Multi-scale simulation of hybrid light metal structures produced by high pressure die casting

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Abstract. In modern automotive structural components, metal sheets are combined with casting parts to enable a light and mechanical stable structure. In this study, the bonding between steel metal sheets and aluminium casting parts are performed as part of the high pressure die casting (HPDC) process. In this way additional bonding steps like welding can be omitted, which saves time and energy. The combination of sheet metal and cast is achieved by a structured surface (ribs) of the sheet, which is filled in the casting process with the liquid aluminium alloy and leads to a mechanical connection after solidification. Coupled flow and solidification simulation is used to analyse the hybrid casting process with a focus on the rapid solidification inside the ribs. A high-resolution (mesoscale) simulation of the interface between metal sheet and aluminium alloy during filling and solidification can capture the details of melt flow and rapid solidification. By coupling the mesoscale flow and solidification simulations to multiphase field simulations on the microscale, the resulting microstructure can be calculated. The solidification conditions inside the ribs as result of the mesoscale simulation can be validated by comparing the calculated microstructure with experimental results found in real castings, performed on a cold-chamber HPDC machine.

1. Introduction

High pressure die casting (HPDC) is an important manufacturing process for large, thin-walled structural parts, especially in the automotive industry. HPDC allows the fabrication of complex large aluminium or magnesium parts, which can be more efficient than combining several forged metal sheets by welding. An interesting new application is the combination of aluminium casting and metal sheets in one hybrid casting process step. In this way additional bonding steps like welding can be omitted, which saves time and energy. The combination of sheet metal and cast is achieved by a structured surface (ribs) of the sheet, which is filled during the casting process with the liquid aluminium alloy and leads to a mechanical connection after solidification. The mechanical connection is stronger than glued connections but weaker then welded ones. Important for the connection strength is the complete filling of the structural surface of the metal sheet.

Simulation of the HPDC filling process is challenging due to the very fast and chaotic filling of the cavity with a significant amount of air entrainment. Most commercial simulation programs use a one-phase approach to describe casting processes [1-4] with some special models to approximate the effect of remaining air. In this work a three-phase simulation of casting processes, including the air, melt and solid phases is used. Both, melt and air are considered as compressible fluids separated by a volume-of-fluid approach (VoF), including special treatment to keep the interface sharp. Reduced melt fluidity during the solidification process is handled by a porous media approach to describe the flow through the dendrite network. At a critical solid fraction value, the melt is stopped completely. This approach is
implemented in the commercial casting simulation package STAR-CCM+ [5]. Correct treatment of the air and fast solidification which may result in misruns are seen to be important for the investigation of hybrid casting, since air entrainment and melt solidification before complete filling of the structured metal sheet surface can weaken the mechanical bond between metal sheet and casting.

Details of the simulation approach are given in the following section, followed by a description of the multiscale simulation approach. Section 4 investigates the filling of the ribs using different process configurations. A multiphase field simulation of the resulting microstructure is described in section 5, which allows to validate the solidification conditions given by the mesoscale simulation. All simulation results are summarized in section 6.

2. Theory

Simulation of the entire casting process is based on a finite-volume method using control volumes (CVs) of arbitrary polyhedral shape. The transport equations for mass, momentum, energy, and phase in integral form are applied to each CV, whereby the surface and volume integrals are approximated using the midpoint rule. Linear equation systems for each variable are solved using algebraic multi-grid iterative solvers. Mass conservation, pressure and velocity conservation are coupled via the SIMPLE algorithm. The transient term is discretized based on an implicit Euler-segregated concept. Details of discretization and the solution method are available in [6-8]. The conservation equation for total energy is solved for the solution variable temperature. For solidification modelling, the volume fraction of solidified liquid is determined using a tabulated fraction solid vs. temperature curve \( f_s(T) \). Latent heat \( L \) is released in proportion to the change in fraction solid \( (L*d(f_s(T))/dT) \). Details of the methodology are presented in [8].

For correct calculation of filling including air entrainment, the method used to track the motion of the free surface must provide a sharp interface. The volume of fluid (VoF) approach is used to tackle the problem: the entire fluid domain is considered to be filled by a fluid, the properties of which vary according to the distribution of volume fractions of melt \( C_m \), solid \( C_s \), and gas \( C_g \) \( (C_m + C_s + C_g = 1) \). The transport of melt, solid and gas is computed by solving transport equations for their volume fractions with a source term for the phase change from melt to solid. To achieve sharpness of the interface, a high-resolution interface capturing scheme (HRIC) [8, 9] is used, which typically resolves the interface within one cell.

The normal force due to surface tension is treated using the continuum surface force (CSF) model proposed by [10], which defines a volumetric source in the momentum equation. Flow resistance in the mushy zone is calculated assuming that the mushy zone acts like a porous medium. The fluid velocity resistance in the mushy zone can be approximated as a pressure drop [11]. Permeability can be deduced from the Kozeny-Carman equation [12] as \( K = \frac{(1−f_s)\lambda_2^3}{180f_s^2} \), where \( \lambda_2 \) is the secondary dendrite arm spacing (SDAS).

