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STRATOCONCEPTION CONTRIBUTION FOR RAPID TOOLING IN DIE CASTING: FROM THE DESIGN TO EXPERIMENTS

Thabourey, J. *; Barlier, C.*; Bilteryst, F.**; Lazard, M.** & Batoz, J-L.**
* Cirtes, 29 bis rue d'Hellieule - 88100 Saint-Dié-des-Vosges, France
** ERMeP, GIP-InSIC, 27 rue d'Hellieule - 88100 Saint-Dié-des-Vosges
e-mail: jerome.thabourey@cirtes.fr

Abstract:
This paper presents the advantage of rapid tooling and more specifically the Stratoconception process in order to realize a die casting mould. A test case of a die casting mould is presented. A complete procedure has been developed in order to improve the efficiency of the tooling especially thanks to improved cooling channels. This procedure includes not only the numerical simulations of the heat transfer and the thermomechanical behaviour of the tooling as a help to design but also the manufacturing of the tooling and experimental manipulations.

Key Words: Rapid Tooling, Stratoconception, Die-casting, Numerical Modelling

1. INTRODUCTION

Competitivity and reactivity are industrial constraints in the domain of die casting. The rapid laminated tooling and especially the Stratoconception process presented in this study could improve the two points previously cited. Like the other rapid tooling processes, it permits not only to reduce the costs and the time of tooling’s manufacturing but also to improve the existing functionalities or moreover to create new ones thanks to the principle of layers.

The laminated tooling is studied by several research centres. The first tooling has been made for the blanking [1]. These tooling were not produced according to the rapid tooling concept because the numerical manufacturing technologies were not developed enough.

Since 90’s, studies on rapid laminated tooling took interest in the plastic injection moulds [2,3], in tooling for stamping [4, 5] and other manufacturing process. The applications of this technique for die casting are sparser [6] not because of the non interest in this subject but because of the difficulties of the die casting process. The solicitations of the tooling are very important: they are due to the very high pressures but also due to the thermomechanical constraints consequences of the thermal shocks.

In this study, we focus on the Stratoconception® process. Our research team supervised by Prof. Claude Barlier has been working since the end of the 80's on finalising this process, which is being protected by relevant trademarks and international patents. It has been widely published in numerous papers (see for example [7]).

Like other rapid prototyping processes, Stratoconception® allows manufacturing, layer after layer, an object designed by CAD, without any lag in the design / manufacturing workflow. This process consists in breaking the part down, by computing, into a set of straightforward elementary layers called "stratum", in which stiffeners and strengthening plugs are inserted (Figure 1).

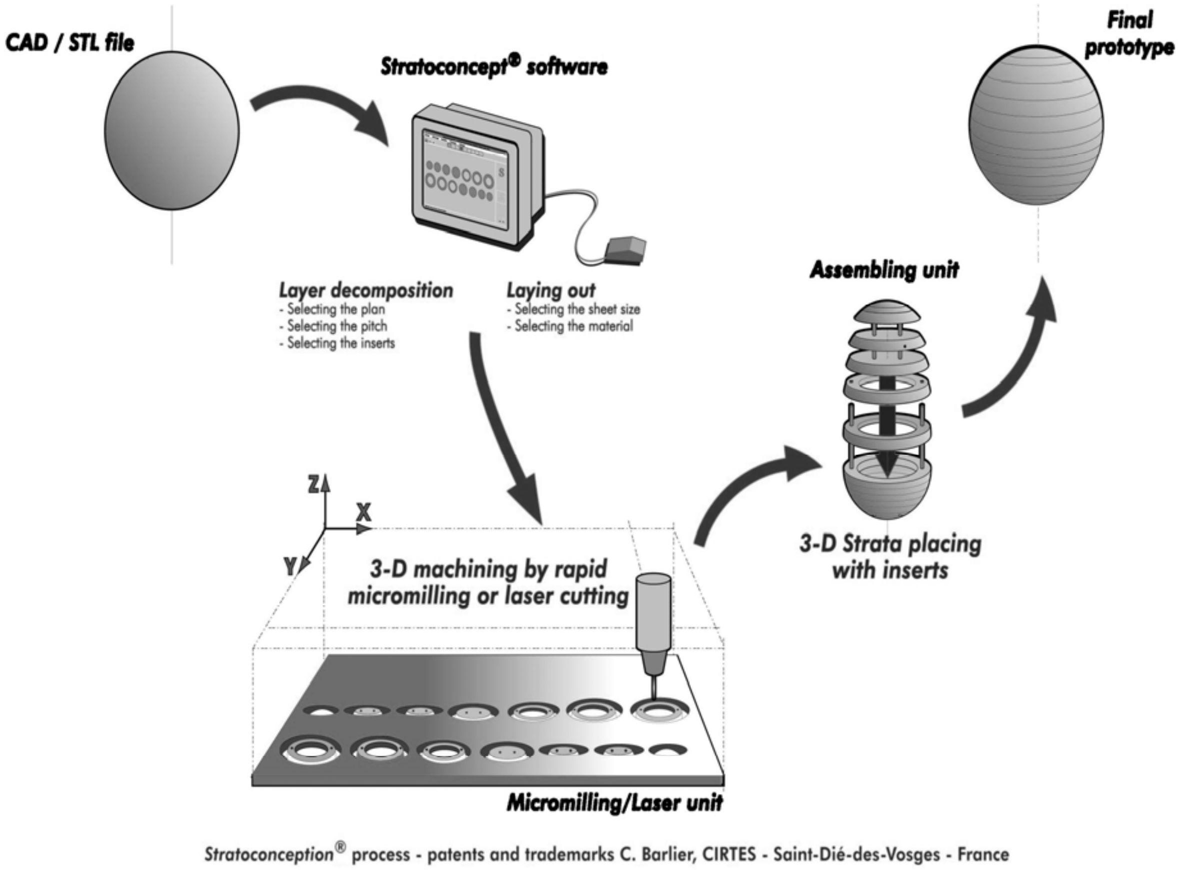


Figure 1: The Stratoconception process [8].

