FEM SIMULATIONS FOR THE OPTIMIZATION OF THE INLET GATE SYSTEM IN RAPID INVESTMENT CASTING PROCESS FOR THE REALIZATION OF HEAT EXCHANGERS

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Abstract

Over the last decades, additive manufacturing (AM) has become the principal production technology for prototypes and components with high added value. In the production of metallic parts, AM allows producing complex geometry with a single process. Also, AM admits a joining of elements that could not be realized with traditional methods. In addition, AM allows the manufacturing of components that could not be realized using other types of processes like reticular structures in heat exchangers. A solid mold investment casting that uses printed patterns overcomes typical limitations of additive processes such as expensive machinery and challenging process parameter settings. Indeed, rapid investment casting provides for a foundry epoxy pattern reproducing the component to exploit in the lost wax casting process. In this paper, aluminium radiators with flat heat pipes seamlessly connected with a cellular structure were conceived and produced. This paper

aims at defining and investigating the principal foundry parameters to achieve a defect-free heat exchanger. For this purpose, different device CAD models were designed, considering four pipes' thickness and length. Finite element method numerical simulations were performed to optimize the design of the casting process. Three different gate configurations were investigated for each length. The numerical investigations led to the definition of a castability range depending on flat heat pipes geometry and casting parameters. The optimal gate configuration was applied in the realization of AM patterns and casting processes

Keywords: rapid investment casting, lost wax casting, heat exchangers, FEM

Introduction

With the evolution of manufacturing methods, new design choices become possible due to the state of the art advance of several engineering components production processes. Additive manufacturing (AM) is a new technology developed in the latest years and now available for functional metallic parts production.

Despite initially applied for visualization prototypes, its application increased with the exploitation of advanced

metallic materials such as stainless steel,^{5,6,19,25,47,58} titanium alloys,^{41,54} aluminium,^{29,44} and nickel-based alloys.¹⁸ Within 10 years (2003–2013), the direct part production passed from 3.9 to 34.7% of the AM total product and service revenue.¹⁰ Directed energy deposition (DED) and powder bed fusion (PBF) are the principal processes exploited to fabricate metallic parts with AM. The former provides for in situ delivery of metal through powder or wires in addition to a focused energy source. In the latter, a powder bed is selectively melted to produce a 3D layer by layer structure. Usually, an electron or laser beam is exploited as the thermal source. However, selective laser melting (SLM) for PBF allows high design freedom and

production of 3D objects with demanding geometries.^{34,40,49,50}

Wire and arc additive manufacturing (WAAM) is a DED-AM process fed by a metallic wire which is relatively simple and low cost compared to other AM methods.¹² However, it involves severe residual stresses because of the high deposition rate and heat inputs.¹⁴ Also, the high energy and wide heat-affected zone produced by the WAAM afflict the metal deposition in the micro-scale level, concerning the powder-based methods.²⁰ However, besides few studies,^{39,46,56,57} a thorough understanding of the thermal history along with mechanical and surface properties as a function of the process conditions lacks is lacking.³⁶

The application of AM for heat transfer devices is of great interest allowing miniaturization and performance improvement. The latter may be achieved with the realization of complex designs, capillarity structures, channel arrays, and more. However, many challenges in engineering AM processes must still be faced to achieve workpieces free of defects and high-quality features to match the tight standards required for engineering applications.⁴⁵

Common AM component defects include discontinuities, porosity, highly textured columnar grains, complex phases, and compositional variations.¹¹ However, most of the features inherited from the manufacturing process can be reduced by post heat treatment like hot isostatic pressing (HIP).^{21,28,31} Nevertheless, porosity production is still a major problem during AM of aluminium alloys.^{8,9,33,52} In WAAM, the metal suffers a complex thermal process and anisotropies within the microstructure and, therefore, in the components properties.^{27,58}

Proper management of the process parameters, e.g., temperature gradient, solidification rate, alloy composition, thermal cycles and high cooling rate, hinder the anisotropies.^{24,59} The SLM process parameters and building strategy also have a broad influence on the structure of the part and, thus, on the mechanical properties. Hence, they must be specifically selected for a given combination of material, geometry and size. In general, a rapid cooling rate produces high residual stresses and fine microstructure. In the powder bed condition, this leads to the creation of porosity. Also, the orientation of the components during the SLM processes exert an influence on grain growth and surface texture.^{43,48} Properties such as density and surface roughness are fundamental as they noticeably affect the heat transfer. Generally, solidified grains present textured large columnar grains tough with equiaxed grains close to the melt pool surface.^{1,23,30,55,63}

The morphology transition within the solidification phase is governed by the ratio of thermal gradient G on the kinetics of mass transfer R rule. Several grains

configuration can be achieved through the process parameter managements, from equiaxed dendritic to planar. These concerns are valid all the more reason when considering thin-walled components.⁶⁰ The smaller the 3D structure thickness, the higher is the defects and morphology influence on their properties.

