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RESEARCH PAPER

Design methodology for variable shell mould thickness and thermal conductivity additively manufactured

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Abstract

Additive manufacturing (AM) is said to be the fourth industrial revolution disrupting the manufacturing industry. A focus on the foundry industry's need, more specifically the sand casting process, is done. The usage of additive manufacturing in this field necessitates a different mould design approach. Indeed, it is important to take advantage of AM and the advantages of casting. The fabrication methodology of the mould is binder jetting technique. The almost limitless design possibilities of additive manufacturing are applied to sand moulds for metal casting. A new methodology to optimise the design of sand moulds is proposed. This optimisation reduces the amount of sand to the minimal need, which corresponds to a shell. The shell is then parametrised to have a specific cooling rate. In this case, the cooling speed can vary via a modification of the coefficient of thermal conductivity and shell thickness. The cooling speed is correlated to the dendrite arm spacing, which determines the mechanical properties such as ultimate tensile strength and hardness. Simulations of the cooling support the mould design methodology.

Keywords Additive manufacturing · Casting · Binder jetting · Sand mould · Optimisation · DFAM

1 Introduction

Additive manufacturing, adding material layer upon layer, is a relatively new technology that has yet to make a big impact on the foundry industry. Foundry is the art of pouring liquid metal in to the mould cavity and allowing the molten metal to cool down to room temperature in a controlled environment. Often, chills are placed into the sand mould to have preferential cooling in certain places.

The mould is a massive block of sand with an imprint in it. The sand casting process traditionally uses a template and loose sand mixed with a binder to create that imprint. The sand is pressed around the template, and then the binder is activated to set the sand solid. The template is then removed, which creates manufacturing constraints. Other fabrication techniques are possible.

The imprint can be a milled out of a block of sand or it can be realised with a die. Such tool can be found in the disamatic process or shell casting, see Fig. 1. In some applications, sand is replaced with a material that melts at a higher temperature than the casted metal. Die casting can be fabricated with conventional techniques such as milling and the more innovative process of selective laser melting (SLM). SLM has the advantage of producing complex structures with internal cooling channels, yet the dimensional tolerances of ± 0.1 mm do not seem to meet the criteria of die casting which requires tolerances of ± 0.05 mm. Improvements can be made at the machine level, such has improving the melting process or at the shot-peening finishing step [2].

Design for additive manufacturing (DFAM) is a relatively new topic as additive manufacturing is only 30 years old. In DFAM like Ponche et al. said, "The purpose is not to limit geometry by an initial idea of the part shapes, but to define it only from the manufacturing process and the functional specification." [1]. Although in this case, we are not optimising the final part geometry, but the tool. The tool geometry is partially set as we want to build a specific part geometry. This approach is

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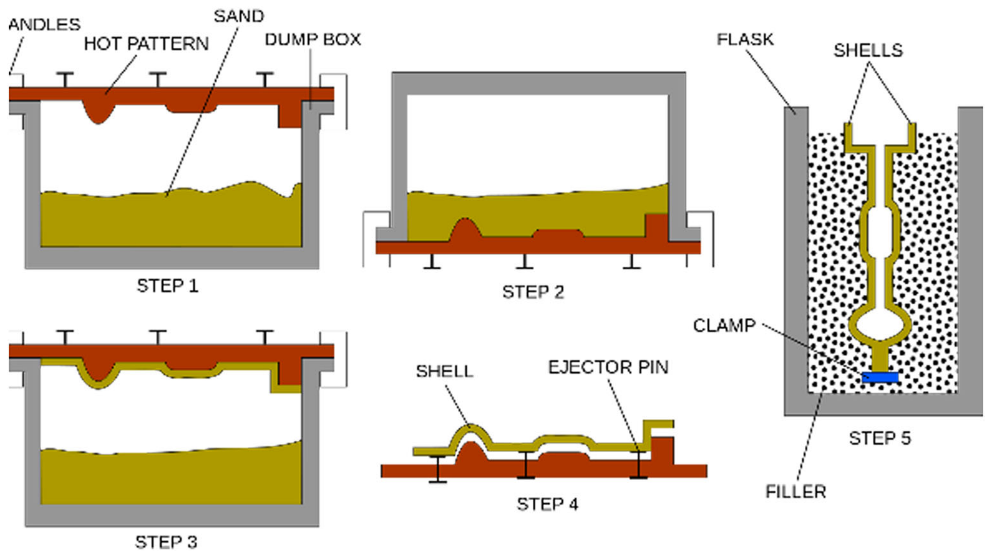

Fig. 1 Schematic of the shell moulding process [1]

also known as indirect additive manufacturing as AM's purpose is to manufacture a tool [3].

The proposed methodology is analogous to the existing shell moulding practice. The novelty is in the design methodology of the shell and the criteria surrounding the dimensioning. The purpose of reducing the thickness of the mould is to reduce the amount of time it takes to manufacture such a mould via additive manufacturing, to reduce the cost by minimising the material consumption and to have a total control of the solidification rate of the casted alloy to improve the quality.

The innovative process of varying the mould's properties according to the desired local mechanical properties is proposed. A link is made between the part's geometry, metal's properties and process's parameters, to the dendrite arm spacing, which is linked to the mechanical properties.

Having a constant thickness for the shell could yield to differences in the thermal dissipation of the mould during cooling. A heterogeneous dendrite arm repartition may result when thickness is constant.

The shell thickness is dimensioned according to a specific cooling rate. The cooling rate depends on the thickness of the casted part, the part's dimensions and the mould's thermal and geometrical properties. The thicker the part is, the slower it will cool down as more energy needs to be transferred to the mould.

Because the parts may have a complex geometry, it may cool at different speeds at different location. It is consequently important to help the part dissipate the heat at a constant rate throughout. A constant rate is less prone to casting defects.

The speed at which the casting solidifies determines the quality of the mould. The quality of the metallic part is defined by its mechanical properties such as the ultimate tensile strength or hardness. Those mechanical properties depend on the grain size, more specifically the dendrite arm spacing. Indeed, the faster the cooling, the smaller the dendrite arm spacing gets. The metal gets stronger and harder as the dendrite spacing gets smaller. It is therefore important to be able to have small dendrite arm spacing.

In this case, the additively manufactured mould consists of a shell that has the required mechanical properties to hold itself. Backing material can be placed behind the structure in order to retain the shape. The backing material can be metal pellet, gravel, loose sand or sand with binder, a curing step may be necessary in that case. The flask and the backing material should be modelled as well during the optimisation.

A feedback loop during the mould optimisation is required. The optimisation involves multiple casting simulations and stress parametric optimisations, which result in a mould with desired mechanical and thermal properties automatically. Simulation of the casting is therefore important in the mould design.