The elementary parts are identified and then directly manufactured (CAM loop) by 2.5 axis rapid milling, or by 5-axis laser cutting from sheet material. These elementary parts are then fitted together and imbricated in order to rebuild the final part. The assembly of the strata is considered from the design step to help withstand the mechanical constraints during use. The plugs then work both as location rods and links between layers. In the case of thin walled parts, these plugs are placed outside the parts using sectile bridges. For high-pressure die casting, these layers are made with special steel and then metallurgically bonded to each other by a high brazing process. Several rapid tooling was manufactured by the stratoconception process: we can point out the achievement of tools for die forging [9], of tools for gravity die-casting [10], in the domains of blow-forming [11], drawing [12] or the achievement of patterns and core box for sand casting and moulds for polystyrene pattern injection [13].

As previously said rapid prototyping processes have been recognized as a key engineering method for lead-time compression and manufacturing cost reduction. But this study illustrates the potential that such layer-by-layer processes have to establish in-house facilities in order to achieve complex or hollowed shapes. Particularly, the Stratoconception process can achieve all the cooling system of a mould during the elementary layers manufacturing before the final tool is rebuilt. Moreover this cooling system can be realized with various cross-sections or complex shapes while one should keep on mind that conventional manufacturing only allows straight cooling passages. As an example, we refer here to a recent research program, which examined the benefits of Stratoconception based on rapid tooling in the domain of blow moulding [14]. The Figure 2 shows the CAD of the shape of the regulation system of the moulds as well as the CAD of an elementary layer constituting this system. The second one shows a picture of the manufactured mould. Each layer includes a part of the “cooling sheet” obtained by micro-milling together with a remaining of the mould. The complete mould and desired “cooling sheet” are obtained by assembly of the layers. In order to avoid the excessive straining and possible rupture of the moulds subjected to the important mechanical loads involved, stiffened beam type connectors are designed between the two surfaces of the “cooling sheet”. These works were completed with numerical simulations based on Finite Element Methods in order to highlight the benefits of such innovating cooling system and its related manufacturing technology when trying to adapt the equipments to meet the new requirements of the market. These works are now protected by international patents [15].

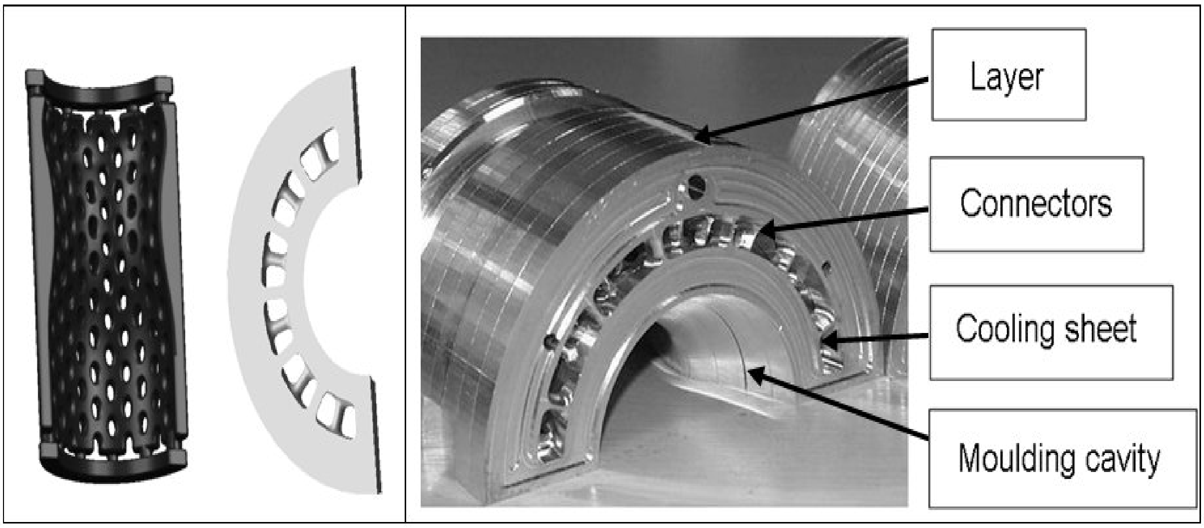


Figure 2: An example of a complex regulation system made by Stratoconception.

This paper presents the applications of these works on the die casting process thanks to a complete design and manufacturing chain and manufacturing that enables the improvement of the efficiency of the tools and particularly the thermal regulation. The design of high pressure die casting moulds has required well-tried knowledge and know-how since many years. The next issue consists in integrating and combining a CAD/CAE toolset with in-house specific developments, an assembly simulation and verification system related to the Stratoconception process as well as the previously cited rule-based knowledge. So this chain takes into account heat transfer and exchanges numerical calculation as well as the FEM based on simulation of the thermomechanical behaviour of the tool. These simulations should be seen as an efficient user help for the design and manufacturing of the moulds and for the leading of experimental stages. Research and development studies have been performed on this application in the frame work of the European project Molstra (G1ST-CT-2002-50325) ended in May 2005. A collaborative work between four research centres (Cirtes, GIP-InSIC, CROMeP/ ENSTIMAC and Inasmet) and seven Europeans firms permits to manufacture a die casting mould studied in this paper and to highlight the complete design and manufacturing chain.

2. NUMERICAL MODELLING

Thanks to this mould, we have developed a modelling of the thermal behaviour of the tools. These simulations are used as a help to the conception of the tooling and more specifically for the regulation channels (Figure 3). The thermal regulation of tooling for die casting is an important functionality which is now important for the manufacturers and the foundry owners. Before these last years, this point was neglected because of underestimated consequences regards to the over cost of the realisation. But thermal regulation plays an important role not only for the tool but also for the part. If the thermal regulation is not adequate, it could make defects or create major problems in the casting part. Thermal regulation permits to master the thermal phenomena in the tooling and as a consequence a great part of the manufacturing. It is important for all the stages of the process: during the heating of the tooling, during the manufacturing process in quasi steady state regime or during the stop or the beginning of the process. The thermal regulation is predominant for three precise points for the competitiveness of the foundries: the lifetime of the mould, the quality of the pieces and the productivity by reducing the cycle time and the defective pieces.

