with the pre-calculated convective heat transfer coefficient mapped around the internal walls of the mould. A 67°C internal ambient temperature was set across the pipe region, identical to the temperature of the coolant. The heat flux transferred from the cast to the mould was evaluated by considering a volumetric heat generation source term with the energy equation. The volumetric energy source was evaluated using the heat of fusion, injection temperature and a solidus temperature, and was found to be 4.5e7 W/m^3. Zero contact resistance was assumed at the mould and cast interface to ensure ideal heat transfer. Adiabatic boundary conditions were applied for the remaining external faces of the tool. Polyhedral cells were applied for mesh discretisation. An overall mesh quality of 97.5% was achieved according to STAR-CCM+®'s diagnostics, and quality controls included a mesh-convergence study. A steady simulation with constant density and conjugate heat transfer model was performed to provide a well-converged primal result before running the adjoint model for both solid regions.

Upon obtaining a result from the steady simulation with energy residuals converged below 1e-5, the adjoint solver was then enabled with an objective cost function defined to minimise the surface temperature standard deviation at the interface between the aluminium cast and the steel mould. Two different shape optimisation approaches were introduced which required separate setup of the simulation based on the initial result.

The adjoint point-set method defines an evenly distributed point-set around the deformation region, that is around the internal conformal cooling region. These points combine with local mesh coordinates will define the movement of both internal and external mesh boundaries. New positions of the points are determined by a radial basis function (RBF) based interpolation and results from the adjoint solver. All control points require calibration between the total number of points, separation, and offset distance from the surface to maintain geometry validity after each deformation iteration. A total of 300 points with relative target spacing and offset distance set to 0.005mm and 0.004mm respectively. A vector function was established between the cumulative morph displacement and the adjoint results of the surface standard deviation with respect to position. This function also includes a user-defined steepest descent constant (SDC) which controls the amount of deformation per iteration. A well-chosen SDC should consider the consistency for each deformation iteration while keeping geometry and mesh valid, it also directly influences the total number of iterations required before obtaining the optimal design. This displacement function is applied at the pre-defined control points, which will deform and stretch the corresponding surfaces based on the results of the current iteration.

Conversely, the adjoint surface method requires no introduction of a point set, however the same displacement function can be applied. Results of the sensitivity displacement function are applied



i – Adjoint point-set method deformation field   ii – Adjoint surface method deformation field

Figure 2: Vector scenes of cumulated deformation field for the conformal cooling pipes, with surface representation of the optimised (blue) and baseline (grey) design using the adjoint point-set method (i) and adjoint surface method (ii)

directly at each individual cell around the defined morph region, in this case the surface of the internal cooling channel regions. A looped simulation operation was created for this adjoint surface case with stopping criteria linked to the maximum skewness and face validity of the mesh, making the simulation automatic and more versatile. A re-meshing process for the deformed cells is required after each optimisation iteration to ensure mesh validity and resolution. Twenty total iterative cycles were defined for the adjoint surface optimisation to allow well-converged results.

3. RESULTS

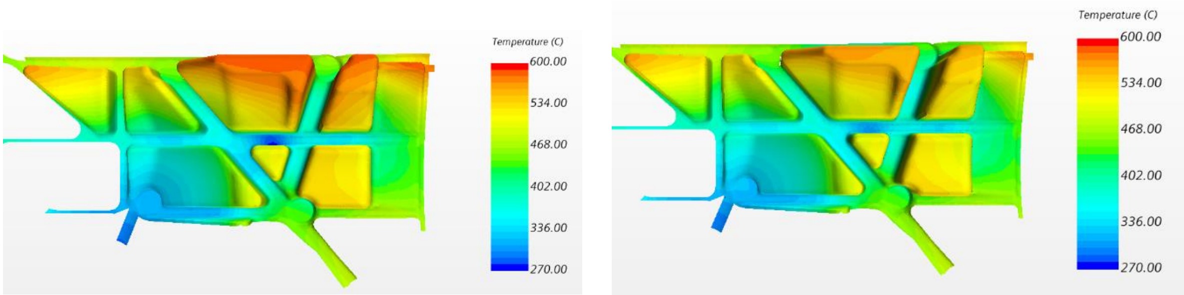
Table 1 shows the surface temperature standard deviation at the mould/cast interface between the baseline design and optimised results for the two different adjoint methods, plus the percentage overall reduction. The initial surface temperature standard deviation of the contact interface was 65.9, with the non-optimised cooling layout. The optimised cooling design using the adjoint point-set and surface method has achieved a new surface temperature standard deviation of 62.7 and 55.9 respectively. This led to an overall increase in temperature uniformity of 4.72% using the adjoint point-set approach, and 15.17% for the adjoint surface method.