2 State of the art

The repartition of isotropic material is organised in three different categories, parametric, shape and topologic optimisation according to the work of Bendsøe and Sigmund in the book *Topology Optimization: Theory, Method and Applications* [4]. The parametric optimisation, the work of this paper, is the science of dimensioning the part size in function of the constraints. The trusses as shown in Fig. 2, in this case, will vary in size according to the constraints. The compliance can be peak stress, deflection or some other physical characteristics. Parametric parameters such as the dimensions (e.g. length, height or thickness) or properties (e.g. thermal conductivity) can be varied. The shape optimisation has the notion of a design space. The shape has design and non-design space. In shape optimisation, the overall shape is optimised in order to

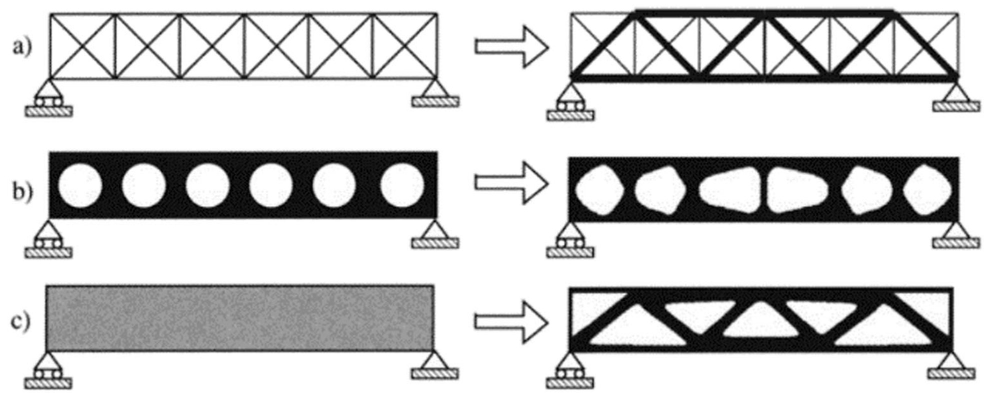

Fig. 2 Three categories of structural optimisation [4]

get a uniform stress distribution. This feature attempts to eliminate stress concentration. Topology optimisation has the most design freedom. A design space is defined to let the algorithm add or remove material and a non-design space in which the material cannot be removed or added. This optimisation often results in the best complaint structure [4].

This investigation differs from the work of Chhabra and Singh who have done in 2011 a study on the feasibility to reduce the shell mould wall thickness fabricated with a ZCast rapid brass casting solution. The thickness of the wall started at 12 mm and a minimum castable wall obtained was 2 mm. The results indicated a reduction of fabrication time by 56.45% while keeping dimensional accuracy corresponding to standard UNI EN 20286-I (1995) [5]. However, the cooling speed and the mechanical properties were not observed.

Sun et al. in 2012 have done a correlation between the wall thickness and the mechanical properties of SR-modified A356 aluminium. Three different types of sands, quartz, alumina and chromite sand were tested in order to analyse their effects on the final casted part. The wall thickness of the mould was changed in order to observe the effects on the mechanical properties. The sand cooling capacity depends on the thermal conductivity and heat capacity. The results indicate that it is in fact possible to predict the final mechanical properties and to reverse calculate the dendrite arm spacing measurements. It is reported that a faster cooling speed induces a smaller grain size, smaller dendrite arm spacing and smaller size of eutectic silicon particles. The cooling speed is indeed correlated to the wall thickness and to the thermal coefficient. Chromite has fastest cooling speed compared to the three tested sands. The wall thickness ranged from 8 to 40 mm. The dendrite arm spacing and elongation depend on the type of sand used. A different regression equation has to be used according the type of sand used [6]. The type of binder and its influence is not mentioned in the article. The article also did not focus on the efficiency aspect of reducing the wall thickness.

The work done by Lušić et al. in 2015 on ABS mould for vacuum casting indicated that an optimisation on moulds is based on the criterion of a deformation limit. This reduced the amount of material needed in the design of a 3D printed tool. The following diagram (Fig. 3) indicates that a structure does need intelligent design in order to reduce the weight and keep an acceptable deformation [7].

This optimisation not only reduces the amount of material consumed, but it also reduced the amount of time needed to build it. Furthermore, a study on the effect of the internal structure design of a cross structure vs. a honeycomb structure is done. The material consumption was roughly the same for

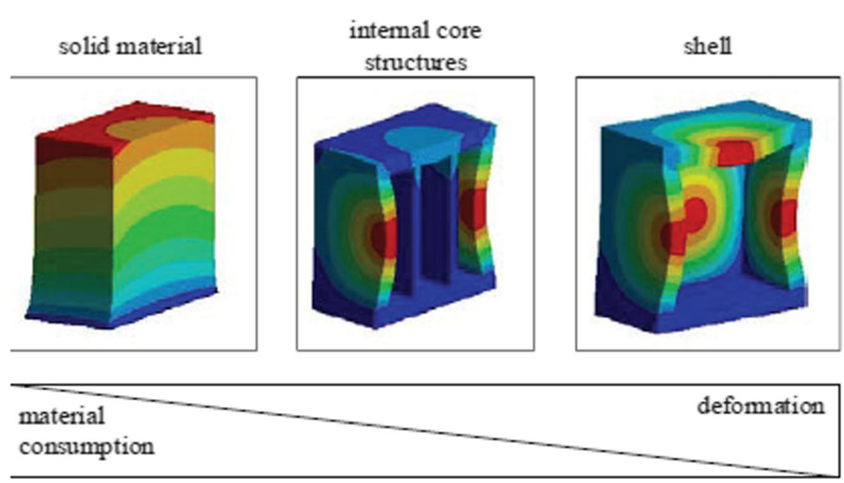

Fig. 3 Minimisation of mass with deformation constraint [7]

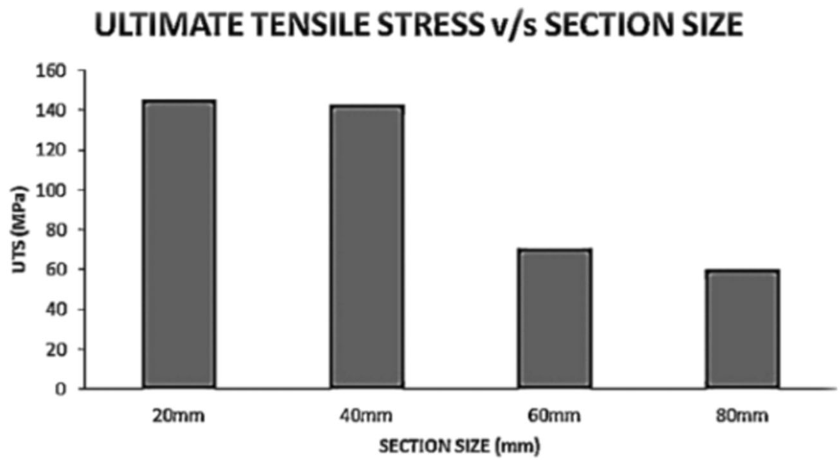

Fig. 4 Ultimate tensile stress of cast component [9]

the same build parameter of internal thickness of 1 mm and spacing of 20 mm. The build time was a marginally quicker for the cross-section as less turns are needed and hence less slowing down.

The cooling speed of different alloys such as magnesium affects the mechanical properties of the final part with a die cast. It has been found that the increase in the cooling rate reduces the grain size and increases the hardness and ultimate strength of magnesium alloys [8]. The cooling rate analysed is between 0.6 to 2.6 K/s.

Akhil et al. have explored the effect of section size on cooling rate, microstructure and mechanical properties of aluminium A356 during sand casting. It is found that a reduction in the section size has an influence on the cooling rate and therefore an effect on the mechanical properties such has hardness and ultimate tensile stress [9]. A cooling rate of 0.067 K/s (20-mm section) results better mechanical properties than a cooling speed of 0.0167 K/s (80-mm section). The thicker section results in a longer cooling period. Their results illustrate that the section size, which is correlated to the cooling speed, results in different ultimate tensile stress as seen on Fig. 4.

AC AlSi9Cu also has a correlation between the cooling rate and the secondary dendrite arm spacing and grain size in a die cast application [10]. The cooling speed in the analysis is comprised of values between 0.16 and 1.04 K/s. The cooling speed of 1.04 K/s results in a smaller grain size and intermetallic compounds and improves silicon modification level.

The solidification of metal is done a specific moment. Figure 5 illustrates the cooling speed of the alloy AlSi9Cu.