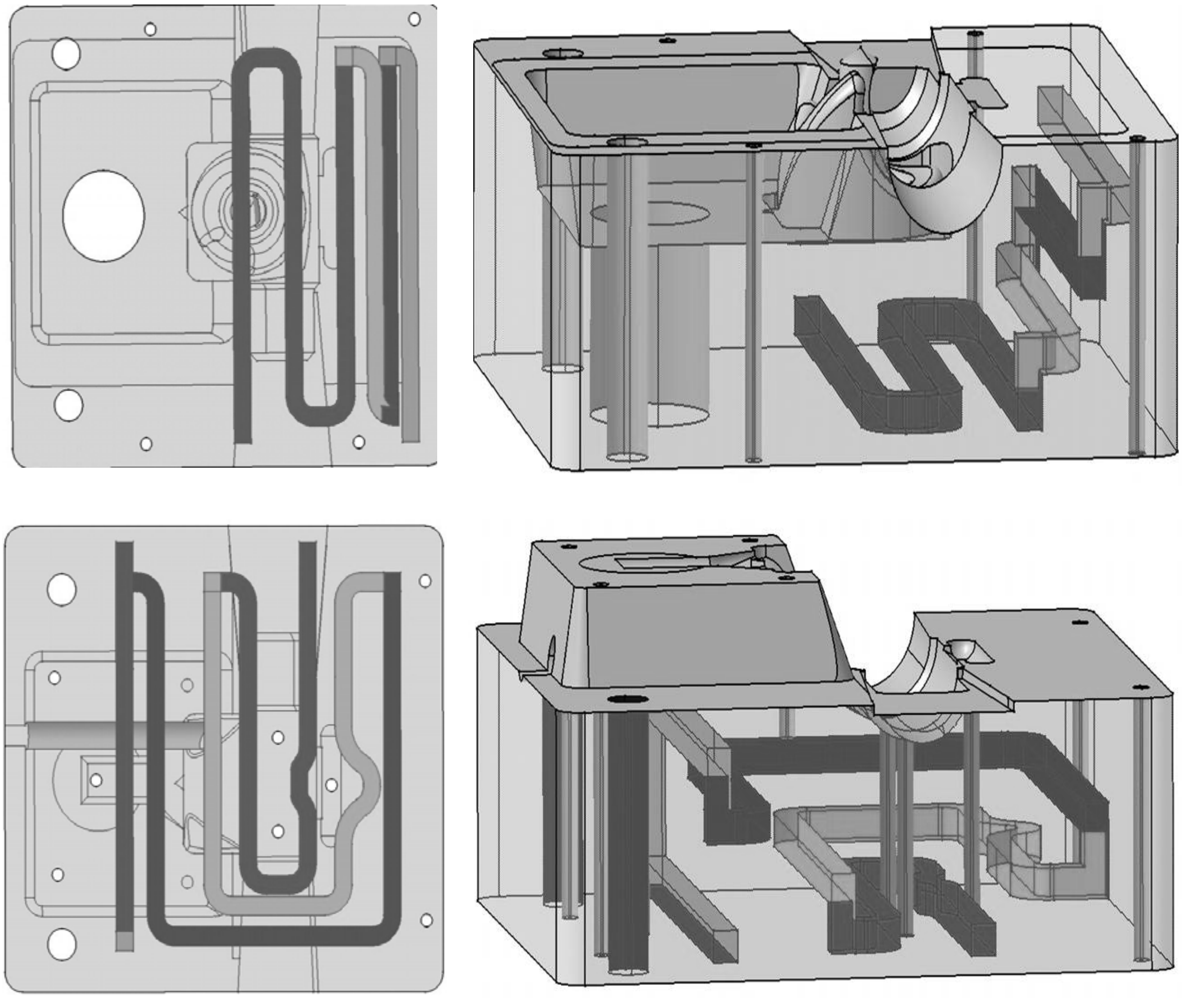


Figure 3: CAD of the regulation system.

This modelling is made thanks to numerical simulations performed with the finite element code Abaqus. The mould realised for the Molstra project is used to perform the simulations. The regulation channels have been determined during the project in order to get a sufficient cooling and limiting the thermomechanical stresses. Here are datas concerning these computations: processor 3.4GHz, 3G RAM, 325820 finite elements, CPU time (for one simulated cycle): 19301s when running with constant heat transfer coefficient (HTC), more than 20 hours when running with HTC depending on the temperature. This numerical simulation computes the transient heat transfer in the injected part and in the mould considered as homogeneous and isotropic. We do not take the layers into account because we do not know the characteristics of the brazed joints and the simulations would be very high time consuming. And yet this is the aim of a recently started research work which could be published as soon as achieved.

The modelling of a cycle has several steps (Figure 5): the injection, the cooling of the part, the ejection of the part cooling and the closing of the mould. The influence of the filling on the temperature fields in the part and in the mould is neglected. The initial temperature of the part at the beginning of each cycle is uniform and equal to the injection temperature.

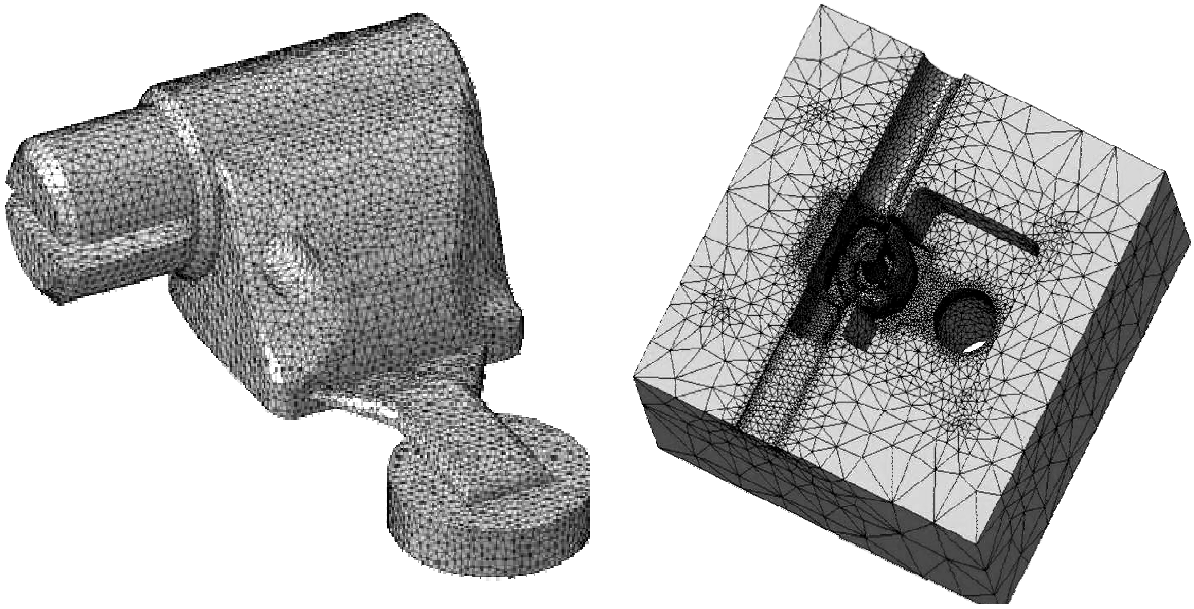


Figure 4: Meshing of the part and of one part of the mould using tetrahedral elements.