Aluminium flat thin pipes find several applications in different sectors such as automotive, aeronautics, conditioning, and heat exchange applications. Up to now, a typical production process of hollowed flat aluminium pipes is continuous extrusion. However, several limitations like expansive production costs and billet pre-treatment requirements afflict this manufacturing process. Also, the welded pipes produced cannot be exploited for high-pressure liquid containment.⁶¹ Instead, flow forming (FF) is a forming process exploited to produce seamless thin-wall tubes from thermally treated preformed tubes prepared by extrusion or forging processes.^{13,35,37} A challenging multiple parameters setting is required for the FF process, which being a dynamic process requires demanding management. Thus, the variables are often set based on engineers' experience and practice. However, the flow-formed pipes can respect the higher standards in specific strength, geometrical tolerance and surface roughness.⁴²

A lately proposed rapid investment casting (RIC) overtake both the limitation of AM and casting. It provides for the 3D printing of meltable models made by foundry resin exploited for a casting process. It has already been proved how this methodology is valuable for metal foams and reticular structure production with outstanding results.^{2,4,62} It is mainly due to the peculiar conformation of the metallic cellular structures, which offer a wide exchange surface.⁷ Indeed, metal foams have already been applied in heat exchange prototypal devices.^{3,22,32,38} In heat exchange devices, this is important as such the contact between these surfaces and flat heat pipes.

Through RIC, it is possible to integrate metallic reticular structure branches within the tube wall bulk in the fundable model. The devices produced by foundry processes will feature a seamless connection between heat pipes and heat exchange surface that improve the heat dissipation performance. The main concerns regard the thickness of the flat tubes achievable with the foundry processes as even modest defects on the thin-walled structure would compromise the device's functionality.

The finite element method (FEM) help to prevent flaw that may arise during the metal casting.^{15–17,26,51,53} Huang et al.²⁶ optimized a casting process through numerical simulations of the gating system for precision 17-4 PH stainless steel rotor used for hemodialysis machines.

Both flow turbulence and inadequate supply and internal shrinkage can be reduced through appropriate numerical

investigation. Fang et al.¹⁷ investigated the preliminary design in investment casting of an exhaust manifold using a numerical analysis with FEM investigation. The results of numerical simulations highlighted the eventuality to optimize and redesign the parameters involved during the casting process. Also, the results obtained were checked and confirmed by the actual production and testing of the exhaust manifold.

The study aims at defining the main foundry parameters to achieve an aluminium radiator free of defects, with flat heat pipes seamlessly connected to a cellular structure. CAD models of the device were produced, considering four different pipes thickness and length. Also, a numerical simulation was performed to design the casting process and avoid defects. The CAD patterns were manufactured through 3D printing and cast with the RIC processes. Numerical investigation and experimental work led to the definition of a range of process parameter values for which the process is feasible, which depends on the geometry of the flat heat pipes.

Materials and Methods

Different radiator models made of AC-44300 aluminium alloy (Table 1) with a different height (20,40,60,80 mm) were designed and realized. Their geometry was produced through Solidworks. Initially, a 2D sketch with four different pipe thicknesses (0.5, 1, 1.5, 2 mm) was realized, as shown in Figures 1 and 2.

The different models are shown in Figure 2. An XFAB 2000 DWS stereolithographic 3D printer was exploited for the realization of the patterns with a photosensitive resin (FUSIA 444) (Table 2). The reticular structure allows a printing process without external supports. The patterns printed were polymerized for 1 hour in a UV oven. Figure 3 depicts the foundry patterns used for the casting process.

Table 1. EN 44300 Chemical Composition %

Elements	min	max
Si	10.5	13.5
Fe	0.45	0.90
Cu	0.08	
Mn	0.55	
Zn	0.15	
Ti	0.15

Figure 1. 2D sketch of the obtained radiators with different pipe thicknesses.

