POLITECNICO DI TORINO

Course of automotive engineering

Thesis of master's degree

Simulation and validation of high-pressure die casting of an electric motor housing for automotive application

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CHAPTER 1

High-pressure die casting

In the high-pressure die casting process we inject at high-pressure melted alloys of Al, Mg, Zn in permanent steel shells called dies. Nowadays we can obtain parts with high-quality standards and compliancy with the trimming specifications, highly complex geometries, minimum thicknesses, tight dimensional tolerances, high mechanical characteristics, pressure seal, high surface finishing, holes ready for threading and minimum machining allowance for the following tool processing.

Figure 1: Fondalpress S.p.a plant

High-pressure die casting can be with hot chamber or cold chamber, in the following we will focus on the latter where it is used an injection system placed outside from the furnace. This technique fits with alloys having high melting points, in this case we will consider the HPDC horizontal cold chamber process used at Fondalpress S.p.a (figure 1) for the production of gearbox housings, transmission housings, engine mounts and engine covers with aluminum alloys. This metal has many favorable properties from the engineering point of view like low density, optimal thermal conduction, high plasticity, remarkable castability and the possibility to reach high mechanical characteristics when bounded with other materials. For the above mentioned properties it is very much used in the industrial world.

1.1 Pros and cons of the HPDC process and thesis objectives

We can now enlist the pros and cons of high-pressure die casting process with respect to the other most diffused casting processes that are typically shell casting and forging.

Advantages:

- Parts with very tight tolerances can be obtained, thanks to the employ of a metallic die and to the fact that during the solidification the metal cannot shrink spontaneously being obliged from the high-pressure applied to stick to the die walls
- Short cycle time, so high number of parts produced per hour
- Cheapness of the single casting
- Substantial savings of material can be generated thanks to the possibility of producing thin thicknesses walls and grant a good mechanical resistance with the employ of ribbed structures
- Metal inserts are easily embeddable
- Sprues, gates, runners and overflow are totally reusable
- Extreme versatility of the machine with the substitution of the die.

Disadvantages:

- Fair high initial investment, both the equipment and the dies with their components are costly with respect to most of the other casting processes. The restraint of the expenses is linked to the cadence of production, for this the casting machines are usually employed with various tools to automate the process, like robots for the withdrawal of the parts, devices for the automatic lubrication of the die cavity and trimming tools

- The presence of small amounts of porosities at the end of the HPDC process will forbid every heat treatment or welding where the temperature exceeds 300 °C. The heat will cause the expansion of the gas in the pores and this will create microcracks inside the part and the exfoliation of the surface
- Some shapes cannot be produced due to the impossibility of extracting the male of the die from the internal cavity
- Really thick parts cannot be produced.

Still today high-pressure die casting is mainly a pure matter of experience and often is called art. The casting process, however, is becoming more and more transparent and the know-how is based on science. There is a broad range of castable parts, the interrelation between the injection parameters and their influence on the quality of the cast is difficult to be fully understood. Overall is challenging to keep under control all the factors during the casting process.

The objectives of this thesis are the analysis of the high-pressure die casting process used for the production of an electric motor housing (carter). This is a new class of components that are being cast for the first time, we want to perform the process simulations with three different software to have a broad view of how they work when dealing with something outside the "traditional" range of products. In the end the results obtained will be compared with the real produced part during the sampling phase. If we will be able to find a match between what is simulated and the reality, the experience and the parameters developed can lead to the definition of guidelines for the following production of similar products.

CHAPTER 2

High-pressure die casting process

The HPDC process is very complex to be analyzed due to the presence of many different elements involved and the influence of many parameters. In the following, we will try to explore each phase highlighting every time which processes are taking place and which are their main characteristics.

2.1 Alloy melting and degassing

The material used to produce the parts is usually obtained from the melting of standard alloy ingots (figure 2) with the addition of foundry returns. Each ingot weights about 7 Kg and arrives at the foundry in stacks of about 1000 Kg. At the material arrival, before the melting, a chemical analysis is performed using an optical spectrometer on a specimen that has been sectioned and polished from an ingot. On average the percentage of foundry returns that are allowed to be remelted with the alloy is in the order of 30÷40%. Normally this value is never exceeded due to the increase of the uncertainty on the chemical composition of the final alloy with the introduction of more foundry returns and the unavoidable introduction of tangible quantities of undesired compounds (figure 3).

Figure 2: alloy standard ingots

Temperatures of aluminum alloys usually employed for high-pressure die casting are more or less similar to each other, about 750 °C. It is not suggested to work at higher temperatures to avoid:

- Loss of metal
- Reduction of magnesium in casting

- Increase of hydrogen absorption
- Increase of dangerous carbide oxide formation
- Destruction of gems of crystallization
- Reaction between the melted mass and the furnace walls
- Costs of energy employed.

It is wrong to believe that increasing the temperature is possible to obtain a viscosity improvement. Overtime we obtain the opposite, in fact higher temperature will facilitate oxide formation that reduces the viscosity. Alloy temperature depends also on the conformation of the part to be produced. With parts having thin walls, small interface between the runner and the part, temperatures are usually around 720 °C; while with parts having thick walls, big interface, it is suggested to employ temperatures of 680-690 °C. After the material melting in the furnaces (figure 4) the alloy is poured into the ladles. The liquid can be purified to eliminate the inclusions through the adoption of ceramic filters. Once the metal is poured into the ladle, this must be closed before the transport inside the foundry.

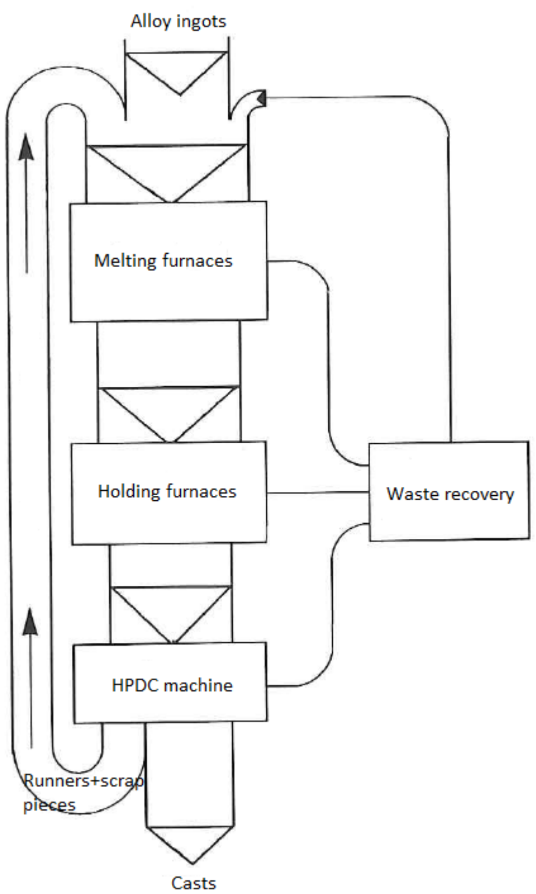


Figure 3: alloy melting path

Figure 4: melting furnace

Before transferring in the holding furnaces the degassing take place, this operation is necessary due to the reaction between aluminum and water vapor according to the equation:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H$$

It is obvious that the oxide formation and the hydrogen introduction go on together and represent the most important impurities in the metal, even if their quantities are small in absolute values, their presence can prove to be deleterious. The gassing phenomenon is influenced by different characteristics (figure 5):

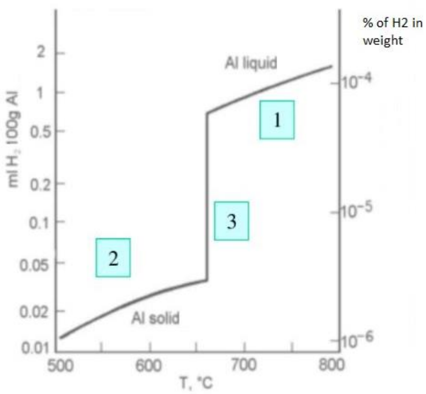


Figure 5: hydrogen solubilization in the aluminum

- A strong dependence from the liquid state temperature that results in an increase of the hydrogen content with increasing T

- Low solubility in solid aluminum
- A sudden solubility change in the correspondence of the melting point
- The presence of elements in the alloy can influence the gas content: diminish with silicon, manganese, zinc and copper; increase with magnesium, titanium, nickel and lithium.

High quantities of H_2 inside the alloy during the solidification can create many gas cavities. Their effects are more evident and more intense in the casts with remarkable mass (very slow solidification speed), on the opposite to the ones with reduced mass (high solidification speed) where their presence is considerably mitigated. Most of the practical difficulties encountered in the foundry can be attributed to an inadequate control of the hydrogen content, the deleterious effects on the casts include porosities, embrittlement, reduction of castability and reduction of mechanical characteristics. To prevent the development of these defects, and produce parts of good workmanship, the hydrogen must be reduced to values sufficiently low. It is necessary to remove as much as possible all the oxides inevitably present inside the melted mass, in fact they represent discontinuity solutions inside the matrix.

