Toward the development of a thermal-stress model of an industrial counter pressure casting process

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Abstract. It is argued that the Counter Pressure Casting (CPC) process is superior over low-pressure die casting (LPDC) in terms of reducing defects and improving cast product performance. To date, there has been relatively little research conducted on the CPC process to provide reliable data to confirm this argument. In this work, a plant trial has been done on an industrial CPC process using a custom-designed ‘H-shaped’ die to acquire an extensive amount of quantitative process data. The data acquired includes temperatures obtained from within the die, the casting, the surrounding environment, and within specific die cooling channels. The data has been processed and analysed to support the development of a comprehensive thermal-stress model of the casting process in order to better understand and quantify the essential macro transport processes. This paper presents a methodology of a coupled thermal-stress model development on the CPC process, and the preliminary results obtained from the models. The results to-date clearly show the need for a fully coupled thermal-stress analysis for the particular casting geometry and process conditions examined. Some of the challenges associated with the current modelling approach are also identified and potential solutions presented.

1. Introduction

In the automotive industry, aluminium has been used to replace iron and steel to reduce vehicle weight in order to improve fuel economy and reduce emissions. As a result, there are on-going activities in the research and commercial sectors to develop casting technologies to improve the mechanical properties of cast aluminium-alloy components. One such technology, the Counter Pressure Casting (CPC) process, was developed based on the conventional Low-Pressure Die Casting (LPDC) process. The CPC process is argued to produce improved cast-properties and has been employed in the casting industry to produce aluminium parts - e.g. steering knuckles and control arms. Generally, the CPC process (schematically shown in figure 1) is similar to the LPDC process. The main difference is that the die, in the CPC process, is placed in a pressurized chamber (~2 atm), whereas the die in LPDC is operated under the atmospheric pressure. Due to this difference, it is believed that the CPC process can reduce free surface turbulence during filling and enhance casting/die interfacial heat transfer during solidification. If true, both of these factors can potentially lead to fewer defects and a refined microstructure, thereby improving the mechanical performance of the component [1, 2].
Figure 1. Schematic illustration of the CPC process: (a) the die and chamber are closed and a new casting cycle begins; (b) the furnace and chamber are pressurized with equal pressure; (c) the pressure is increased in the furnace, the liquid metal begins to fill the die cavity under the counter pressure; (d) the pressure in the chamber is released and the casting is solidified under an elevated pressure; (e) the pressure in the furnace is released; (f) the die and chamber are opened; (g) the casting is ejected and the cycle ends.

Numerical modelling has been widely applied in the casting industry as a means of designing and optimizing casting processes in order to reduce defects and improve yields. Typically, the approaches focus on fluid flow during cavity filling and heat transport. Additional areas of simulation have included microstructural evolution during solidification, macro-segregation and stress/strain evolution. As enhanced interfacial heat transfer may be one of the benefits achieved in the CPC process, a detailed, numerical-based, investigation of stress/strain development in the casting and die would appear justified in order to better characterize the benefits of the technology.

Within the casting group at UBC, there has been a sustained effort over several decades to contribute to the knowledge-base to improve casting process simulation, with a particular focus on light metal alloys. Past examples included Roy et al. [3] and their characterization of the constitutive behaviour of aluminium alloy A356 in as-cast condition, Thompson et al. [4] and their characterization of the evolution of the fraction solid in A356 under different cooling rates and Moayedinia’s [5] characterization of the heat transfer within the water-based cooling channels in the LPDC process. Synthesis of this knowledge in comprehensive process models includes the work Zhang et al. [6] to develop a thermal model for low-pressure die casting of automotive wheels and the work by Wei [7] to develop a coupled thermal-stress model for low-pressure die casting of automotive wheels. This work has convinced the UBC group of the importance of considering the thermal/stress deformation of the die and casting in understanding interfacial heat transfer in die casting processes. Work outside of the group in this area includes studies by Fackeldey et al. [8] and Griffiths et al. [9] to name a few.