Figure 2. CAD models of the radiators. Different heights of the pipes are, respectively: (a) 20mm; (b) 40mm; (c) 60mm; (d) 80mm.

Table 2. Characteristics of Photopolymer FUSIA 444

Technical characteristics of the liquid material	
Environmental values for Use	22-27 °C-max RH 40-60%
Appearance/Color	Liquid/Yellow
Viscosity	300–600 MPa·s at 25 °C
Density	1.08 g/cm ³
Technical characteristics of the resin after UV curing	
Surface hardness	56–63 Shore D
Flexural strength	10–16 MPa
Flexural modulus	240–270 MPa
Elongation at break	6–11%
Tensile strength	6–13 MPa

The plaster mould was produced by mixing plaster powder and water at 25 °C for 30 minutes. The exploitation of a vibrating platform and a vacuum machine after the stirring avoid air inclusions. The expendable pattern is plunged in the plaster suspension in a foundry cylinder. The application of a thermal cycle consolidates the mould structure and allows the removal of the pattern (Figure 4).

The casting process was analyzed through numerical simulation performed with inspire cast. The investigation aim

Figure 3. Resin model of the radiators with 60 mm pipes, (a) upper side view, (b) front-side view.

Figure 4. Thermal cycle imposed to the plaster mold.

was to prevent defects such as shrinkage cavities and porosities. These defects depend on several factors like a non-uniform temperature gradient during metal solidification and cooling, the cooling conditions, component geometry and feeding gate placement. The influence of casting location on the tree is not considered because the foundry machine uses a cylinder with a diameter of 120 mm that not allows the assembly of multiple patterns with these sizes.

The casting process is governed by a few relationships: mass conservation, Navier–Stokes equation, energy conservation, volume-of-fluid function (VOF) and $k - \epsilon$ equations. The former is crucial to calculate the mass conservation during the metal flow in the feeding phase and expressed as follow:

Table 3. Mesh Characteristics of Each Model

Model	Number of nodes	Number of elements
20mm pipes	191650	798042
40mm pipes	340246	1411500
60mm pipes	482963	1995573
80mm pipes	634799	2633214

Table 4. Boundary Conditions Used During Simulations

Boundary conditions	Value
Molten metal temperature [°C]	730
Plaster mold preheated temperature [°C]	580
Casting time [s]	0.5

Figure 5. Gate positioning on the 60mm pipes height model: (a) One inlet gate; (b) Three inlet gates; (c) Two inlet gates (lateral gate is near lowest thickness pipe); (d) Two inlet gates (lateral gate is near highest thickness pipe).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}) = 0, \quad \text{Eqn. 1}$$

where ρ is the fluid density, t is the time and $\bar{u}$ the velocity vector. The Navier–Stokes equation allows evaluating pressure and velocity fields:

$$\rho \frac{\partial \bar{u}}{\partial t} + \rho \bar{u} \cdot \nabla \bar{u} = -\nabla P + \mu \nabla^2 \bar{u} + \rho \bar{g} \quad \text{Eqn. 2}$$

with P as the pressure, $\bar{g}$ gravitational acceleration and μ dynamic viscosity of the molten metal. The energy conservation equation allows the temperature field

Table 5. Simulation Time for the Various Gate Configurations and Pipe Length Analyzed

Pipe length Gate configuration	Simulation time [min]			
	20 mm	40 mm	60 mm	80 mm
1 Upper Inlet	60	100	157	238
3 Upper Inlet	56	140	198	228
1 Upper 1 Lateral Inlet LH	42	92	150	212
1 Upper 1 Lateral Inlet RH	46	88	136	194

calculation and, consequentially, the solidification process management, with the following formula:

$$\rho \frac{\partial H}{\partial t} + \rho H \nabla \cdot \bar{u} - \nabla \cdot (k \nabla T) - q = 0, \quad \text{Eqn. 3}$$

where H is the enthalpy and q the volumetric heat flux. For the determination of the molten metal patterns, the volume function equation was used and combined with Navier-Stokes, written in the form:

$$\frac{\partial F}{\partial t} + \bar{u} \cdot \nabla F_v = 0, \quad \text{Eqn. 4}$$