Figure 5 displays three cooling rates, the liquid alloy cooling rate, the mushy alloy (mix of liquid and solid) cooling rate and the solid cooling rate. The mushy phase starts at T_D (~ 602 °C) and finish at T_E (~ 561 °C). The cooling time between these two points is important as it is the moment where the crystals grow. The shorter this time is, the smaller the dendrite arm spacing are. The time taken to arrive to T_D is somewhat important and will be explained later on, and the time elapsed after T_E is irrelevant. The cooling speed is the difference of temperate at those points divided by the amount

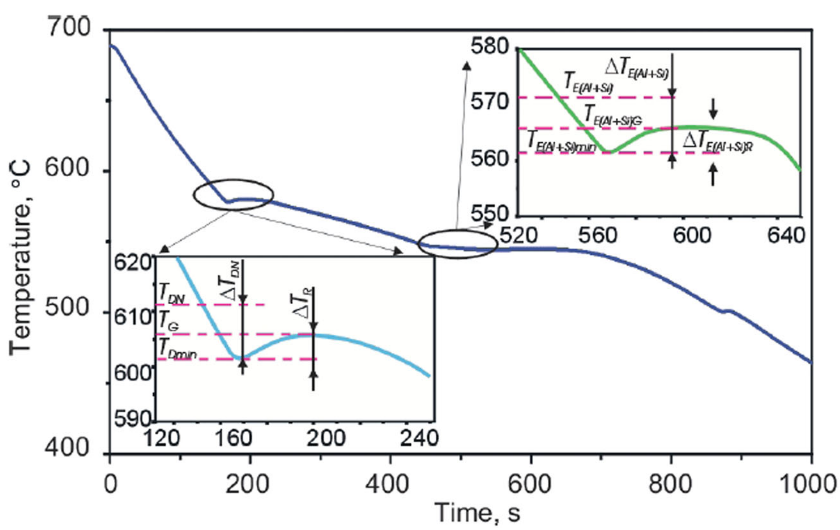

Fig. 5 Cooling speed of AlSi9Cu [10]

of time it took. There is a difference between the cooling rates of alloys in die casting mould and sand casting moulds. A factor of 40 is observed, 2.6 K/s for die casting vs 0.0667 K/s (20-mm section) to 0.0167 K/s (80-mm section) for sand casting. Solidification time, or cooling rate, is therefore important.

3 Methodology

The proposed methodology involves two conditions that have to be successfully met in order to have a sound mould. Firstly, the mould should first be able to hold itself during the pour. Secondly, it should have a desired thermal transfer rate. The methodology is synthetised in Fig. 6.

The 3D part file can be any 3D representation of the part that needs to be casted. The 3D file is converted to the appropriate format for optimisation.

The user selection consists of picking the part's desired quality, such as hardness and ultimate tensile strength. Those qualities can be global or local. The local quality infers that different portions of the casted part may require different local mechanical properties. Different local mechanical properties can be helpful in the design of a desired failure mechanism with weaker areas. The areas can shape a failure line.

After the selection of the qualities, the user can then select the appropriate materials. The material selection consists of castable metals and alloys. Once the part's material and qualities are chosen, the user then needs to choose the appropriate moulding material. Indeed, different users may have access to different materials. The material choice may be limited by the machine type, budget, environmental constraints or user preference. The mould's materials consist of the structural sand, binder, additives and backing material.

After sufficient data is inputted, the algorithm can process to a first check for minimum wall thickness according the mould's material strength and the geometry. Starting the structure optimisation with the finding of the minimum wall thickness according to the material's strength is the best way to ensure that the thinnest wall thickness is found. A strength analysis validates if the mould has the minimum wall thickness while not failing due to metallostatic pressure or even its own weight.

The result of the optimisation renders the next optimisation easier. The following optimisation consists of ensuring a homogenous cooling throughout the part during casting, if global quality is chosen. The thermal coefficient should not be the same throughout the mould, as some parts of the mould will cool faster than the others due to the varying geometry. This results in a need of having slower or faster cooling rate in a certain part of the mould and thicker or thinner shell thickness.

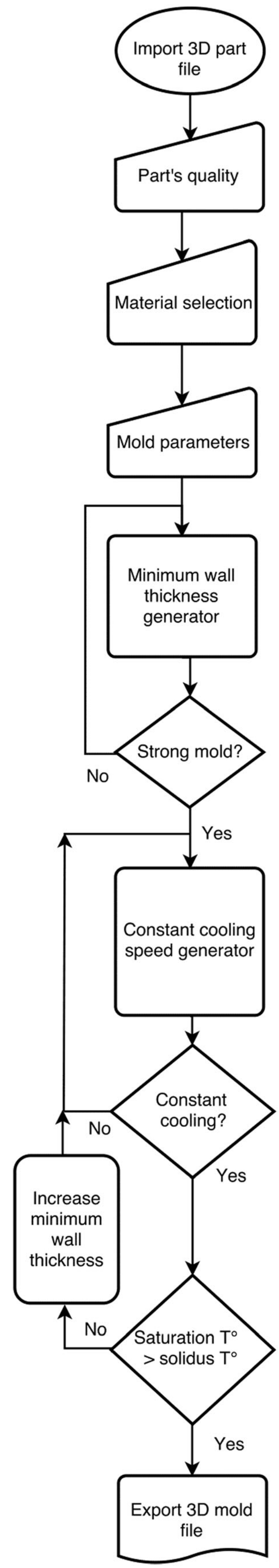

Fig. 6 Design for additive manufacturing of sand mould for constant cooling speed

A few iterations of casting simulation are required to find the best solution. The optimisation changes the wall thickness in a positive manner. Only material can be added. This ensures that the mould still holds its shape.

Finally, the file is exported in interpretable data format for the 3D printer.

The proposed methodology ensures a mould is strong enough coupled with a controlled thermal cooling. Additive manufacturing offers unique possibilities for fine-tuning those parameters that were not possible since the inception of casting 6000 years ago.

4 Simulation

A simple shape is used in order to evaluate the methodology. The simulated casted part is of parallelepiped shape. In the following charts, the measurements refer to the part's length, as the problem is 1D and symmetrical. The mould's dimensions are changed to see its influence. The boundary layer thickness varied with no change in the result, if air is chosen. The results change when the boundary layer is made of water for example, since water is a higher thermal capacity than air. This is not covered here.

The following hypotheses are present during the simulation:

- The phase change of the metal is not accounted.
- Thermal and mechanical properties do not depend on temperature.
- The thermal conductivity value is approximate.
- The heat convection value is arbitrary.
- A specific alloy is studied (AlSi7Mg).
- The simulation is for a parallelepiped.
- Radiation is not taken into account.
- The measured temperature point is in the middle of the part and in the middle of the mould.
- Varying the cooling speed will vary the limits of solidification (T_D and T_E).

The casted material is aluminium with these parameters:

- $\rho = 2685$ kg m^3
- $C_p = 963$ J K^{-1} kg^{-1}
- $k = 237$ W m^{-1} K^{-1}

The sand mould with silica SiO_2:

- $\rho = 1600$ kg m^3
- $C_p = 750$ J K^{-1} kg^{-1}
- $k = 0.7$ W m^{-1} K^{-1}

The mould's boundary layers are in contact with air:

- $\rho = 1.0$ kg m^3
- $C_p = 4185$ J K^{-1} kg^{-1}
- $k = 0.6$ W m^{-1} K^{-1}

COMSOL 5.1.0.136 Multiphysics ® is used for the simulations.

4.1 Conduction

A first approach using solely the conduction aspect of thermal transfer is simulated.