2.1.1 Causes of hydrogen enrichment and alloy impurities

The causes that bring to an increase of the hydrogen or impurities inside the melted alloy are multiple and they are linked to the temperature reached during the melting or during the phase of conservation in the furnaces:

Figure 6: picking with the bucket

- The superficial skin (alumina), which formation is due to the tendency of the aluminum to oxidize after the contact with the oxygen in the atmosphere, prevent the enrichment of H_2 inside the alloy due to the contact with the external environment especially when the liquid metal is kept at high temperatures (760/770 °C). The protective film at each picking with the bucket (figure 6) is broken triggering the gradual gassing of the alloy. This problem can be generated by the oxide layer that it can be pushed and trapped inside the fuse, creating two not wettable contact surfaces that trap the gas.
- During the melting, phenomenon of pollution of the alloy can take place due to the formation of oxides, nitrates, carbides and solubilization of the gas. The sum of the waste compounds is simply called slag and weights on the economic efficiency of the melting center in a percentage with respect to the total weight of the charge oscillating between the 2% (melting of only standard ingots) and about 4/5%, obtained melting a charge made of recycled parts dirty with oil, sprue with stuck sand and other materials arriving from the processing of the cast.
- When an ingot is inserted in the molten pool that is at about 720 °C (processing temperature), even if preheated, a ΔT is instantly triggered with the molten alloy. Assuming to insert a preheated ingot at the temperature of 100 °C (to avoid dangerous explosions), the ΔT will be about 620 °C. In the time between the insertion of the ingot and the melting, elements like Fe, Cr, Cu, Mn, Ni contained in the liquid alloy in contact with the solid ingot cooling down will lose their solubility with aluminum, precipitating at the bottom of the melting pot having a higher specific weight, thickening in coarse constituent denominated hard spots. Repeating the operation many times, at the bottom of the melting pot we will have a thicker and thicker slime layer. This will be dangerous because if agitated the material at the bottom will disperse in the alloy that will be picked by

the buckle to feed a new working cycle. The agitation can be given simply by the loading of the ingot, slagging, etc. The amount of material at the bottom is directly linked to the quantity of alloy processed.

2.1.2 Degassing processes

We can have different degassing processes (figure 7) to limit the hydrogen content, the most used are natural degassing, degassing through solidification, degassing using mechanical actions, degassing with chemical-physical action, vacuum degassing and ultrasound degassing.

Figure 7: degassing station

As mentioned before the oxide Al_2O_3, thanks to its density close to the one of the alloys from which it came, can stay suspended above the melted mass and this will enable the presence of very dangerous inclusions in the produced parts. Deoxidants should mainly act at the physic-chemical level and consequently mechanically. The two most used methods are:

- Deoxidation through solvent action where it is exploited the fact that they have a lower melting point with respect to the temperature of the metal to be treated. The products that are inserted and scrambled into the melting pool melt, the oxides inside the melted mass migrate toward them with which there is higher affinity. At this point the liquid purifier absorbs the oxide plates in the melted pool and became thicker, increasing its melting point it goes up floating

- Deoxidation through chemical action where chlorides and fluorides react with aluminum oxides giving rise to complex salts with high melting point. The oxides can be in different solid phases and the purifier has different reactions depending on the state of the oxides.

2.2 Holder furnaces

Holder furnaces (figure 8) are placed near the high-pressure die casting machine and have the task of maintaining the aluminum transported by the ladle at a temperature higher than the melting point that suits the casting of the component. The holding temperature of the furnaces should be evaluated considering that part of the metal thermal content will be lost during bale out operation and the pouring in the injection cylinder. Another heat fraction will be lost while the metal fills the die being this one at a temperature lower with respect to the metal solidification point.

Figure 8: holder furnaces

2.3 High-pressure die casting machine

For the die closure we must exert a predetermined force and this characterize the dimension of the machine (figure 9). The clamping force should counteract the force generated by the pressure acting on the molten metal developed by the injection piston. This opening force tends to move away the two sides of the die. Usually the clamping force (FLI) is higher with respect to the corresponding opening force of 15÷20%.

$$FLI = \frac{AIM \times pl3M}{100} = kN$$

AIM: projected area on the die division line

pl3M: pressure of the metal

Base cycle:

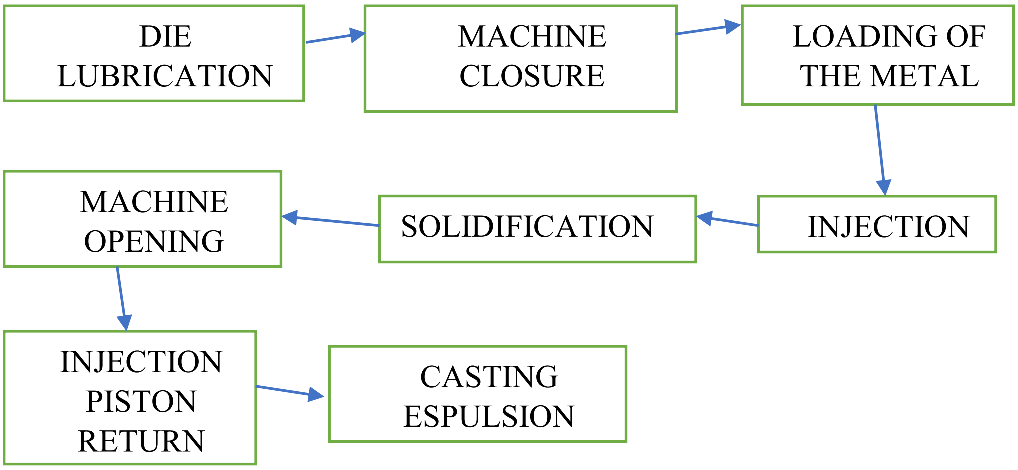


Figure 9: high pressure die casting machine

The functioning of the injection machine can be represented on a diagram called PQ^2. This is a fundamental instrument to understand if the HPDC machine, the injection system and the mould can work together efficiently and reach the target quality performance. The diagram is formed by two curves:

- HPDC machine/cylinder curve that varies depending on the type of machine, cylinder diameter, line pressure
- Mould curve that considers gates sections and charging losses of the runners

The complete explanation of the PQ^2 diagram will be given in the following when considering the actual diagram of the casted part that we are going to analyze.

2.4 The die casting die

It is the component that directly gives the shape to the produced part, it must satisfy different needs:

- Exactly reproduce shape and dimensions of the part
- Ensuring at the operating temperature the relative movement between moving parts
- Resist to the thermal excitation and mechanical efforts coming from the injection and the pressure exerted by the melted metal
- Allow after the metal solidification the extraction of the part without the generation of breaks and deformations.

2.4.1 Structure of the die casting tool

Usually the die is made of a mobile part (figure 11) and a fixed part (figure 10). On the mobile part, or sometimes also on the fixed one it is possible to find radial dowels used to create particular conformations in the cast or having to create holes that are not crossed by the division plane between the two half planes of the die. The division line should be the simplest and the most linear possible, every deviation from a unique planar feature will lead to a higher cost of the die. To allow the extraction of the part the die is manufactured with suitable drafts and the plugs with suitable taper, the extraction of the part however is not possible if the die is not lubricated. The die can be composed by moving parts: lateral dowels (that realize part of the die cavity figure), plugs (allowing the creation of holes in the part). In the foundry slang the ones from the above-mentioned components whose axis are not on the division plane of the die are called "cores".

Figure 10: die fixed side

2.4.2 Main functions and components

The casting device should absolve three essential functions:

1. Carry the melted metal from the injection cylinder toward the die cavity
2. Ease air and gas vent to ensure the regular filling
3. Ensure with the minimum loss the needed pressure to obtain a healthy and solid part.

The main components are:

- Feeder or biscuit: it develops in the injection cylinder after the filling of the die cavity, it is made by the surplus of poured melted metal with respect to the quantity needed for the complete die filling. Due to its thickness this is the last part of the cast that solidifies. Its dimensioning is really important for the prevention of the formation of cavities.

Figure 11: die moving side

- Sprue: channel through which the melted metal passes from the injection cylinder to the die cavity, it should allow the flowing of the material with minimum thermal and mechanical energy losses. To hold at the minimum the thermal energy losses the shape of the channel should be the one that has the smallest perimeter in relation to the section. The channel should be the shortest possible, do not have abrupt direction changes and good rheology.
- Connection between sprue and gate: the gate is always wider than the sprue, so it is necessary to create fittings between the two sections.
- Overflows: they have the task to collect the dirt and oxidized part of the metal entered in the cavity that otherwise will remain segregated in the cast lowering the overall quality. These components usually end with an air vent of which they are the anteroom that improve the efficiency of the overflow and eliminates the air trapped in the part and coming from filling turbulences.

- Air vent: they must allow the evacuation of the air that is inside the die cavity and of the gas that forms when the melted alloy enters in contact with the lubro-separator film.

2.4.3 Thermal behavior and dissipation methods

The die usually operates in a range of temperatures between 200 and 350 °C and it expands increasing the original dimensions of the mold cavity, this must be taken under consideration during the design starting phases to obtain the correct final dimensions. From this we can understand that the cast dimensional precision mainly depends on the thermal control of the process. As said the die has the function of absorbing the heat of the injected alloy till it is solidified and lower the temperature until the reaching of the most suitable one for the cast extraction. For this reason we speak about "thermal work of the mold", in every injection cycle a thermal impulse is given to the die which entity depends on the thermal content of the injected alloy and the total thermal contribution is given by the hourly amount of alloy that pass through the die. The thermal equilibrium point is established at a given temperature in relation to the dissipative capacity of the mold at that given thermal regime. At the time of injection the thermal shock will generate a sudden increase of the superficial temperature of the die in contact with the jet, after the heat will penetrate inside the die. The penetration depth will be determined by the time and by the characteristics of the material of the die. If the machine is working with regular rhythm the thermal impulses given by the sequence of injections will determine a constant mean flux that goes from the mold cavity to the heart of the die and towards the cooling channels.

We can have many different and concurrent dissipation and heat removal strategies:

- Convection dissipation: in the operating phase on the external faces of the die the temperature varies from 70 to 120 °C while the air temperature is about 20÷30 °C. In this case we have a thermal gradient between the die and the air, being this last in contact with the die it warms up and starts a convective motion that takes away the heath from the mold. The amount of heat dissipated in this form is linked to the following factors: die area, thermal gradient and state of quietness or motion of the air. The quantities dissipated in this form are modest if the die is closed but becomes relevant when the die is open and not only the lateral surfaces but also the frontal one, having a higher temperature (200÷300 °C), are exposed to the air

- Radiation dissipation: depends on different factors like the material emissivity, die temperature and emitting surface area. The dispersion by irradiation is closely related to the temperature with a hyperbolic behavior, so the higher the temperature the higher the dispersion
- Conduction dissipation: determined by the contact of the hot die with the colder sides of the machine, in this case a thermal flux is established from the die to the machine. Of the two sides of the machine the fixed one has the higher temperature and dissipates more heat.

