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Research Paper

Experimental and numerical study of section restriction effects on filling behavior in low-pressure aluminum casting

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ABSTRACT

The molten metal flow under low-pressure filling was investigated both experimentally and numerically inside sand molds with different cross sections and different pressure ramps. The proposed fluid dynamics simulation predicts quantitatively the observed filling oscillations. An analytical model is developed to link the over-height with the geometrical restriction and the pressure ramp. The calculated over-height is proportional to the ramp and non-linearly impacted by the section change as confirmed by the experimental results.

1. Introduction

As misrun defects are induced by combined thermic, hydraulic and solidification phenomena, they are difficult to predict by applying simple analytical rules. Therefore, to avoid misrun, industrial parts are commonly cast with high superheat and high filling velocity. However, a turbulent filling flow is known to lead to oxides entrapment in the parts. Campbell (2015) indicates that the oxides formation induced by inappropriate mold filling is still a major industrial issue. The bi-films inclusions, by inducing weak zones, deeply reduce the global mechanical strength of the part. To limit the oxides inclusions, Campbell (1991) proposed a maximum velocity criterion, depending on the melt density and on the surface tension. This criterion, independent of the local geometry, gives an upper limit velocity of 0.5 m s^{-1} for aluminum alloys. This upper-velocity limit can be compared to several experimental results. Runyoro et al. (1992), by conducting experimental aluminum gravity castings, tested the relationship between the gate entry velocity and the resulting bending properties. Results showed a clear drop of bending strength when the gate entry velocity was above 0.5 m s^{-1}. Liu et al. (2015) investigated the effect of the pressure ramp on the resulting bending strength of an aluminum plate cast by low-pressure sand casting and found that when the imposed pressure ramp led to velocities above 0.5 m s^{-1}, the bending strength was reduced. Puga et al. (2016) cast an industrial part by low-pressure sand casting with degassed aluminum alloy with different pressure ramps. The microstructural analysis was associated with the mechanical characterization of the final parts. It showed that a higher filling ramp led to more oxide inclusions, inducing more porosity and reduced tensile strength. The critical observed velocity was again 0.5 m s^{-1}. The consistency of those three studies indicates that limiting the melt velocity below 0.5 m s^{-1} is a key factor to improve the quality of aluminum parts, both in gravity casting and in Low-Pressure casting (LPC).

In gravity casting, the molten alloy velocity is mainly dependent on the filling system design, as the flow is not regulated. On the opposite, in LPC, applying a gas pressure above the liquid metal drives the filling. This pressure is gradually increased in the furnace, and the metal is forced to rise through the rising tube towards the mold. The resulting filling velocity is a consequence of the imposed pressure ramp. Therefore, a link between pressure and resulting filling is needed to choose the adapted process parameter. The relationship between velocity and pressure ramp can be obtained analytically under some simplifying hypotheses. By using the Pascal principle, Hogg et al. (1991) proposed an analytical expression of the rising metal height which was proportionally dependent on the gas pressure. By casting a magnesium automotive part in low-pressure sand casting, the study showed that the measured filling height was delayed in comparison with this simple model, suggesting that this discrepancy was due to pressure loss. Liu et al. (2015) proposed a more developed model based on Bernoulli's equation by considering the mold, the rising tube, and the furnace geometry. The gate velocity was hence calculated as a function of the pressure ramp. The model also indicated that the gate velocity was sensitive to section change in the mold cavity. Using this model, Liu calculated a critical ramp of 900 Pa s^{-1} to limit the filling velocity below 0.5 m s^{-1} for a plate, dimensions 200 × 200 × 15 mm, with a section change of factor of 20. The maximum velocity was indicated to be consistent with the simulated flow. However, the model did not predict some filling oscillations visible on the presented filling curves. Fan and Ji (2005) used similar hydrodynamics hypotheses to estimate the filling velocity during the low-pressure casting of a lost foam mold with sudden section reduction of a factor of 0.76. The

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Nomenclature

$\dot{P}_f$	Measured pressure ramp Pa s^{-1}
S_c	Mold cavity horizontal cross section m^2
S_f	Furnace horizontal cross section m^2
S_t	Tube horizontal cross section m^2
h_m	Mold cavity height before section change *m*
h_{tube}	Tube height m
h_t	Total height ($h_m + h_{tube}$) of diameter ϕi_{tube} m
h	Metal height m
Δh	Over-height of metal m
Γ	Slope of the over-height versus pressure ramp m s Pa^{-1}
ϕ_c	Mold cavity diameter m
ϕ_f	Furnace diameter m
ϕi_{tube}	Tube internal diameter m
ϕe_{tube}	Tube external diameter m
P_f	Measured air pressure in the furnace Pa
P_c	Set air pressure in the furnace Pa
P_a	Atmospheric air pressure Pa
R	Section restriction factor in the mold cavity (S_c/S_t) −
ρ	Alloy density kg m^{-3}
g	Standard gravity m s^{-2}
α	Section restriction factor between tube and furnace (S_t/S_f) −
v	Melt velocity in the tube m s^{-1}
v_c	Melt velocity in the mold cavity m s^{-1}