The viscous porous resistance depends on the velocity of the melt and tends to zero as the velocity approaches zero. Hence, slight creeping of the melt is not hindered, especially if the melt is being pushed by a high force, as in the case of HPDC. To bring the melt to a complete stop, a flow-stop functionality was implemented. If the fraction solid is above a threshold value, the momentum equation is no longer solved for that particular cell. Flow stopped cells are of zero velocity (relative to the cell centre velocity), and fluxes through all adjacent faces are also zero. Pressure remains constant at the value obtained when the cell has been flagged to be stopped. Since the density of the melt depends on temperature, a mass compensation is needed to conserve the total melt mass. The flow-stop-mass-compensation functionality applies appropriate mass and energy sources to compensate for the unphysical mass change in stopped cells and maintains the total mass of each phase.
3. Multi scale simulation of hybrid HPDC processes

The multiscale simulation approach was applied to a hybrid test geometry casted at the foundry institute of the RWTH-Aachen. Figure 1 shows part with gating system, casting and metal sheet. Al-5wt%Mg-1.8wt%Si was filling into the cavity with a casting temperature of 680 °C, a maximal piston speed 1 m/s, die preheating temperature of 200 °C and an intensification pressure of 200 bar on a Buehler H630-SC HPDC machine. The connection between steel sheet and casting is achieved by a rib-structure on the surface of the metal sheet (see high-resolution cut on the left of figure 1). To analyse the filling of the ribs a high-resolution mesoscale simulation is used, which simulates just the ribs area with a fine mesh with cell sizes in the μm range.

The initial and boundary conditions for the mesoscale simulation are calculated using a macroscale simulation of the whole casting process, calculating melt flow, cooling and solidification in a strongly coupled manner. Material data was taken from the STAR-CCM+ metallurgy material database. Figure 2 shows the temperature distribution on the melt during the critical phase of the hybrid process, when the melt fills the casting below the metal sheet. The melt cools down during filling but remains significantly above liquidus temperature. For the mesoscale simulation temperatures around 650°C and velocities between 2 m/s and 4 m/s can be extracted from the macroscale simulation as initial and inlet boundary conditions.

Figure 1. Hybrid HPDC casting with gating system, casting and metal sheet. The metal sheet is connected to the casting by the surface contour of the metal sheet (ribs), which is filled by the melt.

Figure 2. Simulation of the HPDC process coupling flow, temperature and solidification. After ~0.1 s (b) the critical region below the metal sheet is filled. After 0.2 s (c) the melt in the metal sheet area starts to solidify (green line = points at liquidus temperature).
The critical region below the metal sheet was schematically reconstructed for the mesoscale simulation with a round area of ribs with 200 μm width and depth for a systematic analysis of the ribs filling (see figure 3(a)). The round area was chosen to allow a rotation of the rib’s direction relative to the melt flow. Figure 3(b) shows the trimmed fine mesh used for the mesoscale simulation. The ribs are meshed with a cell width of 50 μm. This work focuses on the flow behaviour and not on the mechanical bonding. Therefore, the small inclination of the ribs for the mechanical bonding was neglected. It should have only a minor influence on the flowability, but would increase the numerical effort considerably.

Figure 3. (a) Mesoscale geometry of the region below the metal sheet with 0.2 x 0.2 mm ribs and (b) the trimmed fine mesh. The round shape of the region with ribs gives possibility to use different orientations towards the melt flow direction.

4. Cavity and ribs filling

In figure 4 the filling of the ribs for a filling along the ribs direction is visualized using streamlines coloured with the melt temperature. The melt drops into the ribs and is quickly cooled down below solidus temperature by contact with the cold wall of the ribs. Higher layers of melt remain liquid and can stream out of the ribs again resulting in a chaotic flow pattern near the top of the ribs. The cooling curves given in figure 5 also show a fast solidification of melt deep inside the ribs. At several points inside (negative position, red) and above the rib (positive position, orange) the temperatures are recorded during filling of the ribs (the position of the probe points is shown in the small grey sketch on the right). The temperature of the melt drops below the eutectic temperature with a high cooling rate in the range of 5000 K/s and the melt remains solid during further filling. Melt above the ribs undergoes a much slower cooling with about 200 K/s. After 60 ms the cooling curves show a small jump to higher temperatures (green oval), indicating the starting pressure build up, which presses hot melt deeper into the ribs.

Figure 4. Streamlines showing the movement of the ribs and the temperature of the melt during the filling process after 25 ms.
Figure 5. Cooling curves at different points inside (negative position) and above the ribs (positive position). The small sketch at the right shows the positions of the data recording points.

The effect of the pressure build-up can also be seen in the filling curves of the ribs in figure 6. The ribs are only completely filled after 60 ms, when pressure build-up in the filled cavity presses the melt into the ribs.