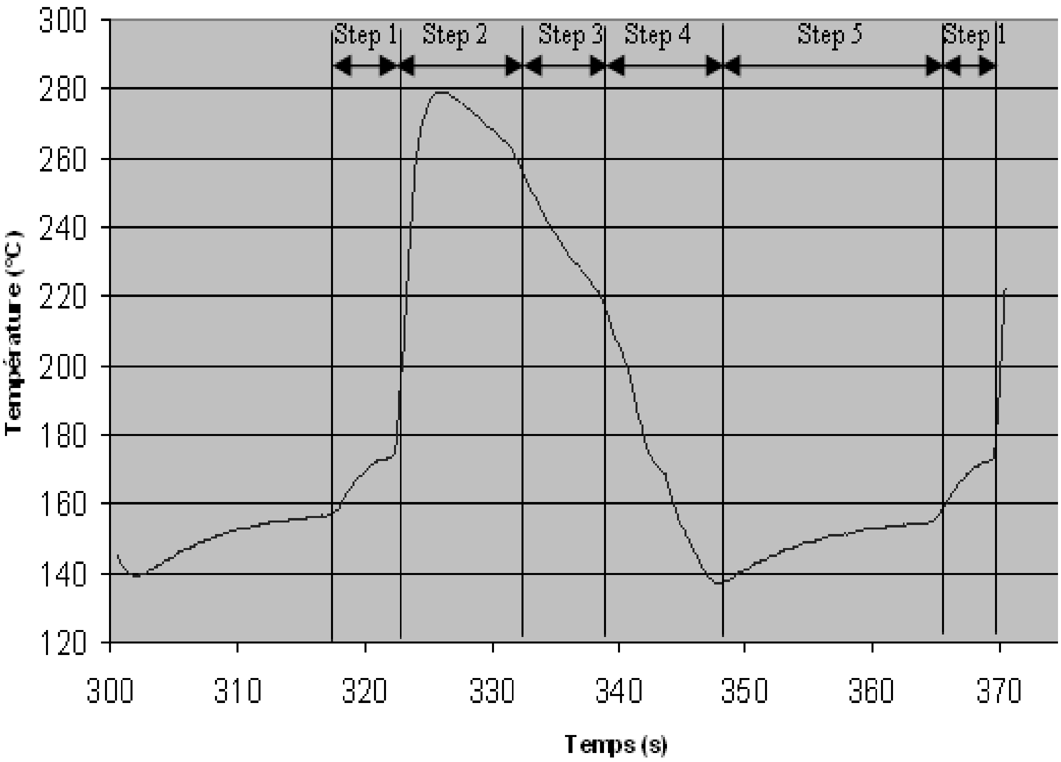


Figure 5: Details of an injection cycle at a given thermocouple.

The boundary conditions make the problem non linear. The heat transfer coefficient (HTC) between the mould and the part is applied as a function of aluminium temperature (Figure 6). This choice is issued from previous studies in collaboration with the research centre CROMeP/ENSTIMAC, see [16]. Other simulations were completed with a constant value of HTC during all the cycle in order in order to be compared to the following experimental results.

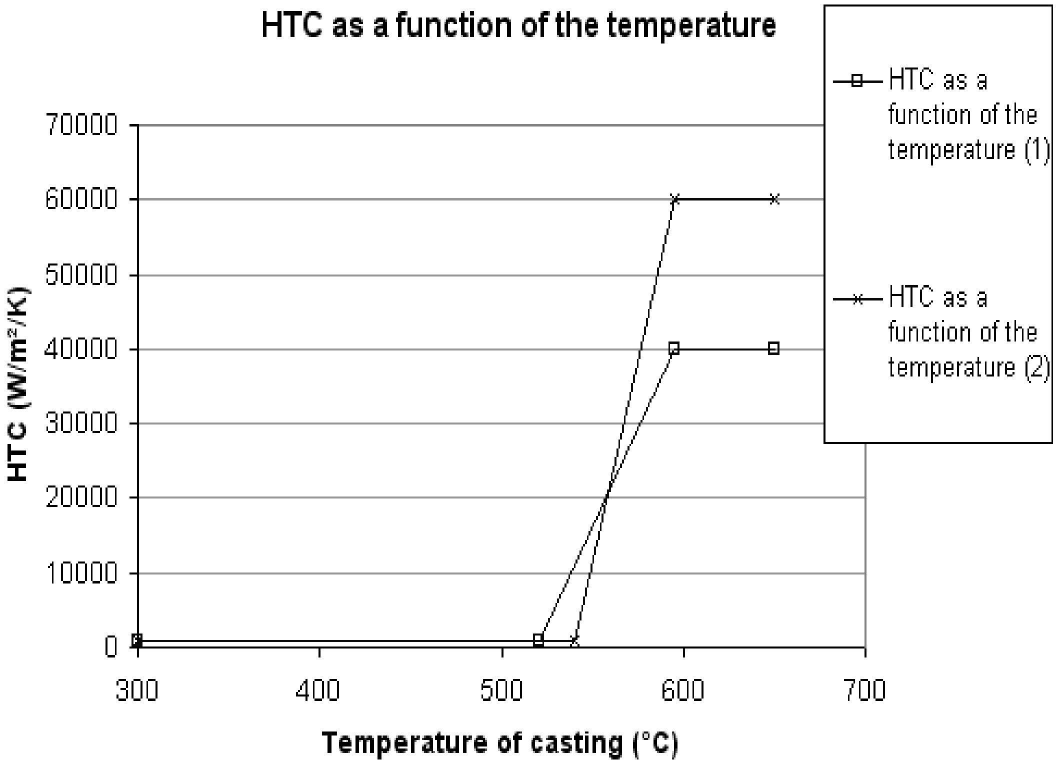


Figure 6: HTC between parts and moulds as a function of temperature.