4.1.1 Varying the part's thickness

To understand all the thermal effects during a cast, all the variables must change one by one. The first one to be studied is the part's thickness. An analysis by varying the part's length is done. The length changes from 2 to 16 mm. The mould is 500 mm thick. The importance of this thickness is explained later on.

As expected, the thicker parts will cool much slower as shown in Fig. 7. This means that if you cast a part with a varying thickness, certain areas of the metal part will cool at different speeds. The different speeds will generate residual constraints and may cause some casting defects. This is why the design guidelines for casted parts require a constant part thickness.

4.1.2 Varying the mould's thickness

It was found that varying the mould's thickness partially help cooling the mould faster. This is normal as the cooling speed is governed by the thermal conductivity coefficient. The change in thickness did change the saturation point. At a certain point, the mould could not store any more calories as illustrated in Fig. 8.

It can be hypothesised that the mechanical strength is very high which will result in the design of an extra thin shell. But if the mould cannot store the calories, then the molten metal will stay molten, if convection is not taken into account. Enough calories need to be taken out to cool the mould down to a certain point. This solidification point differs with each alloy. Once the metal, or alloy, is solid, then the crystal structure will be much less affected. Actual field testing is required to verify that after a certain point, the thinning of the shell will be counterproductive.

The minimal value or boundary limit is set by the equilibrium value of the thermal capacity of the mould and thermal capacity of the metal. The starting temperatures influence the thermal reservoir. If the ambient temperature is lower, the mould will have more "capacity" to store energy. It is inversely true that with the melting temperature of the metal, the

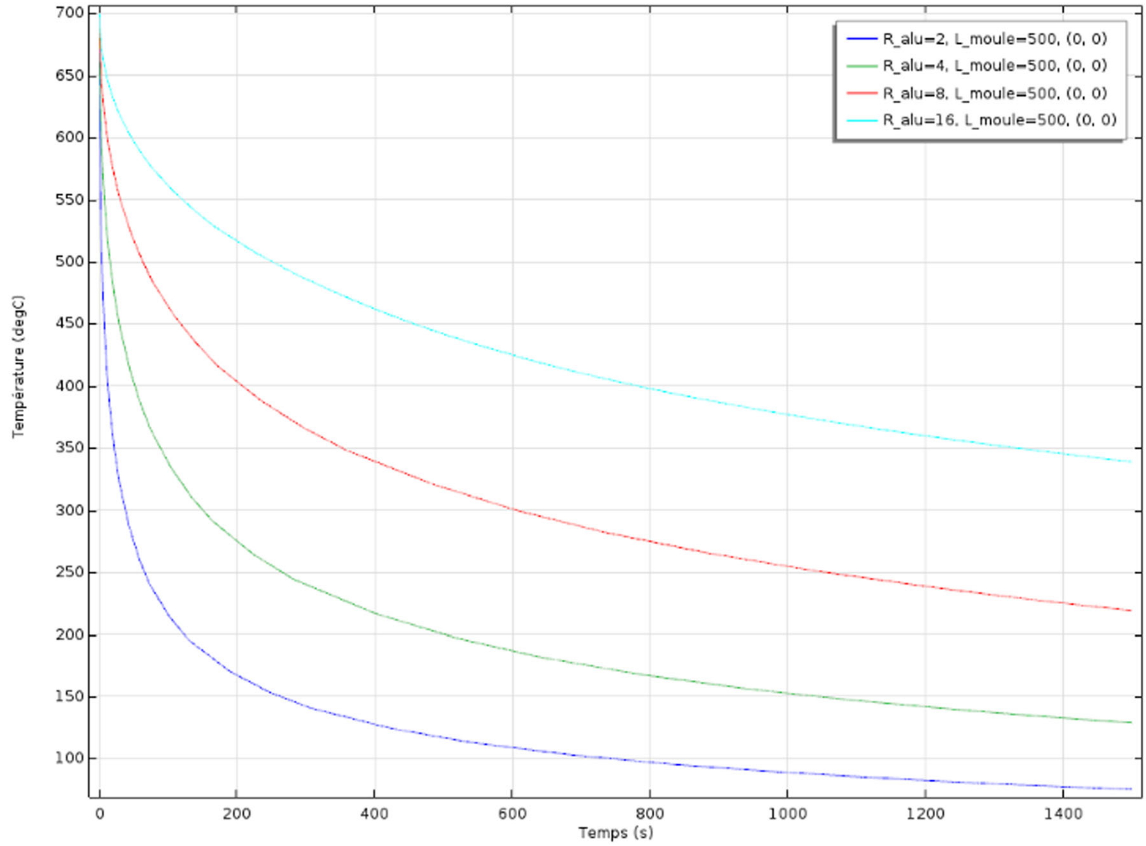

Fig. 7 Shell thickness of 500 mm, varying the part's radius

higher the temperature is, and the thicker the mould will be needed to accommodate for that extra energy.

Thickness does play a role in the cooling speed of the mould up until a certain point. It was found that after a certain thickness, the cooling curve is the same, see Fig. 9. The saturation temperature is roughly the same. Indeed, the part's thickness is much smaller compared to the mould's thickness. This sets an upper limit for optimisation. The extra material does not add value.

4.1.3 Varying the mould's thermal conductivity coefficient

After going through the parameters in mould making, it was concluded that the thermal conductivity of the mould is the simplest parameter to modify. For this methodology to work, it is required to have local conductivity coefficient. This means that the mould will have different coefficient throughout itself.

This functionally graded material (FGM) repartition can be of multiple shades as highlighted by Hascoët et al. [11]. In this case, the gradient is discontinuous taking the shape of a dirac, although an optimal solution would be a continuous gradient.

The focus of the chart was set to 560 °C as it is the solidus temperature of AlSi7Mg; this can be seen on Fig. 10 for the heat conductivity of 1.4 W K^{-1} m^{-1} and Fig. 11 for 0.7 W K^{-1} m^{-1}. This focus is the mushy transition zone of this alloy; the crossing time of 560 °C will induce different mechanical properties.

The effect of the thermal conductivity coefficient can clearly be seen. The temperature for the couple "part's thickness of 16 mm" and "mould thickness of 12 mm" hits the 548 °C mark in 70 s when the heat conductivity coefficient was set to 1.4 W K^{-1} m^{-1} and almost 140 s with a coefficient at 0.7 W K^{-1} m^{-1}.

4.1.4 Same cooling curve objective

To illustrate the possibility of varied part thickness throughout the same casting, it is required to have varying mould geometry and thermal properties. Figure 12 illustrates matching parameters that result in the same cooling curves.

The parameters listed in Table 1 enables a crossing of 560 °C in 120 s for different part geometry.

4.1.5 The equations

The simulation is simplified by simple equations in the case of conduction.