Figure 7 shows the influence of process and solidification parameter on the ribs filling. To compare different configurations with different total filling times, the time is normalized to the switching time, when the cavity is completely filled and the HPDC-process switches from filling to pressure build-up. The following configurations are compared:

- Advanced fraction solid curve from MICRESS® calculations (see below) for the solidification of the melt
- Fractions solid curves from Scheil approximation
- 90° rotation of the ribs from orientation along the melt flow to an orientation across the melt flow
- Filling of a 5 mm thick cavity above the ribs, compared to 2 mm in the standard configuration
- Filling with a velocity of 4 m/s

Figure 6. Volume fraction of melt (red) or air (blue) during filling.

Figure 7. Filling of ribs using different fraction-solid curves, process parameters or geometries (broken lines use Scheil approximation).
The multiphase field simulation of the fast solidification (see section 5 below) gives a fraction solid curve with 20 K undercooling leading to a later start of the solidification compared to a Scheil approximation (see figure 8). The simulation using this fraction solid curve shows a slower filling compared to the calculation using Scheil approximation. The later start of the solidification is accompanied with a later increase of the viscosity. This hinders the small pressure build-up found when using Scheil approximation, which presses the melt earlier into the ribs. Consequently, undercooling of the melt, described by the fraction solid curve calculated using MICRESS®, results in a slower filling of the ribs.

Concerning the process settings the following effects on the ribs filling can be observed: The rotation of the ribs by 90° leads to a later filling of the ribs. Melt is more likely to flow across the ribs then into the ribs. The thickening of the cavity above the ribs to 5 mm hinders the pressure build-up above the ribs and significantly reduces the filling of the ribs. Thus, thin castings are more favourable for hybrid casting applications than thick parts. As to expect a higher melt velocity leads to a later filling of the ribs, because melt is more likely to flow across the ribs with a higher velocity.

Table 1 summarizes the effect the different configurations on the filling. The volume fraction of melt inside the ribs at switching time is compared. Clearly changing the process settings has a stronger influence than changes in the solidification parameter. This indicates that a Scheil assumption would be sufficient when different designs and process parameters are being evaluated.

5. Microstructure simulation

The solidification conditions obtained by the mesoscale simulation of the rib filling process were used as initial and boundary conditions for a phase-field simulation using MICRESS® [13, 14] phase-field software in the thin-interface limit with anti-trapping terms [15] and FD-correction [16]. All material data for the three phases (liquid, fcc-Al, MgSi) was evaluated from the thermodynamic database TCA15 via the TQ-interface [17]. Since the individual fcc(Al) and MgSi lamellae are much too fine to be numerically resolved on this length scale, the eutectic was treated as an effective phase with thermodynamically consistent phase fractions and concentrations.

The mesoscale simulation gives a heat extraction rate of 2x10^{11} W/m³ for the cooling inside the ribs. A series of phase-field simulations were performed under systematic variation of cooling and nucleation conditions. Good agreement between experimental microstructure (a) and simulated (b) microstructure was obtained for a nucleation density of 5x10^{16} m⁻³. Since direct temperature measurement of the fast cooling inside the ribs is very difficult if not impossible, comparing the microstructure is a valuable tool to validate the solidification conditions during filling, cooling and solidification of the metal in the ribs as result of the mesoscale simulation.

| Table 1. Filling of ribs using different fraction solid curves or process parameter |
|------------------------------------------|
| Variants | Filling at switching time |
| fs - Scheil | 99 % |
| fs - MICRESS | 98 % |
| Ribs crosswise | 89 % |
| 5 mm thick | 16 % |
| v = 4 m/s | 79 % |
6. Conclusion

Three-phase coupled flow and solidification simulation is used to analyse the hybrid high pressure die casting process combining a metal sheet with the casting. The focus of the investigation lies on the rapid solidification inside the ribs on the metal surface, which are used to create a mechanical bond between metal sheet and casting part. A high-resolution (mesoscale) simulation of the interface between metal sheet and aluminium alloy during filling and solidification can capture the details of melt flow and rapid solidification, using velocities and temperatures of the macroscale process simulation as initial and boundary conditions. By coupling the mesoscale flow and solidification simulations to multiphase-field microstructure simulations on the microscale, the resulting microstructure can be calculated. The good agreement between calculated and experimental analysed microstructure demonstrate that the meso-scale simulations give the solidification conditions inside the ribs correctly.

The systematic investigation of different process configurations leads to the following findings:

- A pressure build-up above the ribs is important for a complete filling of the melt.
- Undercooling of the melt by 20 K (phase-field simulation result) leads to a slower filling of the ribs. The later start of the solidification is accompanied with a later increase of the viscosity and pressure build-up. The latter hinders a fast filling of the ribs.
- Orientation of the ribs perpendicular to the melt flow leads to a later filling of the ribs, since melt is less likely to flow into the ribs.
- Thickening of the cavity above the ribs hinders the pressure build-up above the ribs and reduces the filling of the ribs. This indicates that thin castings are more favourable for hybrid casting applications than thick parts.
- Higher melt velocities lead to a later filling of the ribs, since the melt flows at a higher speed over the ribs rather than into the ribs.

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