An other condition concerns the die coating which is a heat flux (W/m²) depending on the temperature of the cavity wall [17]. These two boundary conditions need the use of Abaqus's subroutines developed in Fortran. The boundary condition in the thermal regulation is a forced convective coefficient (W/m²/K) determined as a function of the flow rate of the fluid (water or oil) and the ambient temperature, which is the temperature of the cooling fluid. The heat loss with the exterior is applied and determined with empirical formula well known by the tooling designers [18].

Several cycles are simulated in order to get the established regime. In order to illustrate these simulations, the Figure 7 shows the high temperature gradient in a determined direction (normal to the cavity wall). The thermomechanical behaviour was taken into account by complementary simulations. Related knowledge and prediction of this behaviour are essential since the mould, which is achieved with brazed layers, must support severe constraints during a high-pressure die casting process. This computation was achieved by using the FEM based on ABAQUS software. A mechanical load (clamping force, casting pressure) and a thermal load were applied at the same time. Concerning the thermal load, it was a matter of taking into account the computed temperature field during the previous part cooling simulations. The mould was supposed homogeneous and isotropic due to the same previously described reasons. But forthcoming works are actually leaded to compute the influence of the stacking sequence of the brazed elementary layers.

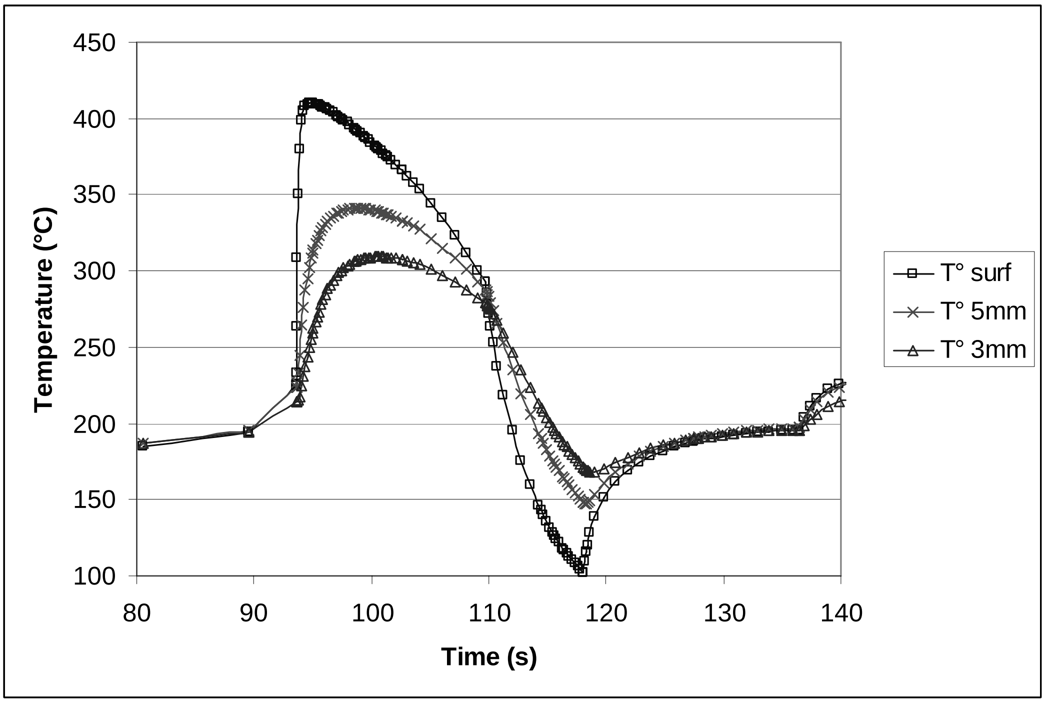


Figure 7: Temperature in the mould as a function of time.

3. FABRICATION OF THE MOULD

Only the two inserts are manufactured by Stratoconception. The grade of the steel sheets used for the manufacturing of the strata is the H11. This steel is very common in the conventional field of tooling in die casting. The thickness of the strata is 6mm and the dimensions of the two inserts are approximately 300*300*100mm. In order to reduce the micro-milling time, each stratum has been rough by laser cutting in two-dimensional. The cooling channels have been obtained directly during this step. Thus we obtained a complex cooling loop without an increase of time and cost. Next, the final shape of each stratum is manufactured by micromilling. After piling, the strata are assembled by brazing. The filler metal grade has been determined in order to support the very hard conditions in die casting. The pre-cut foils of the filler metal are placed between each stratum before the thermal cycle in a vacuum furnace.

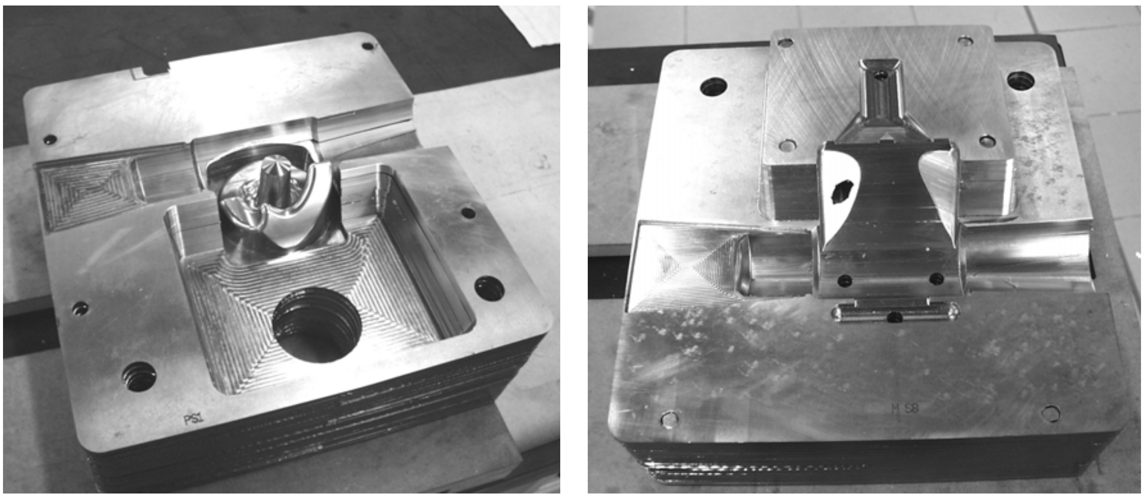


Figure 8: Two parts of the inserts before brazing.