If we consider the heath given to the die by the melted alloy, the number of cycle per unit of time and the consequent global thermal emission, hardly ever it is sufficient to prevent that cycle after cycle the die assumes an higher and higher temperature. To take away this heath we have two devices, the cooling system and the spraying of the die cavity. It is noteworthy that different temperatures in the zones of the cast during the expulsion phase can lead to deformations and a decrease of mechanical properties.

2.4.4 Life of the die casting die

Usually the operative life of a high-pressure die casting mold used with aluminum alloys can be in between 100.000 and 250.000 molded, while the life of some components of the die like cores, males and reported plugs can be between 50.000 and 100.000 molded. Thermal shocks and mechanical stresses are the main causes that limit the die life, other limiting factors even if with lower influence with respect to the previous mentioned are erosions and corrosions. Some influence on the die life is also given by the choice of the material, construction and fabrication of the die, heath treatment, accurate selection of the parameters, care of the molds and their cleaning. The operative life of a die can be increased by a preheating and a suitable cooling. The preheating has among the various utilities the one of reducing the length of the start-up phase before the production of casts with a good surface finishing. Often it is neglected that the increase of the temperature has a remarkable influence on steel toughness and that the influence of the temperature is not linear. In the thermal analysis we can see that steels for mold construction have a transition from brittle to ductile around 150 °C, below this temperature their toughness is by far lower. During the cooling of a die, the thermoregulation equipment (heating/cooling) proves to be effective for a gradual heat transmission without thermal shocks.

2.5 Cooling circuit

Realized through appropriate hydraulic channels machined in the thickness of the mold cavity and arranged to create one or more closed circuits. The heat removal works through the transfer of heat from the die to the cooling fluid (water) that enters at low temperature and will exit at a higher one. The amount of heat taken away by the cooling circuit depends on the thermal gradient between the die and the fluid and on the areas of the circuit where the heat exchange takes place. The exchange intensity between the mold and the fluid is regulated by the type of motion of the fluid, it will be higher with turbulent motion and lower with laminar motion.

Often in the dies there are big males or relevant stands out on the cavity profile. In this case and many others, the geometry of the figure does not allow the realization of the cooling channels where needed. These parts can be cooled with water jet devices called fountains. The heat removal of these devices is very high, so it is necessary to verify that the removed heat does not exceed the overall amount of heat to be taken away causing defects on the part.

2.6 Lubrication

Die lubrication is one of the most important steps of the process, in fact this activity as we will see in the following is fundamental to obtain parts of good quality. Inadequate lubrication of the die cavity can cause defects on the casts, low quality, low productivity, breaking of the plugs, production stops and metallization. The lubricant can be mixed with water or with oil content. Lubricants with oil not having the Linderfrost effect problem remain more concentrated with respect to the ones with water and thanks to this we can use very short lubrication cycles.

Figure 12: interaction between aluminum and lubricant

2.6.1 Functions of lubrication

The main functions of die lubrication are:

- Formation of a separating layer: the separation is given by the amorphous oxide layer created by the chemical reactions, it avoids the direct contact between melted metal and mold steel. The aluminum at high temperatures (above 700 °C) behaves as a universal solvent and tends to dissolve the iron, so with the spraying we create a separating layer that isolates the two parts. When this barrier does not exist or it is broken by the alloy flux entering the mold the result will be the metallization of the die cavity and real weld between the alloy and the die. These amorphous oxide layers have also a pretty low thermal conductivity and this will slow down the thermal exchange between the alloy and the die retarding the solidification of the metal, preventing that too early solidifications impede the optimal filling of the cavity.

- Fluidizer: ease the flowing of the melted metal over the die cavity. The melted metal due to its viscosity meets a certain resistance when flowing in the mold cavity and could cool down too early slowing down or stopping the incoming metal at its back.
- Formation of lubricant film: after the spraying the film is thinned or destroyed and of it remains only a residual fraction and its ashes, these residues should fulfill the task of cast lubrication during the extraction phase. The lubrication required is both static and dynamic:
    - Static lubrication: prevent the cohesion between the two metal that are pressed together and reduces the starting effort for the cast detachment. This last should be contained through the lubricant within the limits of the hot resistance of the alloy, otherwise there will be deformations and breakings. The initial detachment effort is in some ways reduced by the pressure exerted by the gasses produced during the decomposition of the lubricant film. Due to this, the film should not be completely destroyed during the injection phase, in this way the remaining fraction will continue its decomposition even after the injection. The gas developed not finding another way to exit the mold can exert a pressure on the cast and ease the extraction.
    - Dynamic lubrication: it takes place when during the extraction phase the cast should slide on the shape that creates it, the friction that is generated in this case is of the sliding type. Insufficient or inadequate lubrication in this phase will lead to

deformations, cracks and breaking of the cast. There are not precise data in the literature on the friction coefficient between steel and aluminum at high temperature but it can be reasonably estimated in about 0.9. This value is really high and from this we can see the necessity of reducing it with a suitable lubricant. The dynamic lubrication seems to be more critical the more the geometry of the part is hostile to the extraction.

  - Lubrication of mold moving parts: the spraying of the mold cavity inevitably directly or indirectly runs over the parts out of the figure where are positioned moving dowels, plugs, etc. These parts operate at temperatures between 100 and 200 °C and often slides on heat treated (hardened) tracks or rails. In this motion, we have sliding friction between steel and steel. These parts are usually lubricated during the assembly with a special paste, during operation the lubrication is maintained by the portion of the film that deposits especially on the terminal parts as a consequence of the die cavity spraying. Normally the indirect lubrication given by the spraying proves to be sufficient to allow regular functioning.

- Cooling: the lubricant can also be used to cool down the die, in fact it is made of aqueous emulsions that have the cooling of the die as a secondary effect. In this case the cooling takes place in two concomitants ways: heat removal due to emulsion heating ad heat removal due to vaporization. These cooling methods are really effective, in fact the thermal heat taken away by the spraying of the die cavity is the one of the thermal skin of the mold that is the heat accumulated in the first layer of the mold surface and that has not yet penetrated the thickness of the die. In this case the heat is directly removed where it is accumulated not having to wait that it penetrates inside how is although needed when removing heat with the internal cooling circuit. This system has the disadvantage of increasing the thermal stress of the steel causing higher thermal fatigue that can speed up the formation of superficial cracks. The importance of the cooling given by the spraying becomes more and more relevant in relation to the cadence of production.

- Cushioning function: represents the dampening behavior of the lubricant that is the first element hit by the liquid alloy jet. The injection velocity exceeds 50 m/s, so there is the possibility of damaging the die for this shot and the lubricant tends to ward off this.

2.6.2 Mold spraying

When spraying (figure 13) the hot die cavity surface with the emulsion different physical and chemical phenomena take place (figure 14):

- Water vaporization: when a drop of water touches the hot surface suddenly we have the formation of a vapor cushion between the drop and the hot surface that impedes the direct contact between the two parts, the vapor cushion works as thermal insulation. This phenomenon is called Linderfrost effect and it is more relevant the higher the temperature difference between the two parts. The vaporization of a fraction of the drop takes place at the expense of the thermal energy owned by the surface and this tends to lower the surface temperature. The following drops finding a temperature lower and lower will be able to wet the surface in the end.

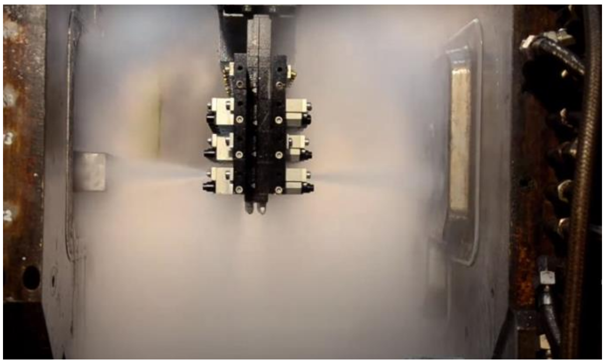


Figure 13: Die lubrication

- Chemical reactions: when the drop particles enter in contact with the steel of the die some chemical reactions take place producing oxidation of the steel surface itself. The oxide layer creates an efficient barrier that protects the steel of the mold from the aluminum aggression and having a low thermal conductivity act as an insulator towards the following emulsion drops that hit the same point.
- Boiling, evaporation: when the emulsion drop succeeds in wetting the mold it heats up till the boiling and the following evaporation. In this phase we have the maximum heat subtraction and the consequent lowering of the die hot surface temperature.
- Active products hook to the mold: the hooking mechanism to the mold of the active products contained in the emulsion that compose the separating and lubricating film, is linked to particular physical effects. Oils, waxes and other active fractions have their own viscosity and adhesiveness. The temperature that they take due to the contact with the hot surfaces highlights capillary phenomena due to which these elements expand over the surfaces and tend to penetrate in the material porosities and in the oxide layer formed in the previous phase by the water evaporation.

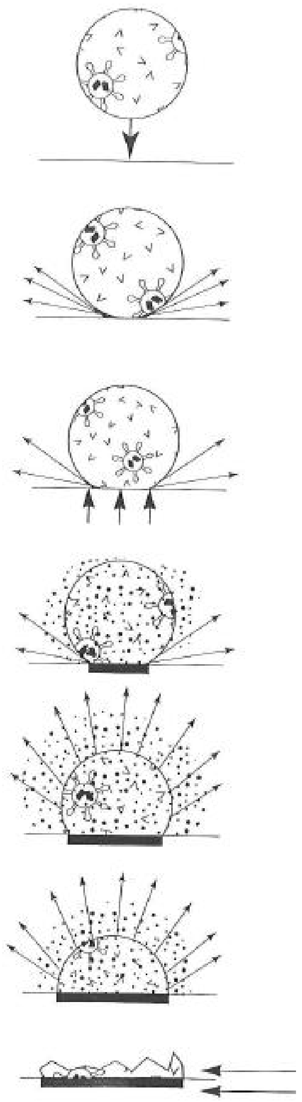


Figure 14: interaction between lubricant drop and the hot mold

To keep the surface of the cavity in good health as long as possible the spraying should be performed from a certain distance. Too narrow distances produce higher thermal shocks and the possible appearance of premature cracks on the mold, even if reducing the time needed for the film formation. The spraying is usually performed in an automated way and its manual version nowadays has been abandoned. The automatic system presents numerous advantages with respect to the manual one for example the reproducibility of the cycle, constant quality of the jet and an increase in the hourly production.