In the present work, a plant trial has been conducted using an ‘H-shaped’ casting to acquire quantitative data from a commercial CPC process. The data, in turn, has been used to support the development and to validate a computational model of the process. The model has been developed using the commercial FE package ABAQUS™ owing to its ability to conduct a coupled thermal/stress analysis and its capability with respect to analyses involving contact between ridged surfaces. In this paper, the foundations of the approach are highlighted.
2. Experimental measurements

2.1. Casting and die design

Figure 2 shows the geometry and dimensions of the ‘H-shaped’ casting that was designed for the research. The intent of the design was to create interfaces between the casting and the die that would form both gaps and pressure, thereby allowing the effect of counter-pressure on interface behaviour and heat transfer to be determined. Figure 3 shows the main die components. The system consists of a top die, a bottom die, a bottom plate, ejector pins and an ejector plate. The die is cooled by water through ten ‘finger-cooling’ elements and two channels internal to the die structure.

![Figure 2. Drawing (in mm) of the “H-shaped” casting](image1)

![Figure 3. CPC die components](image2)

![Figure 4. Commercial CPC machine (CPC 1600)](image3)

2.2. Plant trial

A plant trial was conducted using a commercial CPC machine (see figure 4) at CITIC Dicastal Co., Ltd. facility in China. In the trial, several sets of process conditions were examined with respect to the Chamber pressure, including typical CPC process conditions and conditions in which the counter-pressure in the die chamber was varied. The data collected from the trial included:

1) Temperature data: Temperature data was obtained from 60+ K-type thermocouples placed within the die, the casting, the cooling channels, on the die surfaces and in the environment surrounding the die.
2) Process data: Various process data related to the control of the casting machine was obtained including the various chamber pressures, the PLC signals controlling die motion – e.g. die open, die locking, die open and casting ejection – and PLC signals controlling the on- and off-timings for the various water-cooling elements.

3) Cast defects: X-ray and CT-based scans were performed on the castings produced under each process conditions to examine for porosity and to also identify the location of the thermocouple placed within the casting.

3. Model methods
A series of models were developed using the commercial finite element package, ABAQUS, according to the methodology described below:

1. Analysis 1 - To begin, a thermal model of the casting process was developed and run until a cyclic steady-state was achieved. The model considered only conductive heat transport and ignored die filling. The model was run sequentially, which involved input of the temperature distribution from the die at the end of a given cycle as the initial condition for the die temperature at the beginning of the subsequent cycle. The process was started by assuming an initial uniform temperature in the die and continued until the variation in die temperature between subsequent cycles was approximately invariant to within a specified tolerance. See the section below for starting initial conditions.

2. Analysis 2 - As the geometry of the die, and correspondingly the geometry of the casting, would be altered under steady-state operating conditions due to thermal expansion (relative to their room temperature dimensions), a single step thermal-stress analysis was undertaken to correct the geometry of the wheel. This was done by importing the temperature field in the die calculated from Analysis 1 and tying the die interface to the casting interface. For this analysis the Young’s modulus of the H13 die material was set to its nominal value, whereas the cast material (A356) was assigned to a low value to decrease the resistance of the die to deformation, thereby allowing the casting to deform to the geometry of the hot die, without significantly impacting on the deformation of the die. The updated, deformed, casting geometry was then re-meshed and subsequently used as the initial geometry of the casting.

3. Analysis 3 - In the final analysis, a fully coupled thermal-stress model was run using the cyclic steady-state temperature field in the die obtained from Analysis 1 as the initial condition for the die, and the updated casting geometry from Analysis 2 as the initial cast geometry. The details of

![Figure 5. Model of a ¼ symmetric section of the casting showing: (a) The original geometry of the die and casting at 25 °C. (Note: the legend does not represent the temperature in this image) (b) The deformed die and the original casting. (Bottom view with the bottom die and bottom plate hidden) (c) Zoom in the square area shown in (b)](image-url)
this analysis have been simplified for the sake of brevity. The model also ignored the die filling stage. This approach allowed the correct contact state between the casting and die -i.e. no gaps or pressure – to be used at the beginning of the steady casting cycle analysis. Moreover, this would allow the coupled thermal-stress model to be able to correctly describe the evolution of the casting/die interface geometry and therefore heat transport across the interface within the casting cycle.