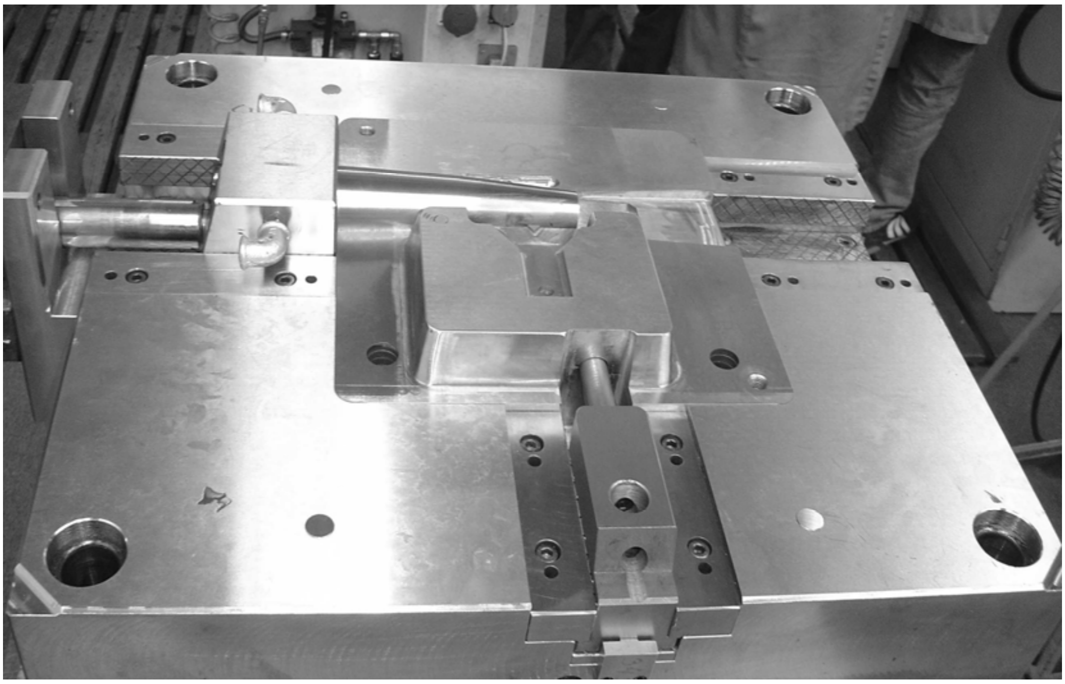


Figure 9: The final mould once polished, adjusted and assembled in the holding block - Craft Project Molstra.

The brazing temperature is higher than the austenitizing temperature of the strata steel. So we made traditional heat treatment after the brazing cycle in order to obtain the characteristics of conventional mould steel. The heat treatment is a quenching and then a double tempering. The steel hardness, which we measured is between 44 and 46 HRC. The manufacturing of the holding block and of the finishing (assembling in the holding block, polishing and adjustment) is made in a conventional way. Thus we obtained a good surface finish.

4. EXPERIMENTAL TESTS

Because of this additive technology, it is possible to incorporate directly thermocouples in the mould. The Figure 10 shows the results of a micro-milling on the surface of a stratum. Small slots are designed and manufactured in order to position thermocouples before the brazing. We are able to position them in strategic places (in hot temperature spot for instance) not accessible by conventional way. This freedom of positioning gives access to more precise data. After the end of the Molstra project, we made an experimental campaign with this mould fit with six thermocouples (diameter 0.5 mm). The distances between the thermocouples and the moulding cavity are between 5mm and 10mm. The first objective is to obtain the evolution of the temperature in the mould in order to validate the numerical modelling of the thermal and thermomechanical behaviours in these rapid toolings. The second objective is to observe the behaviour of this mould in severe industrial conditions. The injection moulding machine is a BUHLER SC34 with a clamping force of 340 tons. The injected alloy is a AS9U3. Around 300 parts have been injected with follow up pressures up to 900 bars and with piston velocities up to 4.5 m/s. We have determined three parameters, which have a great influence on the temperature field in the mould. They are also adjustable and controllable without problem just as well during the experimental tests as during the numerical simulations.