where F_v is the volume-of-fluid function, which is set to 0 when the calculation cell is empty, otherwise to 1. A $k - \varepsilon$ turbulence model was used to define the turbulence parameters :

$$\frac{\partial k_e}{\partial t} + u_j \frac{\partial k_e}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(u + \frac{u_t}{\sigma_k} \frac{\partial k_e}{\partial x_j} \right) \right] + P_{ke} - \varepsilon \quad \text{Eqn. 5}$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(u + \frac{u_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) \right] + C_{\varepsilon 1} P_{ke} \frac{\varepsilon}{k_e} - C_{\varepsilon 2} \frac{\varepsilon^2}{k_e}, \quad \text{Eqn. 6}$$

where u_j represents velocity components in the corresponding direction, ε is the dissipation rate of turbulence kinetic energy, k_e is the turbulence kinetic energy, σ_k is the Prandtl number corresponding to turbulence kinetic energy and σ_ε the Prandtl number corresponding to the dissipation rate. The term u_t is the turbulence eddy viscosity, defined as follows:

$$u_t = \frac{\rho C_\mu k_e^2}{\varepsilon} \quad \text{Eqn. 7}$$

The values of the constants used in the turbulence model were $C_\mu = 0.09$, $\sigma_k = 1.00$, $\sigma_\varepsilon = 1.30$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$. Equations 1–7 describe the physical model of

Figure 6. Filling of the 40mm pipes model at $t = 0,2$ s for each gate configuration: (a) One inlet gate; (b) Three inlet gates; (c) Two inlet gates (lateral gate is near lowest thickness pipe); (d) Two inlet gates (lateral gate is near highest thickness pipe).

Figure 7. Micro-porosity analysis for the 60 mm pipes model at the end of solidification for each gate configurations: (a) One inlet gate; (b) Three inlet gates; (c) Two inlet gates (lateral gate is near lowest thickness pipe); (d) Two inlet gates (lateral gate is near highest thickness pipe).

the molten metal dynamic solidification. Inspire cast solves these equations through a domain discretization (meshing) and a finite element method (FEM) approach. This kind of approach, differently from finite difference method (FDM) one, has a higher accuracy. However, this means higher simulation time, since it is harder to reach convergence each step.

The porosities in the aluminium alloys can derive from contraction phenomena or gas entrapment. The model used for the porosities and shrinkage prediction follows the Niyama criterion, which is used only for the porosities caused by the contraction of the metal during the solidification. The threshold value of the criterion is determined

experimentally for each alloy, and the value N_y is calculated with the following equation:

$$N_y = \frac{G}{\sqrt{R}} < C_{Niyama}, \quad \text{Eqn. 8}$$

where G denotes the local temperature gradient of interest (K/m); R is the cooling rate; and C_{Niyama} is the threshold value of the Niyama criterion. A tetrahedral mesh was used for the simulations. Table 3 shows the number of nodes and elements generated for simulation processes. Boundary conditions for each simulation are defined in Table 4

The working volume of the foundry machine used and the dimensions of the components represent a limit that is

Figure 8. Porosity analysis for the 60 mm pipes model at the end of solidification for each gate configurations: (a) One inlet gate; (b) Three inlet gates; (c) Two inlet gates (lateral gate is near lowest thickness pipe); (d) Two inlet gates (lateral gate is near highest thickness pipe).

considered in the FEM simulations. This condition has determined the orientation of the components inside the cylinder in axis and not inclined. Indeed, the gates were assumed as perpendicular to the casting. The diameter of the gates was adopted constant in accordance with previous experiments. The diameter of gates was chosen to allow during the filling phase to avoid solidification. The cavity feeding process last 0.5 s, according to experimental evidence that highlight how this value limits the formation of cold joints. Then, inlet gates with a radius of 1.6 mm were placed into the model considering different configuration, as shown in Figure 5. In particular, the different layouts analyzed have:

- One inlet gate placed on the upper face of the model;
- Three inlet gates placed on the upper face of the model;
- Two inlet gates placed, respectively, on the upper and lateral face of the model near the lowest thickness pipe;
- Two inlet gates placed, respectively, on the upper and lateral face of the model near the highest thickness pipe.

Sixteen scenarios were investigated for each pipe length and each inlet gate configuration. The best configuration was exploited for the actual casting process.