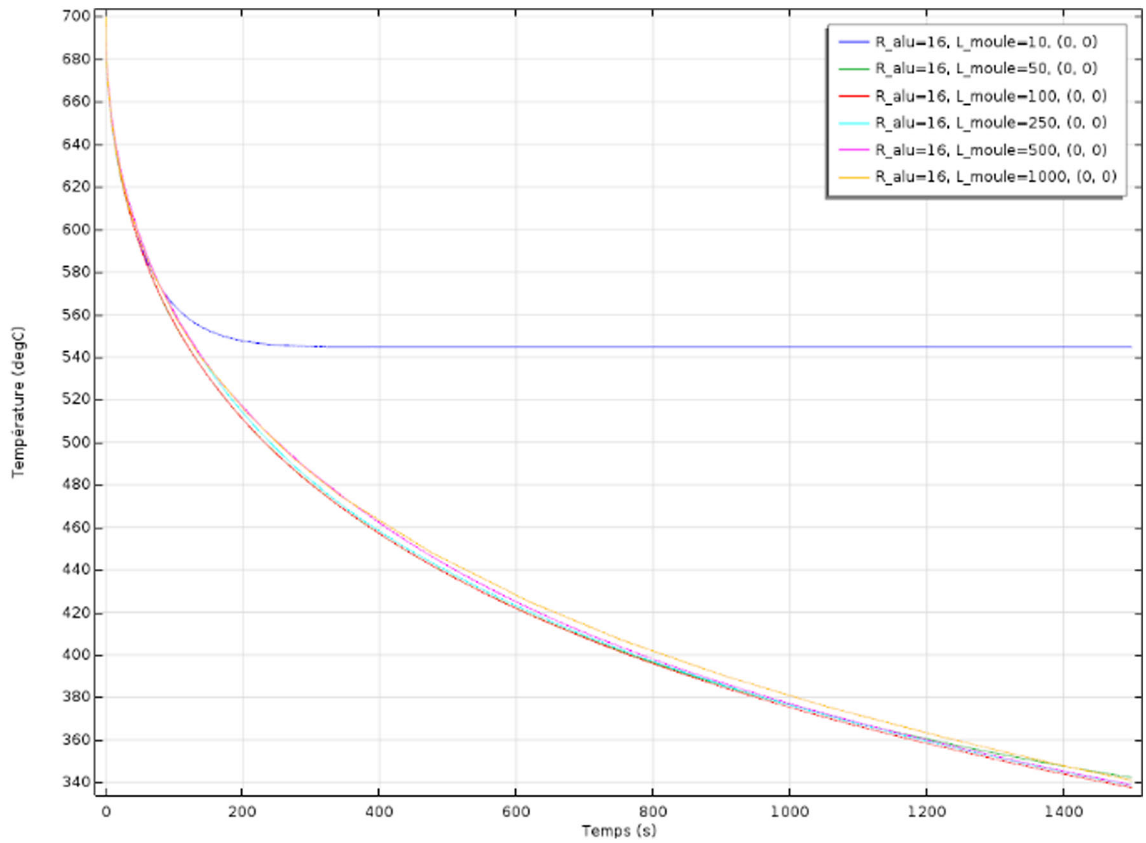

Fig. 8 Part's thickness of 2 mm with varying shell thickness

List of variables:

T_{ini}	the initial temperature of the metal (°C)
T_{amb}	the ambient temperature (°C)
T_{sol}	the solidus temperature (°C)
C_{pMould}	the thermal capacity of the mould (J K^{-1} kg^{-1}
C_{pMetal}	the thermal capacity of the metal, J K^{-1} kg^{-1}
ρ_{mould}	the density of the mould (kg m^{-3})
ρ_{metal}	the density of the metal (kg m^{-3})
λ_{metal}	the thermal conductivity of the metal (W K^{-1} m^{-1})
λ_{mould}	thermal conductivity of the mould (W K^{-1} m^{-1})
L_{part}	the thickness of the casted part (mm)
L_{mould}	the thickness of the mould (mm)

The thermal reservoir, the place where the heat from the part will be conducted, is the mould. Therefore, we have to dimension the mould's thickness, as it is the energy storage. The thermal equilibrium equation, Eq. (1), is used.

$$L_{mould} = \frac{-L_{part} \times C_{pMetal} \times \rho_{metal} \times (T_{sol} - T_{ini})}{C_{pMould} \times \rho_{mould} \times (T_{sol} - T_{amb})} \quad (1)$$

Equation (2) is based on the cooling curve defined by Newton's equation. The constant k is defined by Eq. (3).

$$T(t) = T_{ini} + (T_{ini} - T_S)e^{-(p \times t)} \quad (2)$$

$$p = \left(\frac{\lambda_{mould}}{L_{part}} \times \frac{\rho_{mould} \times \rho_{metal}}{C_{pMould} \times C_{pMetal}} \right) \quad (3)$$

4.2 Convection

A second approach using conduction and convection is simulated to refine the model. The convection coefficient ranges from 5 to 25 W m^{-2} K^{-1}. This parameter cannot be varied throughout the part as it represents ambient air. This parameter is a function of temperature, hygrometry, pressure and wind speed.

4.2.1 Varying the size of the convection zone

Firstly, the size of the convection zone needs to be defined. Multiple simulations have been done to assess that size; Fig. 13 illustrate this work. The simulation has a part thickness of 4 mm, a mould thickness of 2.23 mm and a thermal conductivity coefficient of 0.0599 W K^{-1} m^{-1}; the convection zone varies from 1 to 1000 mm and the convection coefficient is 5 W m^{-2} K^{-1}.

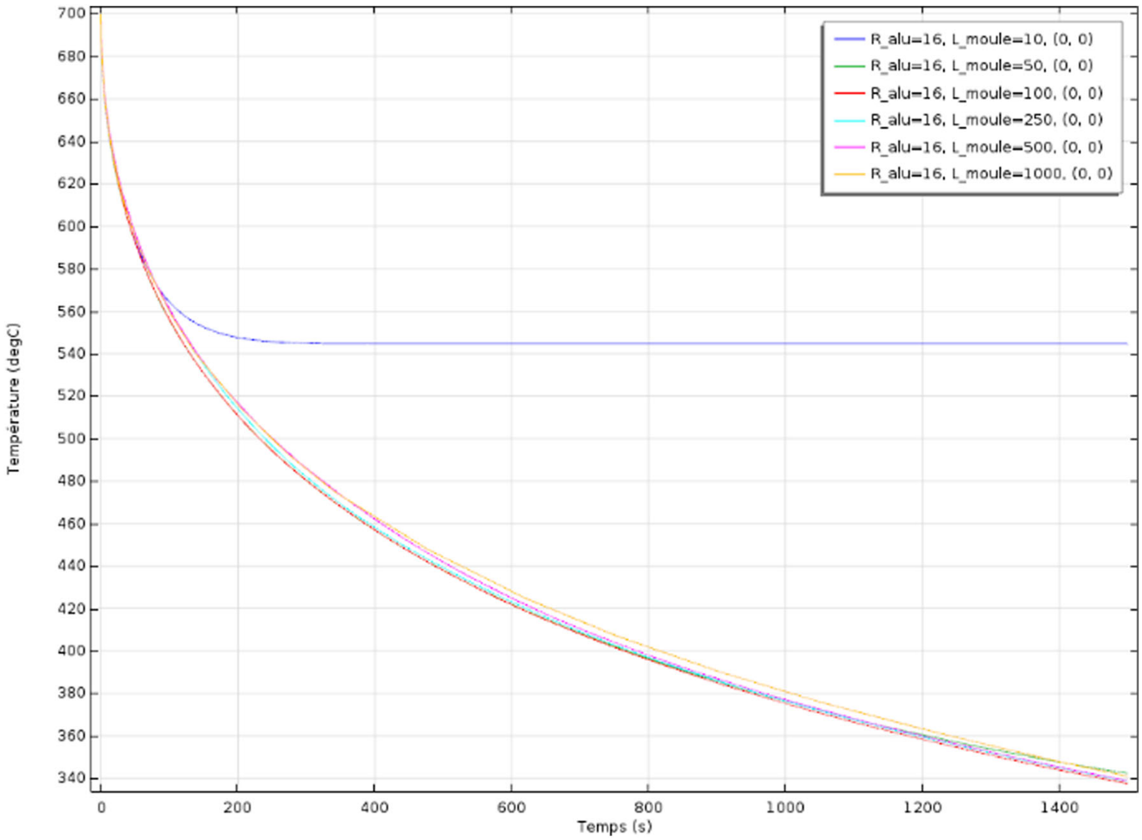

Fig. 9 Cooling speed for different mould thicknesses of a 16-mm part

It is found that the convection zones greater than 10 mm result in the same curves. A convection zone smaller than that will be saturated quickly and therefore will not be representative of reality. For the following simulations, a convection zone of 10 mm is chosen. A greater zone will give the same results but will take more calculation time.