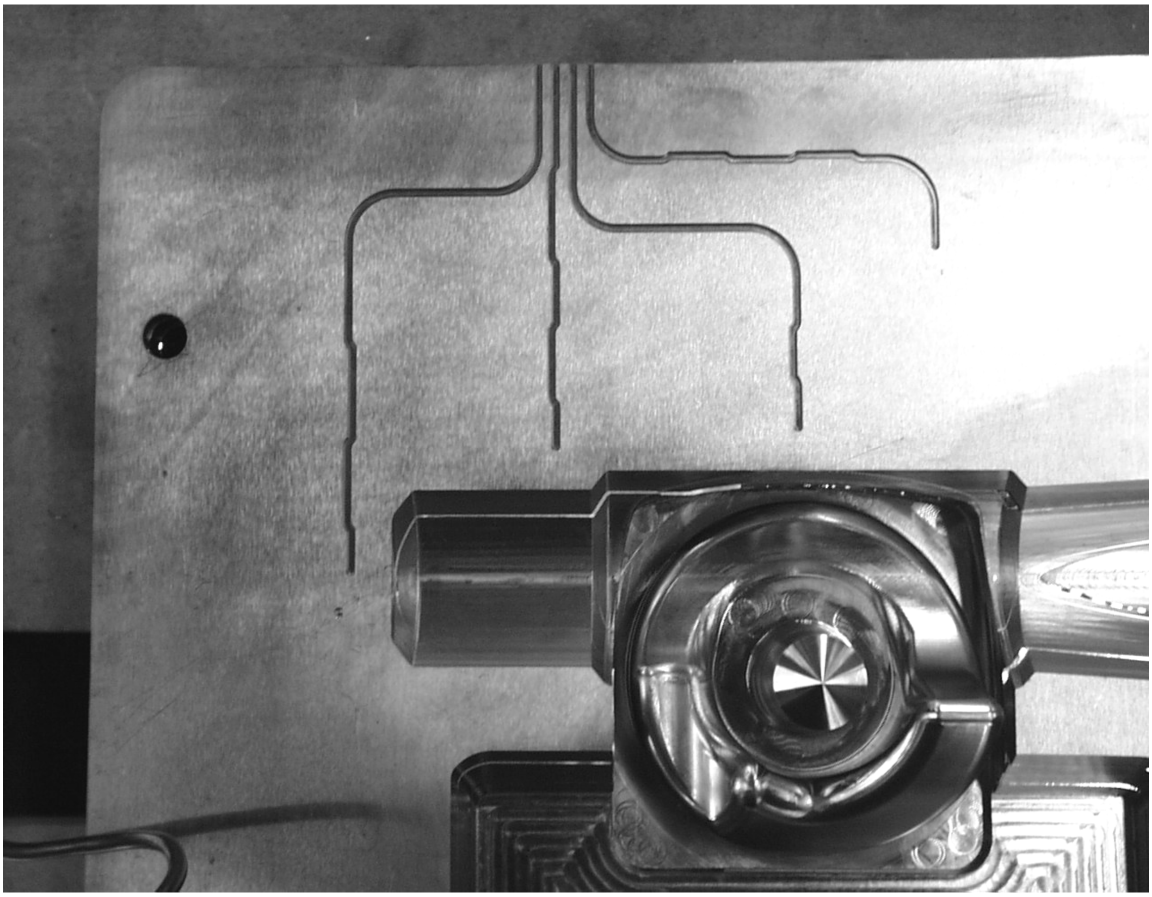


Figure 10: Slots between two strata to incorporate thermocouples.

These parameters are:

[1] temperature of the injected alloy,
[2] temperature of the cooling fluid (oil),
[3] time of lubrication by spraying.

We decided two levels of variation (Table I) for each of the three parameters. The other parameters like the injection parameters (speed and pressure) were fixed constant. As an example, the Table II shows the conditions of one of the different experimental test which were leaded. The Figure 11 shows the different temperature measurements for each thermocouple during the seventh cycle.

Table I: Parameters values.

Injection temperature	670	700
Cooling temperature (oil)	150°C	190°C
Lubrication time	4 seconds	9 seconds

Table II: Set of experimental conditions for one test.

Casting temperature	670°C
Cooling temperature	150°C
Die coating duration	9 s
Cycle duration	47 s
Injection flow rate	2 m/s
Injection pressure	570 bars
Ambient temperature	23°C

Experimental results could be confronted to those coming from the numerical modelling, see Figure 12. We can note that the value of HTC is an essential parameter as well as the value of the heat flux during the heat coating. They must be defined respectively as a function of the alloy temperature and as a function of the temperature of the mould. This is the cost we must pay in order to obtain a realistic numerical model, which could be efficiently used as a help to the design and the placement of the regulation cooling before the achievement of the mould.

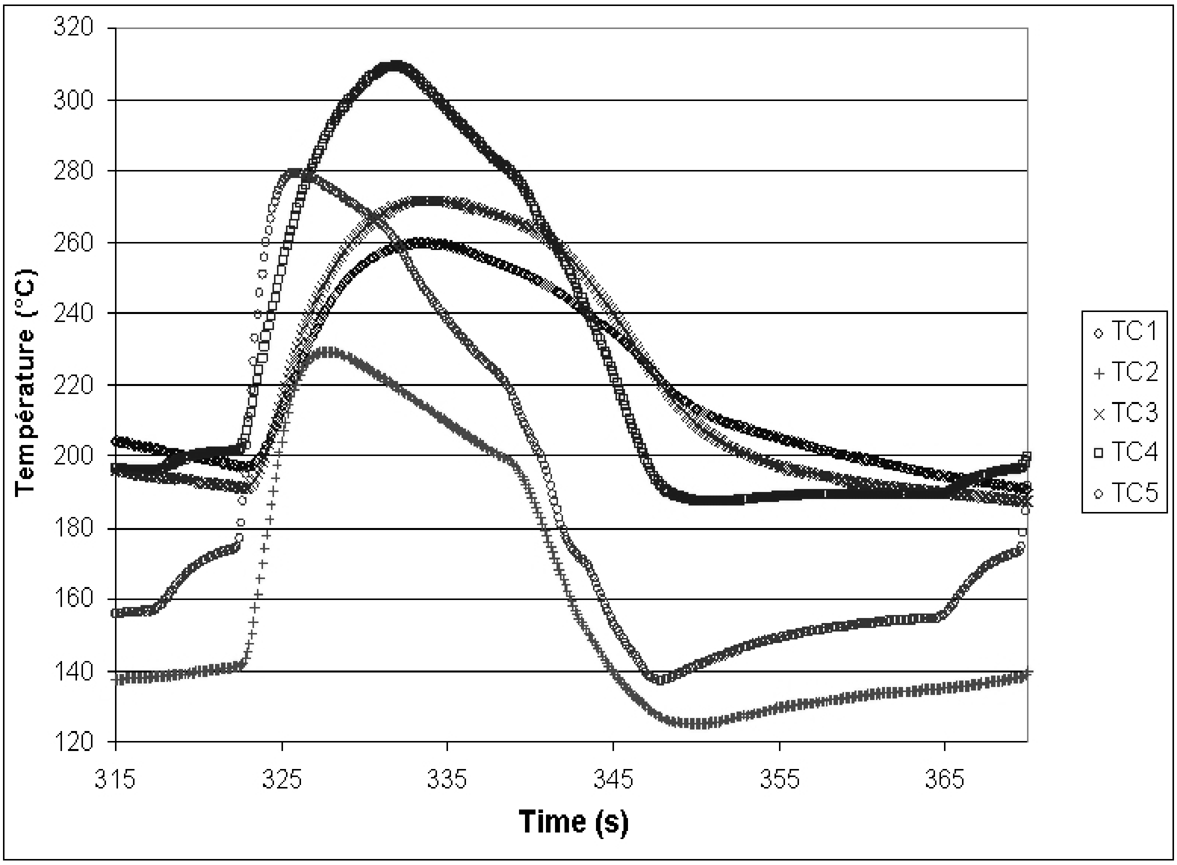
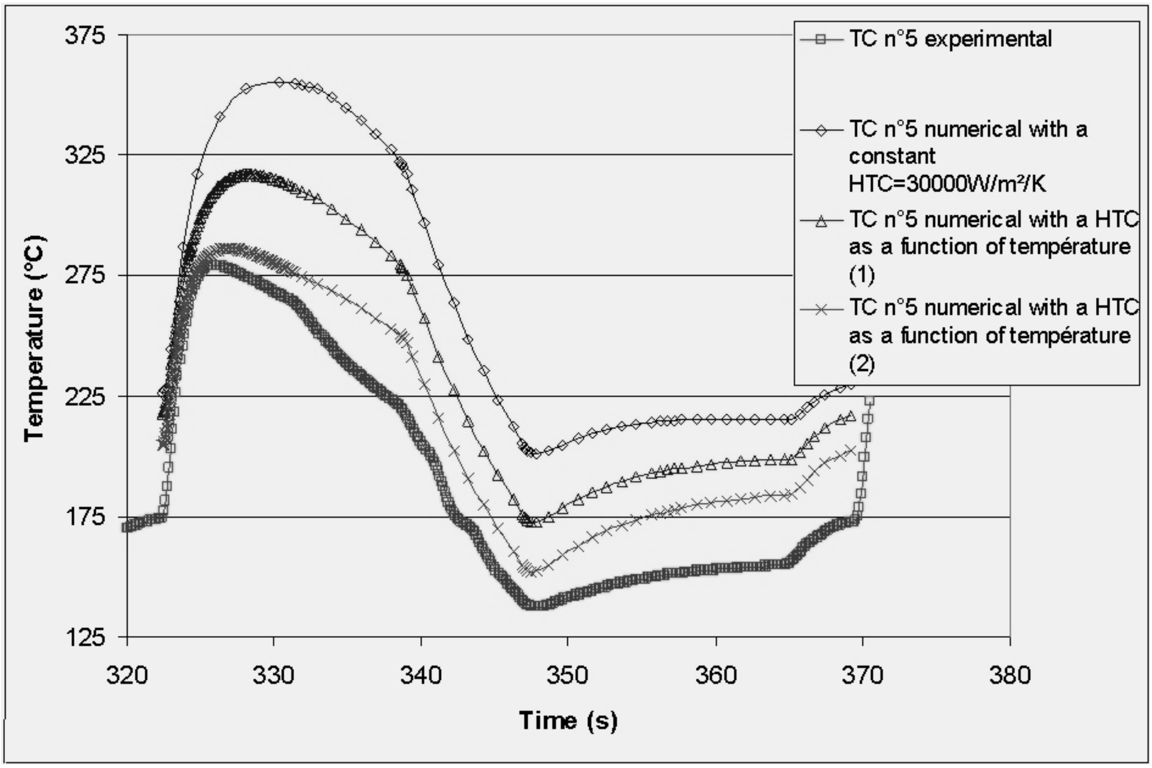