Table 6. Simulation Time for the Various Gate Configurations and Pipe Length Analyzed

Pipe length	Solidification time [min]							
	20 mm		40 mm		60 mm		80 mm	
Gate configuration	Start	End	Start	End	Start	End	Start	End
1 Upper Inlet	273,59	296,84	284,33	317,12	334,81	376,20	380,39	429,04
3 Upper Inlet	274,94	298,04	285,33	317,61	335,19	376,92	380,23	429,68
1 Upper 1 Lateral Inlet LH	275,05	297,50	284,47	316,31	335,81	376,59	380,97	428,23
1 Upper 1 Lateral Inlet RH	274,53	298,06	284,32	317,19	334,81	376,42	380,04	429,61

Results

Table 5 reports the simulation time for each gate configuration and pipe length. The scenario with the highest time provides for, on average, three inlet gates.

Figure 9. Resin models realized with the three upper inlet gate configuration chosen from the numerical simulations.

Therefore, an analysis was carried out to evaluate the trend of mould filling over time. The pipes length does not affect the mould filling; on the opposite, the inlet gate configuration has a significant impact. Figure 6 shows the molten metal state after 0.2 s for the 40 mm model. The cavity filling begins, for the configuration with a single inlet gate, in the central pipes (1–1.5 mm), where the metal reaches the bottom part of the mould. Indeed, these are the closest elements to the inlet gate. Three inlet gate led to a homogenous flow which distributes the metal evenly between the four pipes. This condition allows a reduction of the micro-porosities expected in the connection of the molten metal fronts. The configurations with the two gates have similar behavior concerning the central pipes. However, differences arise due to the different metal fronts produce by the cavity feeding. With the gate on the thinner

Figure 10. Scheme of casting furnace arrangement.

Figure 11. AC-44300 samples with the different pipe length obtained.

tube, (c) configuration, the metal front connection occurs in the 1 mm pipe while in (d) in the 1.5 mm conduit. The molten metal fluxes conjunction area must be carefully considered, since affecting the casting process. High-velocity vectors may produce mold erosion and the embedding of plaster within the final structure. These latter considerations can be extended to the different pipe length. Figures 7 and 8 show, respectively, the micro-porosity and porosity analysis for the 60 mm pipes model at the end of solidification for each gate configuration. A single and the three inlet gate configurations allow achieving a casting without microporosity; on the other hand, two inlet gate produce micro porosities located in the pipes with a higher thickness (1.5 and 2 mm). It is of particular relevance in the last configuration. Figure 8 shows the porosity distribution examined through the Niyama criterion. Except for the last scenario, (a) (b) and (c) configuration have a critical zone between 1.5 mm pipe and the reticular structure. In (d), the porosity is focused between the 2 mm pipe and the reticular lattice, with a small point delocalized near the 0.5 mm tube.

Table 6 shows the solidification phase duration for the different gate configuration and pipes length. The filling period was imposed in the simulations to avoid cold joints during the filling process. Therefore, there are no notable differences in the solidification time between the various gate configurations evaluated.

In the light of the numerical analysis results, the configuration with three upper gates was selected for the actual casting process. The patterns were connected to the inlet gating system, and the casting realized with a foundry machine ASEG Galloni G5. The foundry process was realized in an Argon atmosphere while the metal injection in a vacuum condition. Following the casting process, the plaster was removed from the cylinder after 6 hours of cooling (Figure 9).

Figure 10 shows a scheme of casting furnace arrangement. Figure 11 shows the samples realized through the RIC process. The components realized are free from defect and macro-structural problems. The specimens exhibit accordance between the critical zones identified during numerical simulations, which validate the accuracy of the numerical model.

Conclusions

RIC is considered a very interesting process in the industrial field as it allows to have the advantages of the realization of complex shapes (typical of Additive Manufacturing processes) combined with lower realization costs related to foundry processes. During the design phase, it was possible to realize the interconnected thermal exchange structures (with thermal contact resistance for null hypotheses) with thermal vector elements (tubes).

During the printing phase, the limits have been the realization of models with 80 mm of pipes in how much the resin introduces a stiffness that on objects of this dimension it tends to deform and therefore to make to fail the process. The comparison between the results of the simulations and the samples carried out showed that the differences due to the melting process correspond, allowing the results obtained to be considered valid for the process design phase. Future developments related to this experimentation could be to develop a single module that constitutes a working model to evaluate the thermal performance of components made by RIC.

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