2.6.3 Mold wettability

The factors that determine the mold wettability and the consequent formation of the lubro-separating film are:

- Temperature of the mold cavity
- Pressure and energy of the jet
- Distance and length of the jet
- Angle of incidence between the jet and the cavity
- Amount of product reaching the cavity

A very important role is played by the temperature of the part of the mold that enters in contact with the emulsion, this temperature should be enough to cause the complete vaporization of the water leaving on the die the active parts fractions contained inside. The pressure of the emulsion and the one of the compressed air used for the pulverization characterize the jet in two different aspects. The pressure determines the pulverization degree of the emulsion and determines also the thrust and by so doing the

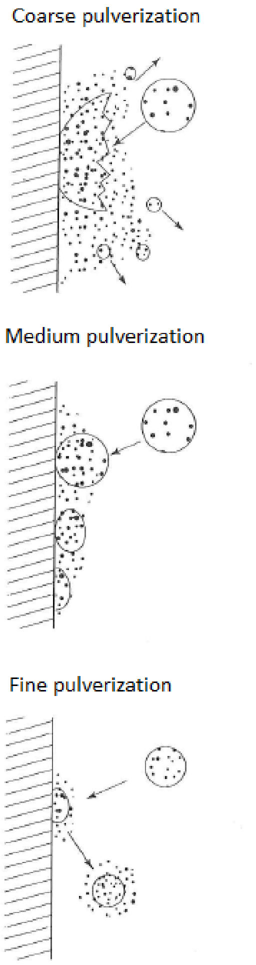


Figure 15: effects of different pulverizations on die wettability

velocity of the jet at the nozzle exit. The distance between the dispenser nozzle and the mold surface determines the impact force of the jet with the die, from which depends on the wetting possibilities and the formation of the lubro-separating film. The spraying jet projected on the hot mold cavity is at first rejected and the emulsion flows away with poor effect for the film formation. This rejection and the amount of emulsion that flows away without any effect are conditioned by the angle of incidence between the jet and the mold cavity. A fraction of the sprayed emulsion drops drown without forming the film, this fraction is variable as a function of the mold temperature, the spraying velocity and the geometrical shape of the cavity. This quantity on average is between 20% and 40%.

The drops dimension together with the other parameters that characterize the spray play a very important role for the formation of the lubricating and separating film. For the optimal film formation the drops that reach the die surface should have enough energy to flatten on it. A coarse pulverization of the emulsion will produce bigger drops, this can lead to a too high impact force sufficient to make them bounce without effect for the film formation. Fine pulverizations produce drops with very small dimensions that determine a reduced impact force. In the end drop dimensions (figure 15) should be the most suitable in relation to the mold temperature.

2.6.4 lubricant film degradation

Once the film is attached due to thermal conduction its temperature equals the one of the zones of the die where it is positioned. The heating of the film will cause its drying and the starting of the degrading process. Keeping the film for a certain time at temperatures equal or superior to its boiling point causes its oxidation freeing the volatile parts contained inside. Once injected in the mold cavity, the melted alloy reaches a temperature of 650-700 °C. The film attached to the die parts came in contact with the alloy and it is deeply altered by the high temperature, the film decomposes and of it remains only residues and ashes. The fraction of the film more or less altered that remains with the residual ashes on the die depends on the film components, on the base of their quantity and their temperature. These residues provide the static and dynamic lubrication necessary for the extraction of the cast without inconveniences.

2.6.5 cavity drying

Right after the spraying and before the closing of the mold, the lubrication cycle foresees the drying of the mold. This is obtained by blowing compressed air at ambient temperature. The blowing is realized using a dedicated circuit positioned inside the lubrication head and activated in the same way of the spraying circuit. This operation is necessary because after the spraying in normal conditions the cavity remains damp or wet and we need to eliminate these fractions that can be dangerous. The utility of the drying can be resumed in the following points:

- If the melted alloy met some liquid fraction inside the cavity it can evaporate so rapidly to originate explosions
- The areas where the lubricant is not dried, remaining dump, tend to present defects of various nature, first among all the unsightly dark spots due to which the cast is considered scrap
- With the drying it is possible to remove from the die solid impurities, metalized or sprayed aluminum film that will determine defects in the cast or actually missed closure of the machine.

Insufficient drying can determine the above-mentioned problems, on the contrary, we do not have particular problems using it not considering the not negligible problem of increasing the cycle time.

2.7 Injection

Particular attention must be dedicated to the temperature in the injection cylinder. In fact already at this point we can have the formation of presolidified points that in the following will show in the cast as inhomogeneities, negatively influencing resistance, tensile strength values and eventually the workability. Due to this the residence time in the cylinder must be kept as short as possible.

The tolerances of the injection piston are very important for trouble-free casting. This last varies on the base of the piston and cylinder temperature. The tolerances gap between piston and cylinder change with the temperature, when it exceeds 0.12 mm we should fear the infiltration of metal in the injection piston that over a long period can cause damages to both the piston and the cylinder.

The filling of the cavity can be divided in three phases (figure 16):

1. Prefilling of the cavity: the metal is introduced into the injection cylinder, the piston starts to move and expels the air that is in the cylinder, bringing the metal near the gate of the mold. For not having the air trapped in the cylinder the speed of the piston should be below 0.25 m/s, for higher velocities the metal regurgitates and the air remains trapped being successively introduced in the die cavity. At the end of the first phase of injection we find the so-called point of intervention of the second phase, this determines the position reached by the

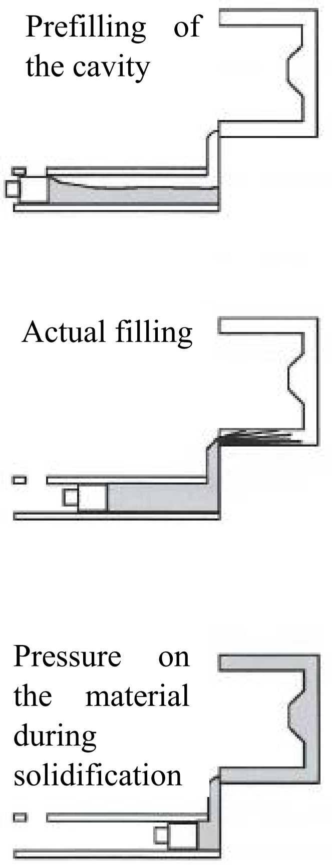


Figure 16: three injection phases

metal at slow speed with respect to the sprue. This point should be positioned as close as possible to the gate, in fact if it is positioned rearward the porosity of the cast can increase.

2. Actual filling: due to the motion of the piston we have the filling of the die, this phase should be as short as possible compatibly with the cast wall thickness. In this case the velocity of the piston will be higher and will be determined by the amount of metal to be introduced in the die in that available time interval, generally from 1 to 5 m/s. The amount of alloy poured in the cylinder is always greater than the quantity needed to fill the cavity, so the second phase stroke is shorter than the one given by the useful length of the cylinder. The alloy in surplus solidifies in the cylinder creating the so-called riser or biscuit and it is from this volume that during the final pressure phase on the metal is drawn material to feed the solidification shrinkage of the alloy inside the mold cavity.
3. Pressure on the material during the solidification phase: when the piston stops due to the completion of the cavity filling a pressure is exerted on the metal, this propagates across the still liquid metal in the cavity compressing it and feeding the part during the solidification.

Times and ways of mold filling are conditioned by the possibility of exhausting the air contained in the mold and in the injection cylinder. Theoretically we should have the entering metal that pushes forward the air that must be expelled through dedicated openings in the mold (overflows). One of the determining factors for the aspect of the part surfaces is the velocity of the metal jet entering the mold together with the filling time. The velocity of the melted metal jet is called velocity at the gate and should be in the order of 20÷60 m/s, in most of the molds we have vMA 40÷60 m/s. The velocity is in turn determined by the section of the gate and by the section and the velocity of the injection piston. The maximum admissible speed vMA depends on different factors: bounce angle, metal temperature, type of alloy, amount of alloy, surface and temperature of the mold. For what concerns the filling time normally it varies from 0.03 s and 0.3 s, in most cases it varies between 0.03 s and 0.1 s. Knowing this value is really important to define the heat lost during the mold filling. One of the necessary conditions to produce a good quality cast is that the alloy at the end of the die filling is still liquid.

To obtain an ideal die filling without damages, we should focus on the flux that we are going to create with the injection. The flux inside the mold is influenced by the following factors:

- Position of the gate
- Velocity at the gate vMA
- Velocity of the metal at the entrance of the mold
- Temperature of the metal
- Alloy (viscosity)
- Mold temperature (solidification during filling)
- Lubricant film (mold surface).

The die filling is considered ideal when it is possible to fill completely the die cavity with still liquid metal and evacuate all the air through the overflows, or vacuum it using a vacuum channel. Moreover the die should not be damaged by erosions, cavitation, corrosions and metallization.

2.8 Air vent

It is possible to distinguish two types of vents, natural vents (overflows) and forced vent (vacuum). The maximum velocity of the air in the venting channel is 333 m/s (sound speed), due to the shockwaves (sonic bang) at the end of the stretch of seal of the venting channel it is not possible to reach higher velocities.

If not enough air is evacuated, due to the increase of the pressure inside the mold the mixture of air and gas is integrated inside the nebulized alloy. The oxygen contained in the gas united with the alloy will form Al_2O_3 (aluminum oxide), the other gas will remain as micro porosities. Gas accumulations can cause visible porosity. The venting of the mold is very important and the forced venting (vacuum), for many applications, has big advantages. To obtain a good structure it is necessary to evacuate as much as possible the mixture of air and gas from the die.