Figure 11: Temperature data for each thermocouple during the 7th cycle.



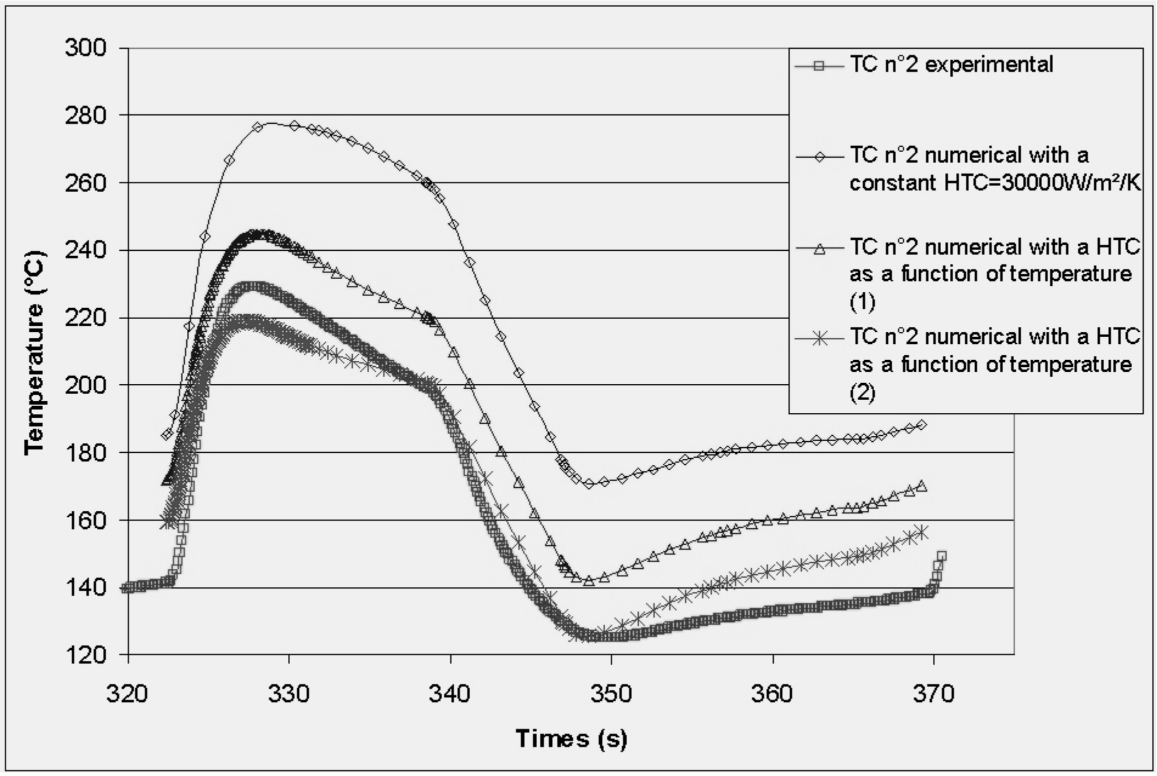


Figure 12: Temperature data for two thermocouples during the 7th cycle.

5. CONCLUSION

This study describes a case study of a mould, produced by Stratoconception, for high pressure die-casting. After showing the advantages of rapid prototyping technologies for the manufacturing of tooling and especially for the capability of positioning of the cooling channels in the tooling, we focused on the complete procedure of this mould manufacturing. This innovative approach includes the design with numerical simulations, the fabrication of the mould by the Stratoconception process and an experimental validation with 300 injections of aluminium parts in real industrial conditions. We presented a numerical modelling by finite elements of the heat transfer in the mould and in the part in order to predict the cooling of the part and to integrate numerical simulations as a design help of the cooling system. This modelling has been validated by experimental tests with different values of main parameters. Measurements of temperature variations in the mould during the injections have been carried out to be compared with the numerical results.

Even if future works are needed in order to propose a complete integrated toolset combining rapid tooling knowledge and related numerical models, it is realistic to think that the actual research program is a first step before talking about rapid intelligent tooling.

6. ACKNOWLEDGEMENTS

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