3.1. Geometry and mesh
Figure 6 presents an overview of the model analysis domain and mesh, including the four pillars, the top die, the casting, the bottom die, and the bottom plate. The casting, cooling channels as well as the casting/die interfaces on the die side were seeded in 6 mm increments for meshing, while the rest on the die components were seeded in 10 mm increments. The mesh was changed smoothly between the two regions. The mesh type for the thermal model was the 4-node linear heat transfer tetrahedron (DC3D4), and the mesh type for the coupled thermal-stress model was the 4-node thermally coupled tetrahedron, linear displacement and temperature mesh (C3D4T).

3.2. Part materials and the properties
The casting material was A356 (Al-7Si-0.3Mg), and the die material was H13 tool steel. The thermophysical and constitutive properties of these two materials used in this model were extracted from the literature – see references [4, 6]. These properties include density, specific heat, thermal conductivity, latent heat, Young’s modulus, Poisson’s ratio, thermal expansion coefficient and yield stress.

3.3. Initial conditions
In the thermal only model (Analysis 1), the initial temperature affects the total number of cycles that are needed to achieve cyclic steady-state. To reduce the execution time needed to reach steady-state, initial temperatures of 200, 350, 350 and 300 °C, were imposed on the pillars, top die, bottom die and bottom plate, respectively. The initial temperature of the casting was set to 720 °C in all the analyses. In Analysis 2, which calculated the deformation of the die and casting at beginning of a cycle the initial temperature of the die was set to 25 °C and ramped to a final temperature of the cyclic steady state temperature distribution at the beginning of a cycle. In the coupled thermal-stress model, the initial temperature of the die components was set to cyclic steady state temperature at the beginning of a cycle.
3.4. **Boundary conditions**

The necessary mechanical boundary conditions used in the model are described schematically in figure 7 and were specified based on the installation of the die assembly in the trial. There are three different types of thermal boundary conditions used in the model.

3.4.1. **Surface film heat transfer.** A surface film heat transfer boundary condition was used for the die and casting surfaces that were exposed to the ambient environment either continuously or periodically within a casting cycle. The convective heat flux on surfaces was described using the equation:

\[ q = h(T_{\text{Surf}} - T_\infty) \]  

where \( q \) (W·m\(^{-2}\)) is the heat flux, \( h \) (W·m\(^{-2}·K^{-1}\)) is the surface film coefficient and \( T_{\text{Surf}} \) (K) and \( T_\infty \) (K) are the surface and environment temperatures, respectively.

3.4.2. **Interfacial heat transfer.** An interfacial heat transfer boundary condition was applied in those locations where two surfaces are in contact with each other. The heat flux across the interface was described using the equation:

\[ q = h_{\text{int}}(T_{\text{Surf},1} - T_{\text{Surf},2}) \]

where \( h_{\text{int}} \) (W·m\(^{-2}·K^{-1}\)) is the interfacial heat transfer coefficient (IHTC), and \( T_{\text{Surf},1} \) (K) and \( T_{\text{Surf},2} \) (K) are the surface temperature of the surface 1 and surface 2 at the interfaces of the two components, respectively. For the casting/die interface, a temperature-dependent IHTC was applied in Analysis 1 – the thermal model -see figure 8. In the fully coupled thermal-stress model development, gap size and contact pressure-dependent IHTC was employed in the thermal-stress model development – see figure 9.