4.2.2 Using the conduction simulation parameters

Secondly, a simulation is done using the matching curves parameters presented in Table 1. The thermal convection parameter is changed from 0 to 5 W m^{-2} K^{-1} and 25 W m^{-2} K^{-1}. The crossing of 560 °C is reported in Table 2 and graphically in Figure 14.

The difference is noticeable. The convection parameter is predominant the case of the 30-mm-part thickness. This could be due to the part's thickness, mould's thickness or even the thermal conductivity.

5 Discussion

The charts indicate that it is indeed possible to modify the casting speed by varying the mould's thermal and geometrical properties. Usually, those parameters are constant throughout the mould due to manufacturing constraints. The additive manufacturing possibilities enable the fabrication of moulds with local properties and dimensions. This methodology changes the foundry part design guidelines.

It is harder to match the curves for the convection simulation. The first section of the curve still seems to match as the thermal conductivity "fills" the mould in calorie; the second part depends on multiple parameters. The divergence of the curves is dependent on the thickness of the part, the thickness of the mould, the thermal conductivity coefficient and the thermal convection coefficient.

Furthermore, the reduction of the wall's thickness also helped the efficiency of the process. Caution needs to be taken with extra thin walls, as with a wall thickness that is too thin, the sand shell may break and molten aluminium could be spread everywhere.

The reason to reduce the amount of material is to reduce the build time and the cost. The cost is linked to the quantity of material, sand and binder. But it is also linked to how much time the machine takes to build the part. The quicker it builds it, the cheaper it will be.

Reducing the amount of material also reduces the amount of time during shakeout as less material needs to be taken out. Recycling cost is also cut as less bound material needs to be recycled.

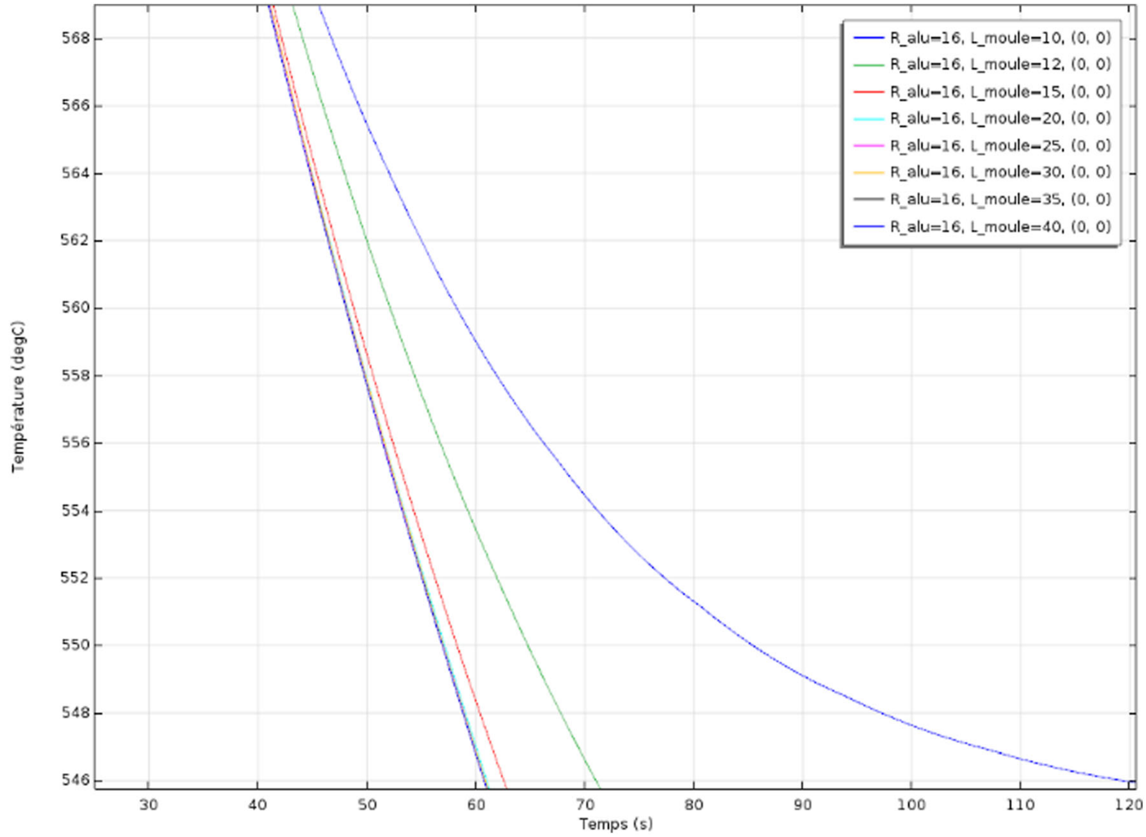

Fig. 10 Heat conductivity coefficient set at 1.4 W K^{-1} m^{-1} with a part thickness of 16 mm with a varying shell thickness

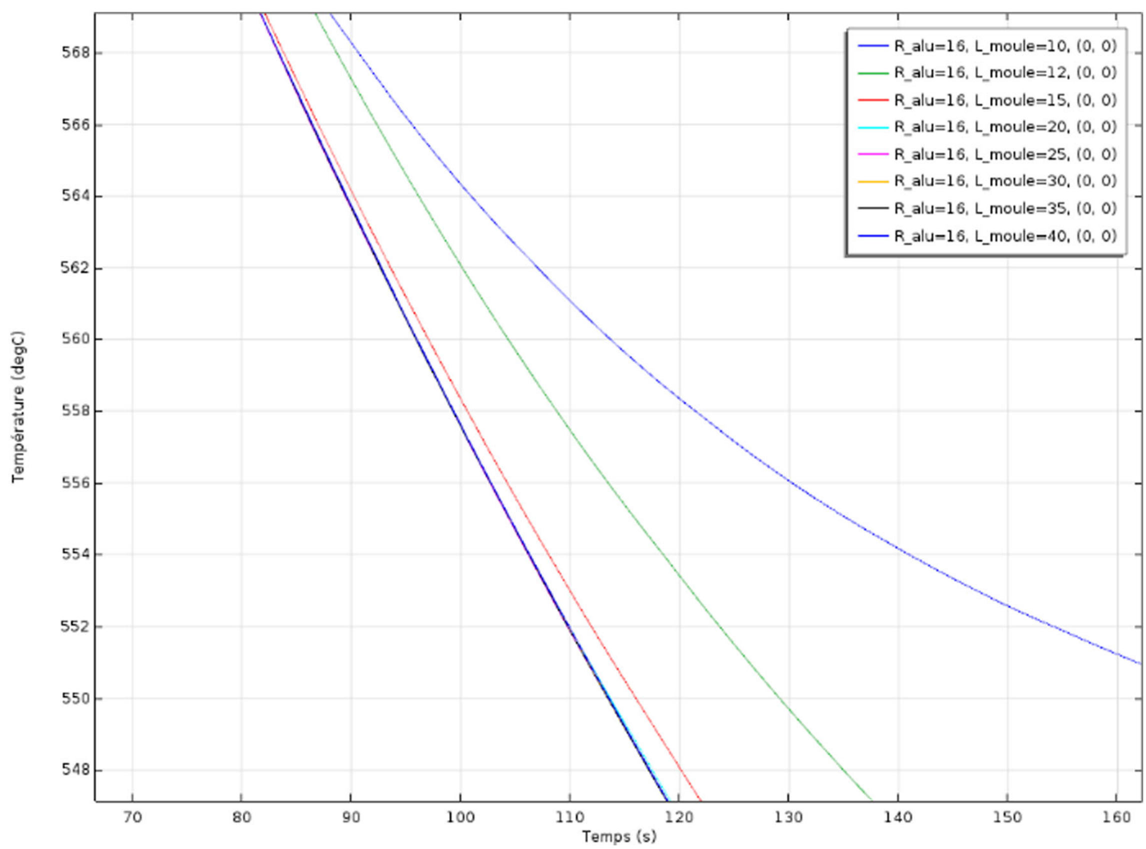

Fig. 11 Heat conductivity coefficient set at 0.7 W K^{-1} m^{-1} with a part thickness of 16 mm with a varying shell thickness