Table 1: Iteration results of surface temperature standard deviation for each adjoint method

Optimisation method	Surface temperature standard deviation	Overall reduction (%)
Baseline design	65.9	--
Adjoint point-set	62.7	4.72
Adjoint surface	55.9	15.17

Figure 2 shows the vector scene of cumulative displacement of the internal cooling channel layout. Colour contour and vector size indicate the amount of surface displacement and relative magnitude of deformation. It also shows the surface representation of the baseline (grey) and optimised (blue) cooling designs resulting from the two different adjoint optimisation approaches. Results using the adjoint point-set method focused more on small surface tuning around the corners and sharp bends, with a maximum surface deformation of 9.74mm. The adjoint surface approach concentrated on moving the entire bend or corner by a larger deformation factor with a maximum displacement by 12.2mm.

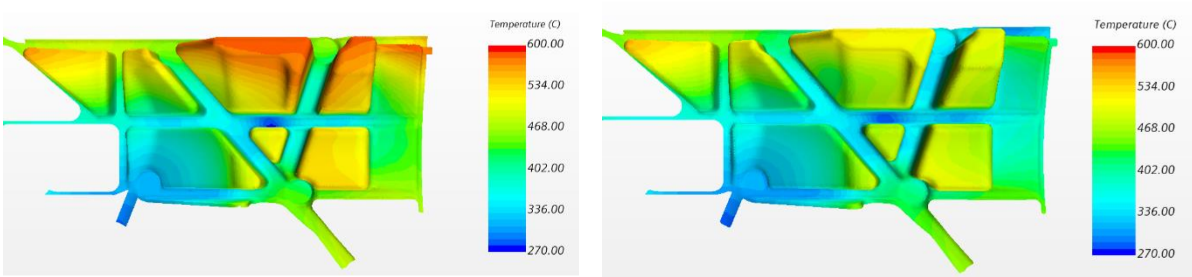
When comparing with the surface adjoint method, the adjoint point-set method allows more precise tuning of the mesh around the morphed region, it is best suited to small scale and complex geometries with limited clearance between two adjacent surfaces. With the supporting offset points, it is also more robust and less likely to fail due to self-intersection after a large deformation iteration than the surface adjoint approach. However, problems with the discrete point-sets approach could end up with non-



i - Original interface temperature distribution

ii - Adjoint point-set optimised interface temperature distribution

Figure 3: Temperature distribution at the mould cast interface between the original (i) and optimised (ii) cooling layout using the adjoint point-sets method



i- Original interface temperature distribution

ii- Adjoint surface optimised interface temperature distribution

Figure 4: Temperature distribution at the mould cast interface between the original (i) and optimised cooling (ii) layout using the adjoint surface method

smooth surfaces, it may also require more computational time for each cycle. Conversely, the surface adjoint method is more versatile and flexible in dealing large scale geometries, allowing pronounced deformation of the baseline geometry. A total of 10 iterations was required to obtain the optimal design using the adjoint point-set method, whereas the adjoint surface required 20 iterations. However, each iteration of the adjoint point-set method required more than double the computational time of the adjoint surface method, which makes the adjoint surface method more efficient overall.

Both cooling designs using adjoint optimisation have improved the thermal uniformity across the interface when compared with the baseline cooling channel design. Figures 3 and 4 show the temperature distribution at the contact interface on the mould side between the original layout and two optimised cases with adjusted temperature scale. It shows the highest and lowest temperature regions of the original design are located at the extruded profiles and grooves between the two extruded surfaces at approximately 594 and 273 degrees respectively. The temperature gradient obtained using the adjoint point-sets method has reduced from 321 degrees to 279 degrees, the adjoint surface method has further reduced this value to 270 degrees. The thermal distribution contour shows that the adjoint point-sets approach focused more on refinement of small and dense low temperature regions, whereas the adjoint surface method concentrated on high temperature zones over a much larger region. This reflects the deformation results of the cooling channel design, as adjoint point-sets focus on small precise tuning of the channel and adjoint surface focused on larger deformation of the whole cooling layout.

4. CONCLUSIONS

Two shape optimisation approaches using the adjoint method have been applied on an industrial HPADC insert aimed to achieve more uniform cooling between the aluminium cast and steel mould interface. Commercial CFD software was employed to obtain a primal solution of a steady model for the HPADC process, with the assumption of constant volumetric heat generation and minimal thermal contact resistance at interface. An optimised cooling design was generated using both the adjoint point-set and the surface method, which successfully improved the temperature uniformity at the interface by 4.72% and 15.17% respectively. Future studies for this work will focus on implementation in a transient model, and validation against industrial trial results. Modification of the objective functions toward a blended function which targets multiple design parameters such as the boundary heat flux and pressure drop around all cooling layouts to achieve higher performance will also be investigated.

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