2.9 Metal solidification

The time over which the solidification takes place is linked to:

- Solidification interval that is the difference between the temperature of solidification start and the one of the solidification end proper to each alloy
- Temperature of the metal
- Mold temperature and cast wall thickness.

The heat removal causes the solidification, if the heat transfer from the melted metal to the mold is too fast cold spots and blooms can appear on the cast. If the heat transfer is too slow the cycle time lengthens and we have a reduction of productivity. The aluminum, during the phase change from liquid to solid lose about 8% of its volume, we should reintegrate this volume using high-pressure through the gate, but the gate after the filling remains open only for a small fraction of time. In the hot zones the injected metal remains liquid for a longer time with respect to the colder zones of the cavity. The liquid metal will flow towards the solidification front feeding the cast. The injection piston exerts a pressure on the still melted metal in the riser, forcing it to flow from the riser to the sprue and to the gate, filling the holes that form during the solidification. The zone with the higher thickness will be the last to solidify and the feeding of the shrinkage of this part will be prevented by the occurred solidification of the previous part of the cast. The zones with the higher thickness will behave as a lung for the feeding of the nearest parts till the complete solidification, leaving a void. The overall shrinkage will determine in the cast the porosities and the voids of the thickest section.

After we can compress the alloy with an external post compression pin (squeeze pin). The post compression pin should not remain immersed for too long, otherwise it is not anymore possible to extract it due to the increase of the diameter caused by the thermal dilatation. The gate should be solidified before the post compression starts.

The thermal regulation of the die is very important to get the desired mechanical characteristics, these improve with the increase of the number of grains for unit volume. This means that having two equal alloys the finer the grains the better the values of tensile strength and hardness. In high-pressure die casting grains dimension is undoubtedly linked to the local cooling time, short cooling times give fine structure with high mechanical characteristics.

2.10 Casted part Extraction

The systems for the expulsion of the cast from the mold matrix are generally characterized by a plate positioned under the mobile half die on which are fixed the extraction plug. This plate is moved by the extraction system of the machine to which is linked using beam passing through the mobile plane. It can be performed when the solidification is completed and the mean temperature of the cast has dropped down to a value between 350 and 250 °C.

Figure 17: robot transporting the cast to the trimming machine

For cooling the metal to this temperature it is needed a certain amount of time normally called cooling or solidification that depends on the metal/mold temperature and the ability of this last to dissipate heat. The value of this time interval is one of the factors that determines the production cadence. With higher temperatures with respect to the optimal one the alloy will be in a state of fragility and distortions and cracks can take place. If the time interval is too long the metal shrinkage will make difficult the extraction of the cast, especially with complex geometries.

2.11 Casted part trimming

This is the part of the process where sprues and overflows are eliminated. The robot positions the cast on the trimming machine (figure 18), this is made by a matrix on which is positioned the part and by a punch that coming down cut the parts. Usually at the gate 2 mm of space are left between the cast and the sprue, this is the point where pass the punch to complete the cut. The cut parts will constitute the scrap that as said before will be melted again.

Figure 18: trimming machine

CHAPTER 3

Most relevant process parameters

The physical and mechanical properties of an aluminum cast can be altered due to:

- Chemical composition: the chemical and physical properties of the component that will be realized are strictly related to the composition of the used alloy. With the aluminum can be bounded a big number of elements that promote certain characteristics on the final cast.
- Cooling speed: this determines the final dimension of the grains from which the physical and mechanical properties of the produced cast depend.
- Casting process: as said before there exist different casting processes in the industrial environment, for what concerns the high-pressure die casting it is divided mainly in hot chamber and cold chamber. Each process is characterized by different degrees of heat removal and different solidification speeds.

Before analyzing the parameters that govern this process it is useful to list some concepts over which is based on the high-pressure die casting process:

- The cast is formed gradually while the melted metal, injected in the mold, solidifies
- The solidification takes place due to the transfer of heat from the melted alloy to the mold
- A uniform solidification determines homogeneous structures in the different zones of the cast
- The time and the uniformity of the solidification condition, considering the employment of the same alloy, the values of mechanical resistance of the cast

In the high-pressure die casting process the most relevant parameter is the filling time of the die cavity that is directly proportional to the part thickness. Considering that the metal solidifies on both faces of the die cavity obtained on the two half mold sides, it is useful to consider the solidification as a phenomenon that from the heart proceeds through half the thickness of the cast. One of the main characteristics that should have the parameters listed below is regularity i.e., they should be constant during the cycle.

3.1 Part thickness and solidification module

It is hard that the casted parts with high-pressure die casting have a uniform thickness, a good approach to forecast the solidification mode is given by the theory based on the so called solidification module or cooling module.

$$mean\ conventional\ thickness = \frac{volume}{surface}$$

At this point, we have to consider that the part solidifies on the two faces of the die cavity, so the solidification/cooling module will be given by:

$$cooling\ module = \frac{mean\ conventional\ thickness}{2}$$

3.2 Cavity filling time

As said before this is the most important parameter of the process, in fact we must keep in mind that the metal should solidify only when the filling ended. Filling times can be related to cast thickness, the optimal time should be chosen as a function of the effective process conditions that can differ on the base of:

- Temperature of the mold cavity (varying in a range 150÷320 °C)
- Alloy injection temperature (varying in a range 620÷700 °C)
- Solidification interval (varying for every alloy on the base of the chemical composition)

3.3 Volume of the cavity

The mold cavity is the sum of the own volume of the cast and of the volume of all that parts that even if they do not constitute the final part are required for the high-pressure die casting process like the riser, the sprue, the overflows and the vacuum channels. In conclusion we should consider all the volumes that will be filled by the metal that are positioned after the injection cylinder.

3.4 Filling flow rate

For the transfer of the alloy volume in the mold cavity, in the time available and considered on the base of the part thickness, it is necessary that at the gate pass a determined alloy flow rate Q(dm^3/s). The flow rate is in turn given by the filling gate section and by the velocity at which the metal passes by on the base of the formula:

$$\mathrm{Q}(dm^3/s) = A(dm^2) \times w(\frac{dm}{s})$$

We should consider that these two quantities cannot vary arbitrarily, but the gate area is linked to the thickness and the geometry of the cast, while the velocity at the gate depends on the filling pressure.

The exercisable pressure on the metal to give it a certain velocity is determined by the high-pressure die casting machine characteristics and more precisely by the force of the injection system related to the piston surface. For a given metal speed at the gate, it is necessary a pressure determined by the mold characteristics in relation to the resistance to the flowing given by the casting systems overall.

3.5 Rheology of the metal at the gate

This is the speed of the metal while flowing by the filling opening of the die. It can be determined by measuring the speed at which the piston moves forward and finding the ratio between the piston area and the one of the gates.

$$speed\ of\ the\ metal\ at\ the\ gate = \frac{piston\ area}{gates\ area}\ x\ piston\ velocity$$

The most used velocities are between 25 a 50 m/s.

3.6 Gate thickness

The choice of the gate thickness is conditioned by many factors:

- The cast thickness
- The type of alloy conditions the thickness in relation to its composition
- The type of cast and the required quality
- Pressure seal and high mechanical resistance requires maximum gate thickness
- Surfaces appearance needs minimum gate thickness.

Currently the thickness is often affected by post-machining needs, therefore we use thicknesses that ease these operations. The gate has normally a rectangular shape or better for draft reasons slightly trapezoidal.

CHAPTER 4

Most relevant defects on casted components

The analysis of the defects of a product starts from the research of imperfections on the part. By imperfections, we mean a deviation from the standard characteristics for which is required a deep analysis. If a cast has imperfections this does not mean that it will be necessarily not suitable to be used, to understand if the cast can be utilized the imperfection should be analyzed through an appropriate scale on the basis of the project requirements. At the end of this chapter is possible to see the mean frequencies with which these defects appear in high-pressure die casting (figure 25). In the following, we will analyze the six main defects that can be found on the cast.

4.1 Porosities

Porosities are small holes or bags with air inside the cast (figure 19), these forms when during the injection phase air remains trapped in the mold with the liquid alloy. Porosities can be divided into macro and micro if they are visible or not with the naked eye respectively. Porosities can never be totally eliminated, also the best producible cast will have them inside, what we usually try to do is beyond reducing them to move in less sensitive areas. The most used methods for porosities check are X-ray and tomography as non-destructive methods and the analysis of a sample at the microscope as a destructive method.

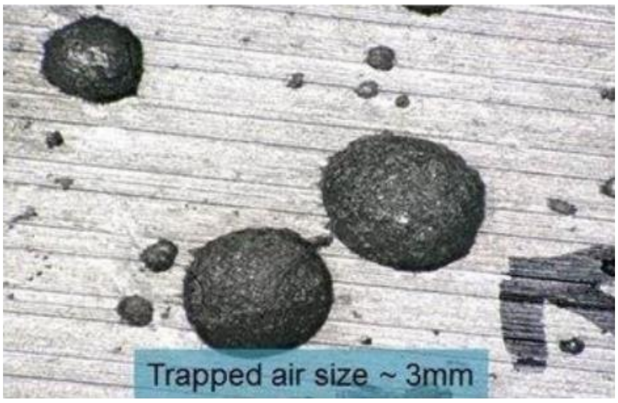


Figure 19: trapped air defects

The main causes of porosities formation are:

- Incorrect choice of gate position that causes the formation of vortex in the metal while entering the cavity
- Not enough melted metal in the injection chamber
- Too high velocity at the gate that provokes turbulence
- Not enough die ventilation
- The die cavity is too deep
- Too much lubricant on the die walls
- Incorrect alloy degassing

Porosities can be also caused by a high presence of H_2 in the alloy during the solidification phase that can generate high number of cavities due to gas (figure 20). The internal pressure of the pore formed during the solidification is strongly influenced by:

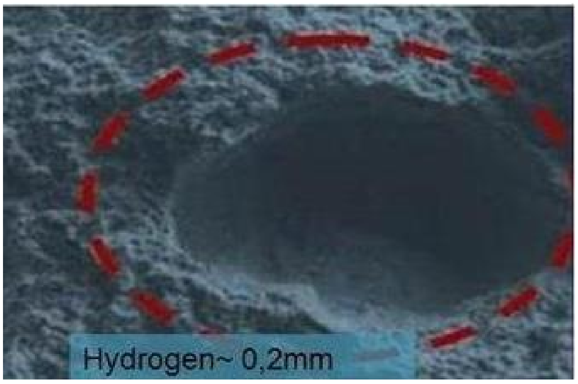


Figure 20: hydrogen inclusions defects

- Internal pressure of the gas seen as hydrogen accumulation in the interdendritic zone
- Cooling speed: by increasing it, the number of porosities and the mean dimension of the pores decrease, due to the shorter time available to the hydrogen to spread in the interdendritic spaces
- H_2 concentration in the melted aluminum pool
- Addition of modifiers
- Grain refining that takes place with an increase of micropores uniformly distributed.