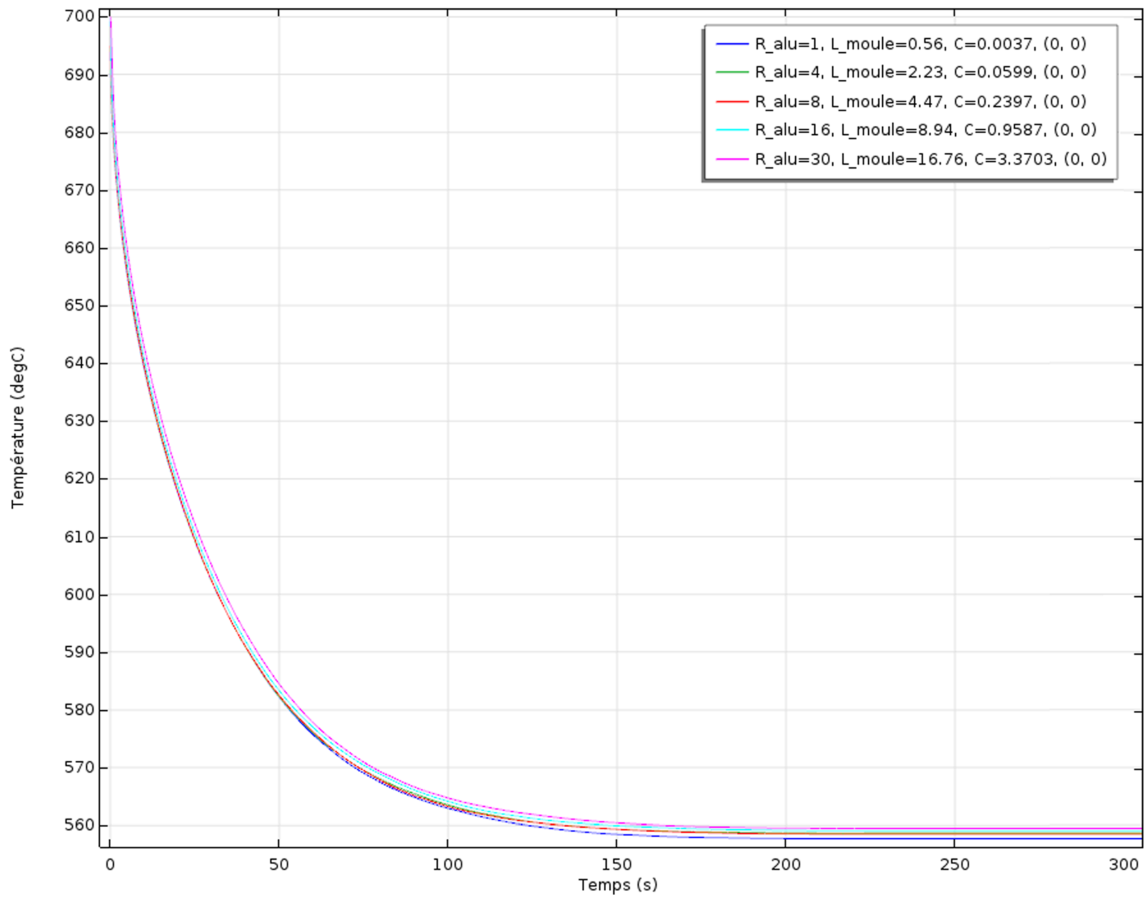

Fig. 12 Matching parameters to get same curves

Furthermore, the reduction of the mould's thickness will enable more parts in the same workload. This will reduce the mould cost. This may not be true for all cases.

Varying the mould's thickness did help in reducing the amount of material needed during the build.

A minimum thickness is required as a mechanical strength is required but it is also needed in designing a calorie container.

A link is made between the part's thickness and the needed wall thickness of the shell casting mould. The ratio needs to be constant throughout the part in order to cast a homogenous part.

The technique could be used for mould and cores.

The simulations used a constant value, in regard to thermal change, for the heat conduction coefficient despite a change of the temperature. Little to no data is available in simulation software and in scientific literature. Further studies need to be done in this field.

Table 1 Parameters for a crossing of 560 °C in 120 s

Part thickness (mm)	Mould thickness (mm)	Thermal conductivity (W K^{-1} m^{-1})
1	0.56	0.0037
4	2.23	0.059
8	4.47	0.24
16	8.94	0.99
30	16.76	3.37

The starting temperature is important. The higher the temperature of the alloy in the crucible before the casting is, the thicker the mould will be needed. It is evident that a higher starting temperature has more energy that needs to be dissipated within the mould. The casting simulations will need to optimise the down sprues in order to have the lowest possible casting temperature.

Although current 3D printers are not capable of manufacturing functionally gradient materials, this methodology indicates the added value of such capability.

Physical testing of the methodology will confirm the need to use FGM to have better cohesive moulds. Indeed, it is speculated that the different zones of heat conductivity may not stick well together and a transition zone may be required.

6 Perspectives

6.1 Energy and material flow analysis

The model of Meteyer et al. can be used in order to assess the amount of energy and material use for the fabrication of the