![Temperature-dependent IHTC](image8.png)

**Figure 8.** Temperature-dependent IHTC in the thermal model

![Gap size and contact pressure-dependent IHTC](image9.png)

**Figure 9.** Gap size and contact pressure-dependent IHTC in the coupled thermal-stress model

3.4.3. **Water cooling heat transfer.** In the CPC process, the die was cooled by water, and the heat flux within the cooling elements can be described by the equation:

\[ q = h_{\text{CC}}(T_{\text{Die}} - T_{\text{Water}}) \]

where \( h_{\text{CC}} \) (W·m\(^{-2}·K^{-1}\)) is the heat transfer coefficient associated with the water cooling element and \( T_{\text{Die}} \) (K), and \( T_{\text{Water}} \) (K) are the temperature of cooling channel surfaces and water, respectively. Heat transfer within the various cooling elements is complex and may involve boiling-water heat transfer, forced convective-water heat transfer or forced air-convection heat transfer (forced air-cooling is used to purge water from the cooling elements at the end of the cycle). In the model, a temperature-dependent IHTC calculated based on Moayedinia’s work [5] was applied when water was on, and a relatively high IHTC was implemented based on the trial-and-error method when water was off.
4. Results and discussion

Figure 10 shows a comparison between the model predictions (both thermal-only and thermal-stress models) and the experimental data at the approximate locations of TC6, TC10, TC13 and TC21 – refer to figure 11 for locations of the four thermocouples. Figure 12 shows the regions on the casting where the two types of interfaces (gap and contact pressure) are distributed. Starting with the measured data, as shown in figure 10, all of the temperature curves obtained from the experiment show the same behaviour – i.e. a brief period of cooling associated with the die closing, a rapid rise in temperature associated with the liquid metal entering the die followed by a relatively slow decline associated with solidification and cooling of the cast component. Note: also the slight increase in cooling rate at ~253 s when the casting was ejected from the top die associated with the inner die faces being exposed to the ambient environment.

![Figure 10](image1.png)

**Figure 10.** Comparison between model predictions and experiment data at the locations of (a) TC6, (b) TC10, (c) TC13 and (d) TC21.

![Figure 11](image2.png)

**Figure 11.** The locations of the TC6, TC10, TC13 and TC21 in the die (4 views)

Another observation from the measure data was that there was a difference in the time at which the temperature rapidly increases from 30 to 50s. This indicates a difference in the time taken for the metal to
reach the location of a given TC within the die. The difference in time is large and is believed, at this stage, to be due to a combination of the back pressure and inadequate venting in the die.

Turning to the comparison between the model predictions and the measurements, it can be seen that both the thermal model and the coupled thermal-stress model predict temperatures close to the experimentally derived data, with the maximum differences around 10-40 °C. On closer inspection, it can be seen that, for the TC’s located in the contact pressure region (TC6 and TC10), the model predictions matched the experimental data better than for the TC’s located in regions expected to generate a gap (TC13 and TC21) (maximum temperature difference less than 20 °C). Furthermore, for TC6 and TC10, the coupled thermal-stress model fit the empirical data better than the thermal-only model.

For those TCs located in the gap formation region (TC13 and TC21), the prediction results were worse for the coupled thermal stress model indicating that the IHTC needs to be reduced further when a physical gap form. Work is on-going to correlate the IHTC with gap size and contact pressure. A critical assessment of the effects of counter pressure on temperature evolution, defect generation and microstructure will be the subject of forthcoming publications.

5. Summary
A new methodology for developing a thermal-stress model was introduced in the paper, which accounts for the steady, expanded, geometry of the die. With this method, the casting/die interfacial behaviour can be better described. Moreover, a large amount of reliable data was acquired in a series of experiments conducted on a commercial CPC machine. Using this data, a thermal model and a coupled thermal-stress model of the CPC process were established and validated in ABAQUS. The preliminary results indicate that the both models can describe the casting process well. However, due to the fact that the thermal-stress model accounts in detail for the effects taking place during the casting process, it is expected that with further refinement of the gap dependent IHTC it will lead to more accurate results.

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