The most effective ways to reduce the porosities in the casted parts are:

- Choice of the points where positioning the gates and their dimensions

- Shape of the sprue
- Position and dimension of overflows intake zones
- Vents shape after the overflows
- Mould division plane.

4.2 Inclusions

As seen before after the melting the aluminum in contact with air creates an oxide layer (alumina). In some cases due to turbulences created by the moving of the liquid metal pool this oxide layer can be trapped inside the aluminum. The oxide film is pushed inside and trapped in the fuse, creating two not wettable oxide surfaces in contact. The film tends to refold on itself generating the defect called bifilm.

There are two main methods to reduce the inclusions, first ensure the cleanness of the alloy pool and second use of a special bucket to take the alloy from the holding furnaces. These special buckets have a hole at the bottom, the bucket stays above the of surface of the alloy pool and is filled by the hole at the bottom. In this way we are able to take the alloy under the oxide layer formed on the surface. These special buckets are actually used by the company.

4.3 Shrinkage

If the metal once in the die cavity cools down and shrinks without sufficient melted metal to fill the left holes some channels that extends inside the cast can be generated (figure 21). These defects that can start from the surface and reach the heart of the cast are

Figure 21: shrinkage defects

called shrinkage. The more relevant is the lack of feeding, the larger will be the zone interested by the defect and the dimension of the single cavity. All the above mentioned is valid for the macro cavities shrinkage, however we can have also micro cavities shrinkage. These last can be generated by an insufficient feeding as in the case of macro cavities or by a non-correctly performed alloy treatment where the interdendritic spaces are not correctly cemented at the eutectic Al-Si having in the end the formation of voids.

Shrinkages are generally due to:

- Alloy injected at too high temperature
- Wall mean thickness is too unequal forming hot spots
- Too low pressure
- The injection cylinder is too small and the remaining metal at the end of injection (biscuit) is not sufficient to compensate for shrinkage
- The gate is too small
- The local temperature of the die is too high

Shrinkage can be reduced with the use of squeeze pin that compresses the alloy during solidification.

4.4 Hot crack

They form with the shrinkage of the material during the cooling down. In fact with the cooling the alloy shrinks passing from liquid to solid, if there is not enough liquid alloy to compensate this volume lost hot cracks (figure 22) are generated.

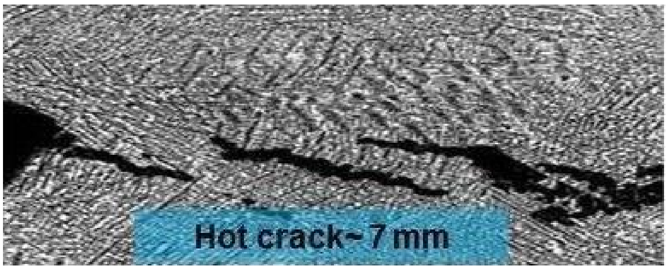


Figure 22: hot cracks

The main causes are:

- The liquid alloy is not able to reach the critical point for the material shrinkage
- Too low temperature of the mold
- Too late opening of the die and sliders retire

Normally the major cause of hot crack are zones with too high thickness on the casted part. This is due to the fact that the customer that designs the part may not have knowledge of the high-pressure die casting process. What we try to do is to work in synergy with the customer to improve the design of the part for a better castability.

4.5 Cold joint

They form due to joining of two fronts that are at a too low temperature to generate a metallurgic junction (figure 23). Physically the two parts are joined, but the mechanical properties of the junction can be extremely low.

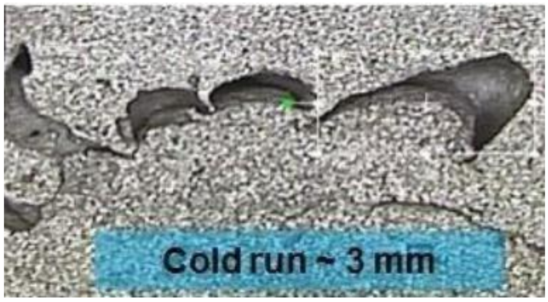


Figure 23: cold joints

Cold runs mainly form due to:

- Too cold temperature of the alloy or of the die
- Composition of the alloy not corresponding to the standards, scarce fluidity
- Too high filling time

The most important parameters to look for to reduce cold joint are:

- Choice of the point where to position the gates and their dimensions
- Shape of the sprue

- Optimal distribution of the temperature over the die

4.6 Aluminum alloy/ die interactions

It is possible to have two main types of defects due to metal die interaction. The first is the formation of an oxide (figure 24) due to high temperature difference between the melted alloy and the die. This defect can be identified as a surface like orange peel and it forms always in the same zone.

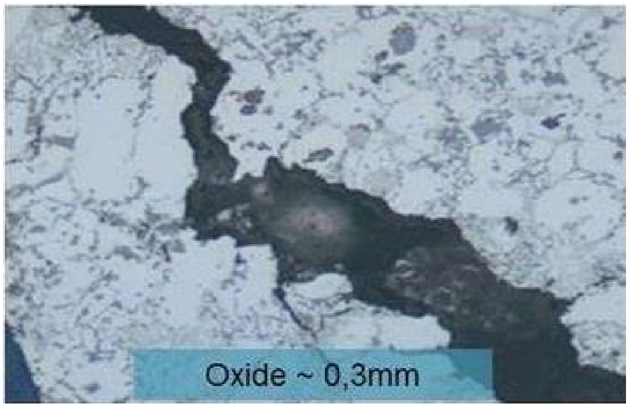


Figure 24: oxidations

The second type of defects are welds visible with the naked eye like black stains. These form when the aluminum takes away a part of the metal of the die and are due to too high temperatures and lack of lubricant.

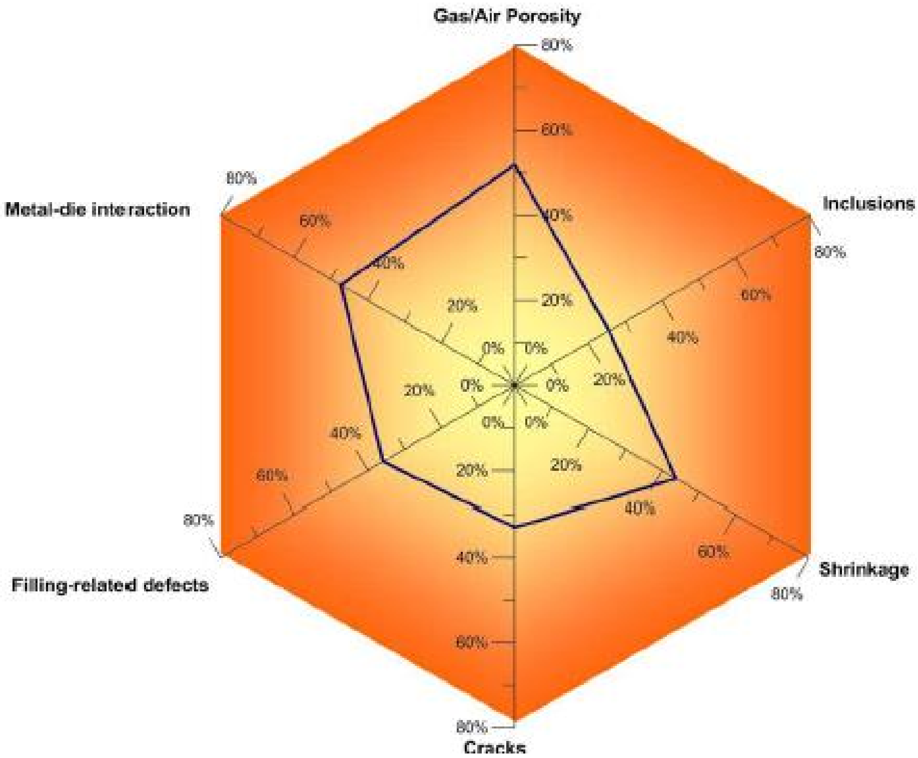


Figure 25: mean frequency of defects in the cast

CHAPTER 5

The case study and the process simulation: PSA front housing

The part that we are going to analyze is the frontal cover of an electric motor housing (figure 26). In particular this one is used by the PSA group on the new generations of electric motors that will equip their car.