experimental metal height evolution did not show clear oscillations and was in good agreement with the analytical model. Zeng et al. (2009) used the momentum principle and proposed a nonlinear second order equation to simulate the counter-gravity filling dynamics. This study suggested that under some process conditions, which were not detailed in the research paper, the filling velocity had an oscillating behavior. These oscillations were observed to be lower when the viscosity of the melt was higher. Puga et al. (2016) studied two different pressure ramps applied to an industrial aluminum component. These works showed qualitatively that a higher-pressure ramp led to higher fluid velocity. However, the analysis of the presented curves did not reveal clear oscillations. Therefore, the analytical link between filling parameters and resulting filling flow is still unclear. As filling oscillations were observed in some studies and not in others, the origin of this phenomenon is not identified yet.

In previous numerical simulations, different geometry simplifications were considered in order to model the LPC system. Puga et al. (2016) considered the whole LPC furnace: the metal in the mold, the rising tube and the furnace and the pressurized gas in the furnace. Under these assumptions, they determined the appropriate pressure evolution to limit the flow velocity. However, the comparison between experimental and simulated filling velocities was not investigated. Considering also the whole furnace, Viswanath et al. (2017) simulated the low-pressure filling of a part with water for different pressure ramps. The comparison of their simulations results with experimental filling video sequences showed large filling time differences, which were attributed to the pressure regulator discrepancies. Liu et al. (2015) only considered the metal in the rising tube and the mold. The experimental flow characterization by X-ray radiography was observed to be qualitatively consistent with the flow simulation results. Kuo et al. (2001) simulated only the mold to adjust the pressure evolution when casting an industrial die-cast wheel. However, no comparison between experimental and numerical filling was proposed. Moreover, as only the mold was taken into account, several hypotheses had to be made to link the gas pressure in the furnace with the metal boundary condition at the tube and mold interface. Duff (1995) proposed to consider that the filling follows the Bernoulli's equation by neglecting both dynamic pressure and pressure losses. Experimental and numerical filling of a die-cast aluminum wheel by LPC were compared. The experimental filling dynamics was not correctly predicted using a velocity boundary condition, but the simulation results were improved when considering a pressure boundary condition instead. However, some experimental points were delayed close to 1 s compared to the simulation of a total 8 s duration. No clear assessment of the effect of each considered geometry on the fluid flow simulation in LPC was encountered.

As it can be seen from the above survey, keeping the velocity of the fluid below 0.5 m s^{-1} is a key factor to obtain suitable mechanical properties. As pressure is used as a setting parameter in LPC process, a

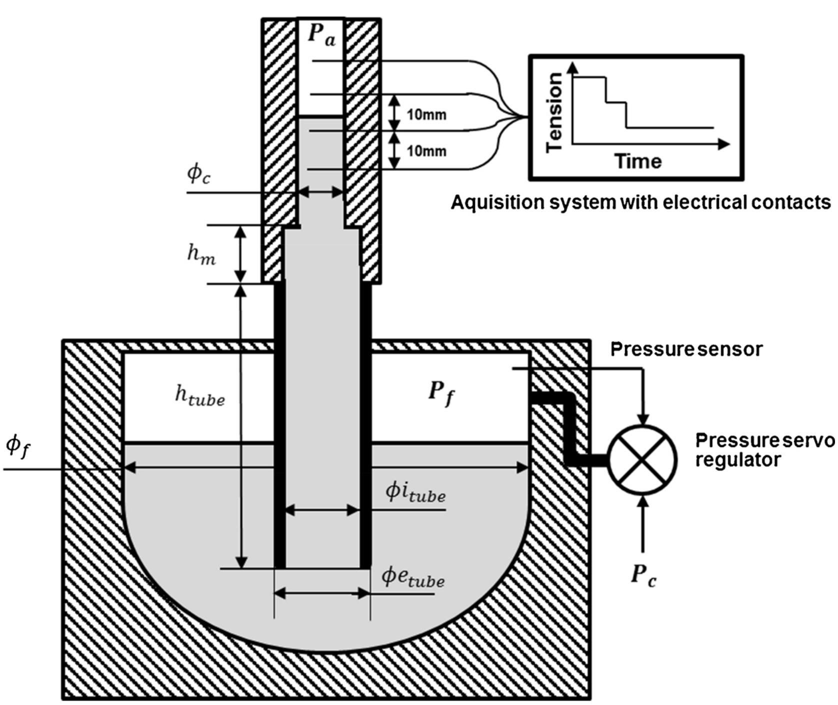

Fig. 1. Vertical cross section view of the Low-pressure casting system and instrumented sand mold.