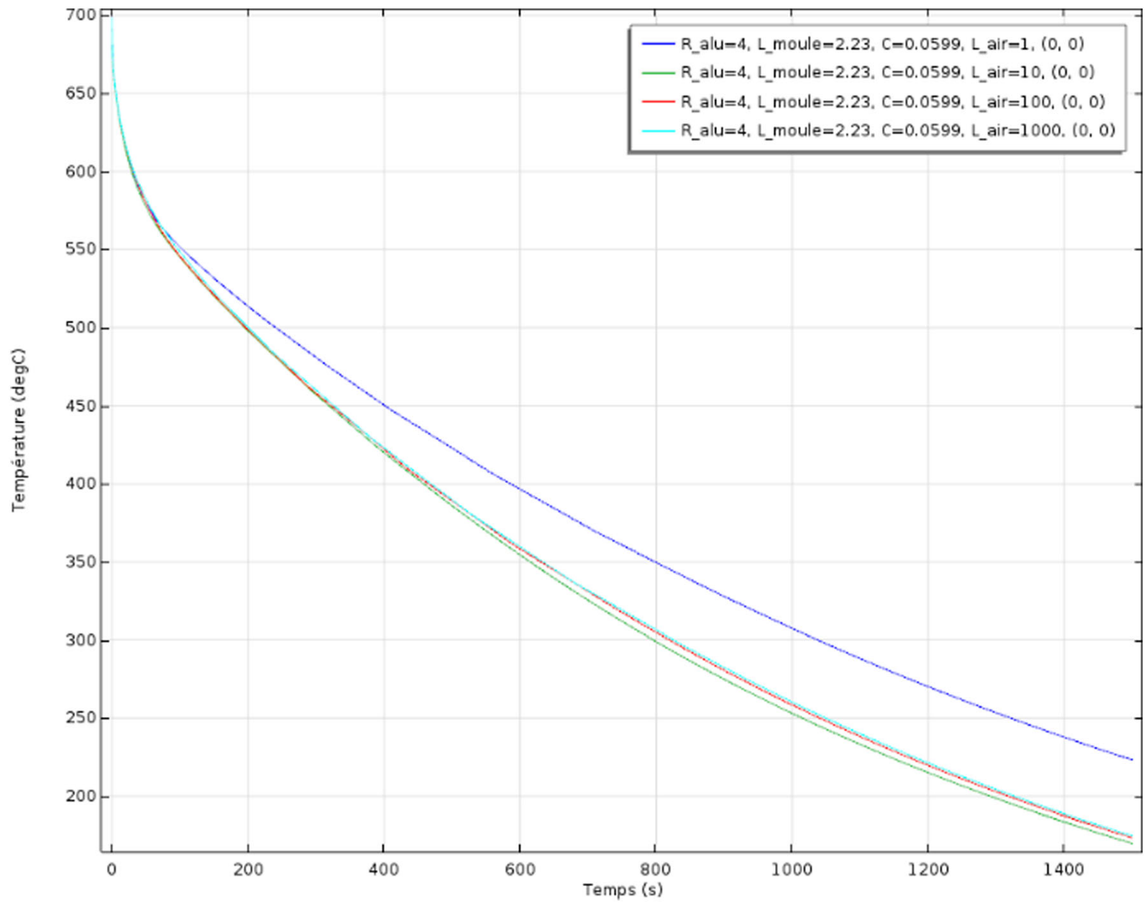

Fig. 13 Varying the size of the convection zone

prototypes [12]. The model was designed for the ExOne machine and may work as well with the Voxeljet machines. The work of Dalquist et al. on the life cycle analysis of sand casting parts should give a hindsight on the process [13].

The reduction of the amount of sand and binder needed is thought to reduce the amount of time taken to build the mould. The reduction of the amount of the mould's material will also reduce the amount of time needed to recycle the mould's sand.

6.2 Mechanical stress analysis

Analysis of the mechanical properties of 3D printed sand parts needs to be done. The values of strain-stress compression need to be implemented in an analysis software. The analysis of the mechanical loads upon the mould needs to be confirmed.

6.3 Thermal simulation

A few hypotheses have been made during the simulation. Those hypotheses need to be addressed in order to refine the model.

6.4 3D printers

Varying the thermal conductivity of the 3D printed mould on the fly is not yet possible on the Voxeljet 3D printer.

6.5 Casting defects

The possibility to design the part with a varying geometry without causing defects is envisioned. Fabrication of such part should confirm the theory.

6.6 Forced convection

Forced convection will enable a coefficient greater than 25 W m^{-2} K^{-1}. This will result in a faster cooling. A fluid flow analysis surrounding the mould needs to be simulated as calories will not be taken evenly.

6.7 Equations

Equations (1) and (2) can be manipulated in order to find the part's thickness, the thermal conductivity or the time it takes to reach a certain temperature.

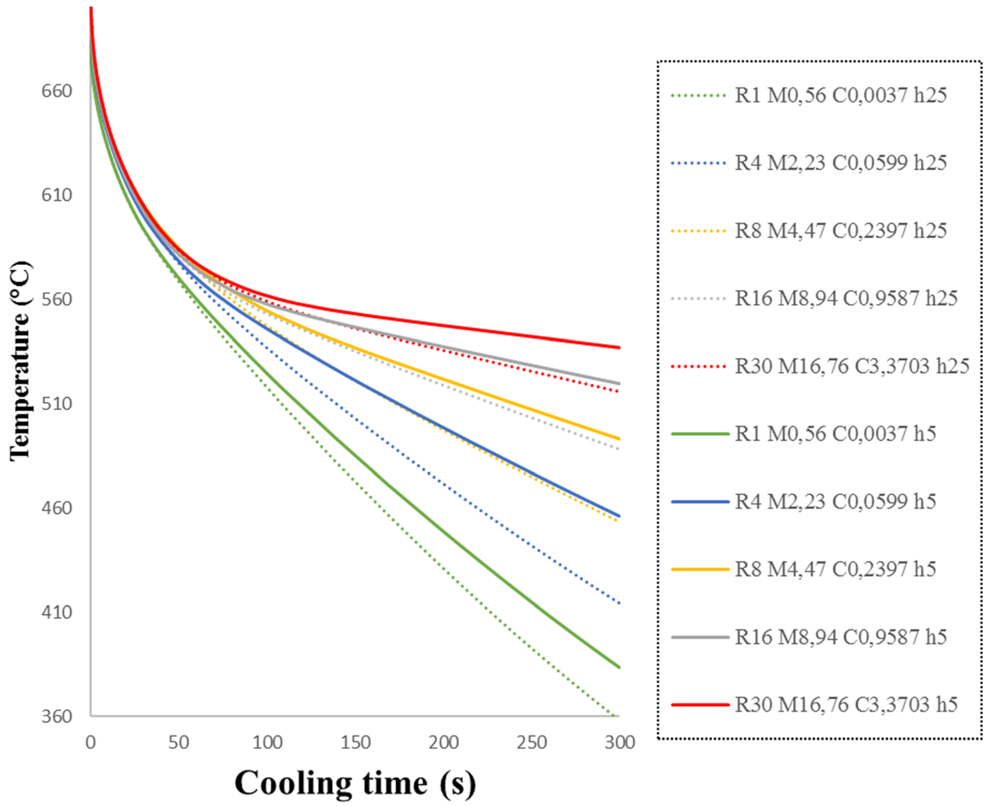

Fig. 14 Effect of the thermal convection on previously matching curves

The equations can then be plugged into the equations that correlate the cooling speed to the mechanical properties. This enables vast design opportunities.

6.8 Materials

The choice of sand, binder and additive can help speed the cooling process.

6.9 Selective laser sintering

Selective laser sintering works in a similar way of binder jetting. The manufacture of a part with this technique is done layer by layer; a laser sinters selectively a pre-coated pack of pre-binder-coated grain of sand that is thermally activated. The proposed methodology could be partially transposed to selective laser sintering (SLS). The shell aspect can be transposed, but the variability of the binder to create FGM part cannot be reproduced.

7 Conclusion

The cooling rate varies with the part's thermal conductivity coefficient. The mould's thickness changes the amount of calories taken from the molten metal, which results in a minimum temperature.

Different wall thicknesses may be required for different part thicknesses. Different thermal conductivity coefficients are needed to obtain a specific cooling speed.

Thermal conductivity of the mould is an important criterion in this case. The sand needs to dissipate as fast as possible all the calories.

The removal of the right amount of calories at a specific speed, in other words power management, is the underlying

Table 2 Effect of the thermal convection parameter

Part's thickness (mm)	Mould's thickness (mm)	Thermal conductivity (W K^{-1} m^{-1})	Crossing 560 °C	
			5 W m^{-2} K^{-1}	25 W m^{-2} K^{-1}
1	0.56	0.0037	60 s	58 s
4	2.23	0.059	75 s	70 s
8	4.47	0.24	87 s	80 s
16	8.94	0.99	94 s	85 s
30	16.76	3.37	110 s	90 s

philosophy behind the proposed methodology. The thermal conductivity governs the speed and the thickness the amount of stored energy.

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