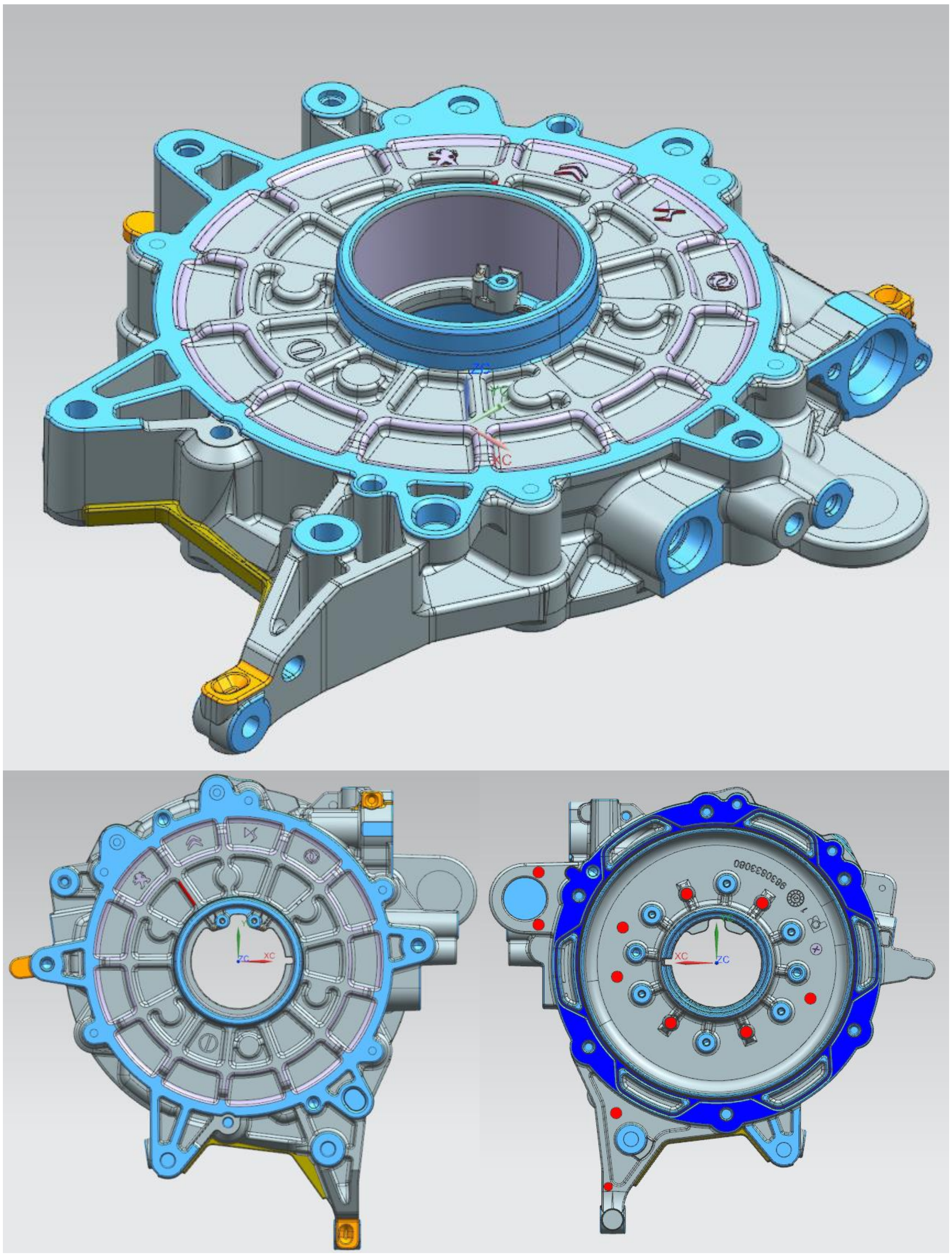


Figure 26: PSA front housing model

This component is something innovative and being applied to a fully electric car will be produced for many years following the electric revolution. The main problem with these parts is that being new and being the first time that they are cast, there is no literature to which make reference and there are no reports of past experience with similar products. What we will try to do in the following with the simulations is to identify the guidelines that will constitute the basis for the production of good quality products.

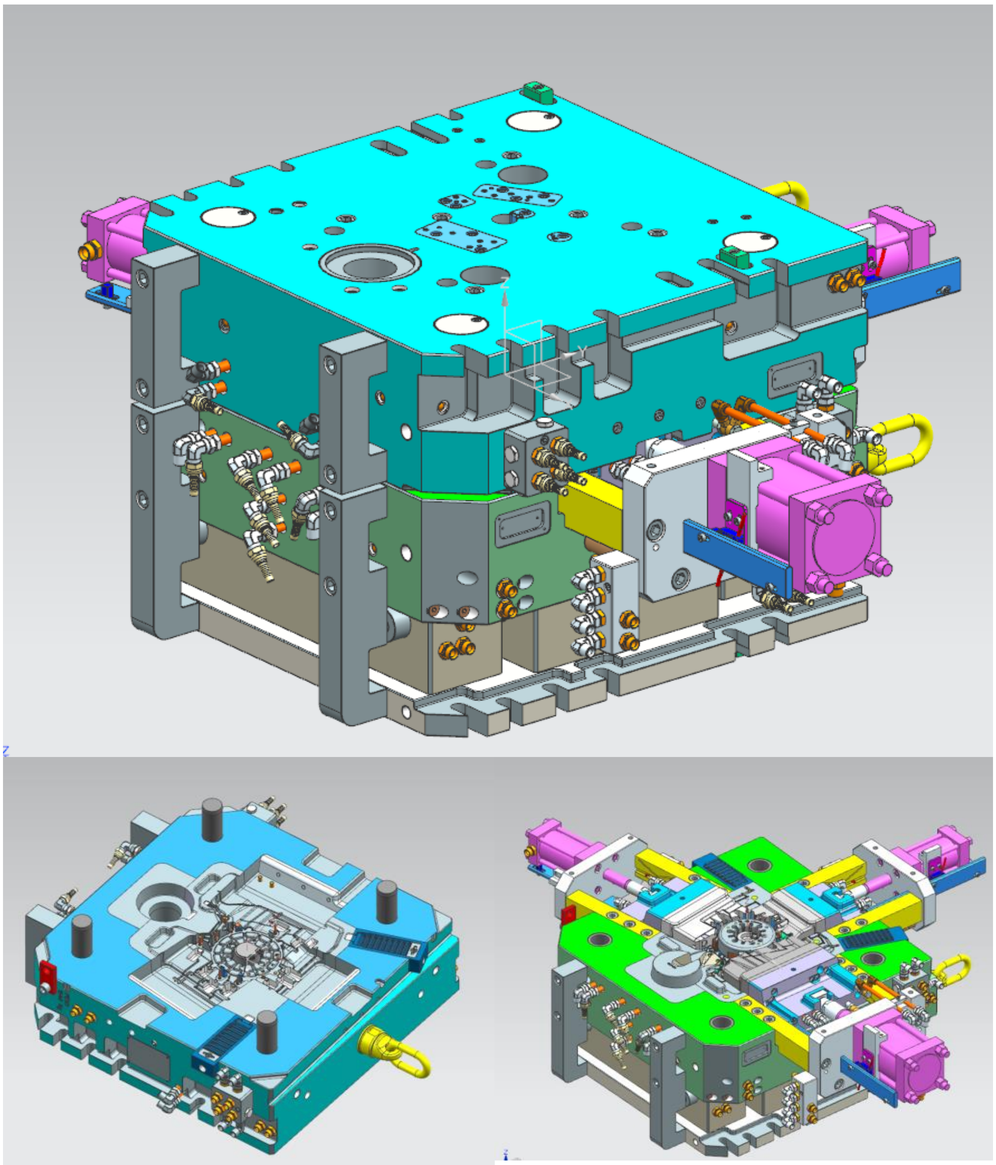


Figure 27: PSA front housing die model

As we can see from the images of the cad model the part is highly complex with the presence of many holes, ribbed structures and machined surfaces. The central hole should be machined to accommodate a bearing having to support the axle exiting from the engine. The cast is crossed by channels that transport cooling fluid (water) while the central zone where it is positioned the electric motor is filled with oil. The orange parts are the locating points, i.e. the points that lock the motion of the component in the three different directions and the starting points for the following machining. The blue surfaces are the ones that give the sealing preventing oil and water leakages. The green part is where the melted metal enters during the high-pressure die casting process. The red circles are the points where the pins of the expulsion system push the cast out of the mould after die opening. The light blue parts are all the zones where machining will be performed to meet design requirements.

The dimensions of the part are 304X290X90 mm, and it has a mean thickness of 7.5 mm. In the table below we can see the main geometric characteristics (volume and weight) and the process parameters.

Table 1: model and simulation base information

<table>
<tr><th colspan="3">CAST GEOMETRY</th></tr>
<tr><td>Part</td><td>Solid volume [cm^3]</td><td>Weight [kg]</td></tr>
<tr><td>Sprue</td><td>249.58</td><td>0.661</td></tr>
<tr><td>Cast</td><td>1092.53</td><td>2.895</td></tr>
<tr><td colspan="3"></td></tr>
<tr><th colspan="3">PROCESS PARAMETERS</th></tr>
<tr><td>Alloy</td><td colspan="2">Aluminum 43400</td></tr>
<tr><td>Temperature injected metal</td><td colspan="2">630 °C</td></tr>
<tr><td>Die surface temperature</td><td colspan="2">200 °C</td></tr>
</table>

The mould does not present particular differences from the classical ones, it has five fountains in the central zone to improve the cooling and aven if at the moment is not used it has the predisposition for the vacuum system. As we can see from the mould model (figure 27) on the mobile part we have three radial cores that are used to form the lateral surface geometry. These parts then during the extraction phase move backward to allow the expulsion of the cast from the die.

All the requirements for the part are inserted by the customer in the STL file (laboratory technical specifications). The specifications aim to define metallurgical and mechanical characteristics, the acceptable level of material soundness and the acceptance level of defects on the machined faces. In this document we have as first specification the ones regarding the material, the heat treatment and the hardness.

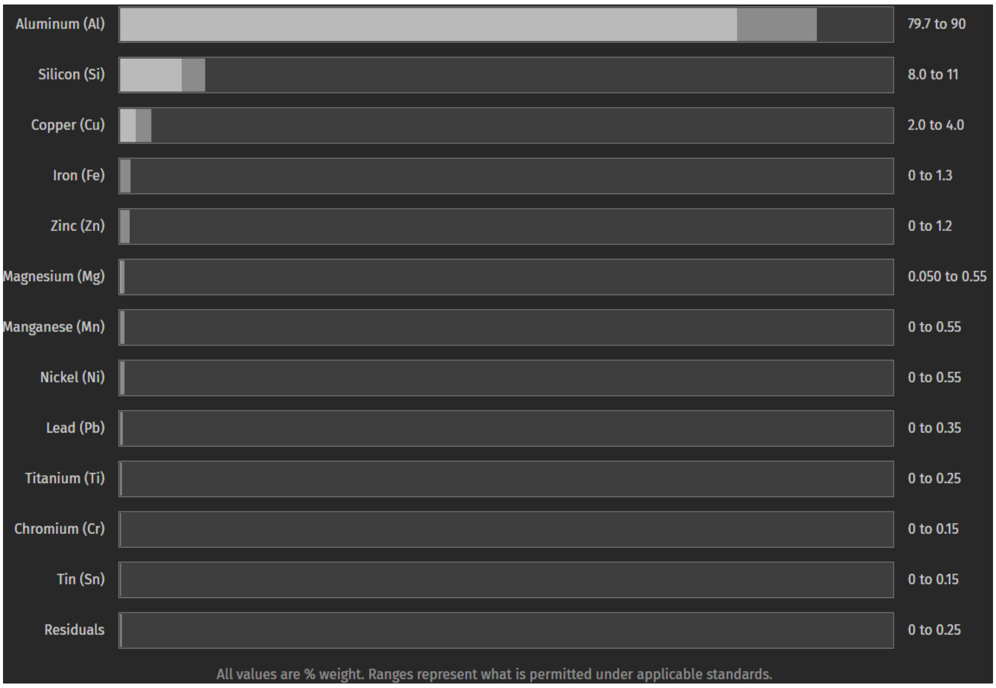


Figure 28: alloy composition

Due to material requirements the alloy used is the Aluminum 43400 (figure 28) this has been chosen instead of the more popular 46000 for the excellent castability properties and the resistance to the hot tearing. It has also good machinability and resistance to the chemical attacks. So it best suits complicated, thin-wall, pressure-tight, high-strength corrosion-resistant castings subjected to fatigue loading. The main difference from the chemical composition point of view with respect to the 46000 is the very low amount of copper in the alloy.

The STL also identifies the control checks to be performed, in this case using X-ray, and the type, the number, the dimension and the distance between the defects. Obviously the prescription has different severities on the base of the zone where the defect is located. In the end, we have also specifications dedicated to the defects present in the threaded holes.

5.1 The simulation, advantages and limits

Nowadays with the increase of the computers computational power it is possible to obtain simulations with a good precision that are able to reflect within certain limits what happens in the reality.

To perform a simulation the software divides the part with a 3D pattern called mesh, as we will see in the following the finer the mesh the higher will be the precision of the simulation but also the computing time. Once defined the mesh dimension we obtain a certain number of elements that can be with various shapes (squared, triangular, trapezoidal...) depending on the chosen type of mesh. These elements constitute the fundamental unit on which the software applying the formula implemented in the solver algorithm performs the simulation. The computation proceeds in an iterative way so for each element the equations are solved and the results are checked for the continuity with the ones of the adjacent elements. All this is performed for each time instant from the start of the filling till the end of the solidification for each element. The simulation can be divided in three main steps:

- Die cycle: in this phase the die opening and closing cycle, the lubricant spraying and the drying are simulated with their relative duration. This computation is repeated for 5/10 cycles till the reaching of a constant die temperature that should correspond to the one of the real die during functioning. For this phase is very important to determine the heat exchange values between the die and the environment

- Filling: all the phases from the start of the piston motion till the complete filling of the overflows are simulated at this point. This is for sure the most expensive phase from the computational time point of view, but also the most important because we can understand how a large number of defects that are in the final cast originates
- Solidification: final phase where it is simulated the cooling down of the cast inside the mould before the extraction.

All the above-mentioned phases allow to obtain more information on the behaviour of the liquid alloy once in the die. Information that otherwise will be difficult to evaluate in real time, in fact we have to remember that in reality all these phases take place in a couple of seconds and cannot be appreciated with the naked eye.

As said before the more demanding phase from the computational point of view is the filling, during this part of the process the alloy can be in all the three possible aggregating states that interact one another moving at very high speeds, this all contributes to complicate the computation.

Having seen how the simulation works we can now list the main advantages and disadvantages of using this tool.

5.1.1 Simulation advantages

One of the main advantages of the use of simulations is the possibility to try modifications on the mould and see directly the effects on the cast. This can be done not having to spend money on real die modifications. Linked to this we must consider that once a modification is performed on a die then it is permanent and is difficult to come back to the original form if it has not brought the desired results.

Another field where the simulation proves to be effective is the setting of the machine parameters. In this case we can try different combinations of parameters, for example following the D.O.E (design of experiment) procedure, trying to find the best trade-off.

From the point of view of defects generation the simulation helps us to analyse frame after frame the filling phase highlighting abnormal behaviours of the flow. Nowadays most of the casting tools have incorporated scripts that allow to identify the possible formation of defects and the localization.

In the end the simulation can be useful for new products to evaluate the castability and the related costs of production. In the optic of continuous reduction of costs it can be also used to try changes that can be applied during the manufacturing of a new die.

5.1.2 Disadvantages

The first disadvantage is the cost of the tooling, the cost of the software depends on the accuracy of the results given and can be very high. We must also consider that to have useful and accurate results with an acceptable computing time powerful computers are needed and not all companies can afford them.

Once you have the software and the pc you need skillful people that are trained on the use of the software but that also have a deep knowledge of the real process. In fact the familiarity with the software is needed to set the correct parameters and to run successfully the simulations. On the other side the knowledge of the process is fundamental to obtain meaningful results that are coherent with reality. One of the main neglected problems is that being the simulation a tool it will always give a result and it will be then who performs the simulation that has to understand if it is plausible or not. This is true especially on a process like the high-pressure die casting where we have a lot of parameters and simply changing one of them can lead to completely different results.

The last disadvantage is that the simulation is always an approximation so it cannot fully represent your actual process, there will be always an amount of variability that cannot be taken into account.

5.2 Accuracy versus simulation time

As mentioned before the dimension of the mesh is one of the most important parameters for the success of a simulation. It is estimated that about 30% of the time passed on the model preparation is spent adjusting the mesh. Obviously the trade off is between the accuracy of the results and the computational time taking in consideration the available computational power of the pc. Many software nowadays suggest a preset dimension of the mesh depending on the mean thickness of the part analysed. It is however with the increasing experience of the operator that he can decide to increase or reduce the mesh dimension locally on the base of the phenomenon/particular that he wants to track.

As briefly said before the dimension of the mesh and the total volume of the part analysed will determine the overall number of elements on which the calculation is performed. Obviously the higher this value the higher the precision of the calculations. In fact while solving the formulas implemented in the program the software will approximate what happens in an element volume with one value for the temperature, another for the velocity and so on. So the simulation tells us what happens in mean in that volume, but if the mesh dimension is too coarse small changes in this values may not be showed leading to completely different results as we will see in the following.

We are going to analyse the results in terms of temperature, die erosion, trapped air, velocities at the gates and solidification time for four different mesh dimensions. In table 2 we can see the parameters set for all four simulations.

Table 2: simulations parameters

SIMULATION PARAMETERS	
Metal temperature	903.15 K
Mould surface temperature	473.15 K
Piston diameter	90 mm
first phase velocity	0.2 m/s
second phase velocity	2.8 m/s

In the table 3 we can find the different values of mesh dimensions, number of elements created and the total computing time of the simulation.

Table 3: mesh dimensions and simulation duration

MESH DIMENSIONS [mm]					
Part	Gate	Runner	Mold	Elements [millions]	Duration [hours]
7.5	6.75	7.5	32.7	0.132	00:14
3.7	3.33	3.7	30.5	0.428	01:33
2.5	2.25	2.5	30.2	1.1	08:20
2	1.6	1.8	30.2	1.98	25:30

Now we have to make two considerations on the number of elements and on the duration of the simulations. Having performed more than fifty simulations on different components and different computers we have seen that independently from the component analysed we have an increase of the computing time with the increase of the number of elements. This increase is more sensible if the parts added to the base component analysed are overflows or complicated variations in the geometry of the runner. For the computing times these results should be taken as an example because the hardware used to perform this simulation, even if it was a dedicated workstation for enterprises, was not the most suitable one. In fact to reduce the computing time it was suggested to use a workstation with two processors in parallel (the company is nowadays buying one). We esteem that with the new hardware the computing times can be at least reduced of about one half.

Another point that we must take into consideration for the computing time is that the simulation durations enlisted on the previous page refers (as can be seen in the results in the following pages) to the analysis of only the cast and the sprue. Adding all the parts needed for the correct casting of the part will at least double the computing time. We can easily understand that a normal simulation with the cast, the sprue, the injection piston, the overflows and the complete opening and closing cycle of the die can easily take more than two days of computation.

Before analysing the obtained result is possible to anticipate that the difference with the coarser simulations can be seen already with the naked eye during the observation of the temperature variation. In fact already at this point we can see that the coarse simulation (7.5 mm) shows a flow that proceeds to fill the cavity in a uniform way not being too much disturbed by the obstacles that encounters and the geometry variations. What sudden appears clear is that this flow cannot be real being too perfect. Another problem linked with a mesh of bigger dimension is that it fails to well approximate the thinner planes or the more intricate corners. Passing to the other simulations we can see that with the increase of elements the fluid appears more realistic and with a rheological behaviour that seems to better approximate the actual one.

The point now is how much we should reduce the mesh dimension to obtain a good approximation of reality, because in principle we can use extremely fine mesh that will give a very good idea of how the fluid will move in the die but that on the other side will take days or weeks of computation on a computer cluster. This perhaps will suit the needs of a research centre but will never be applicable by a foundry that needs maybe less precise indication but in shorter times.

5.2.1 Mesh

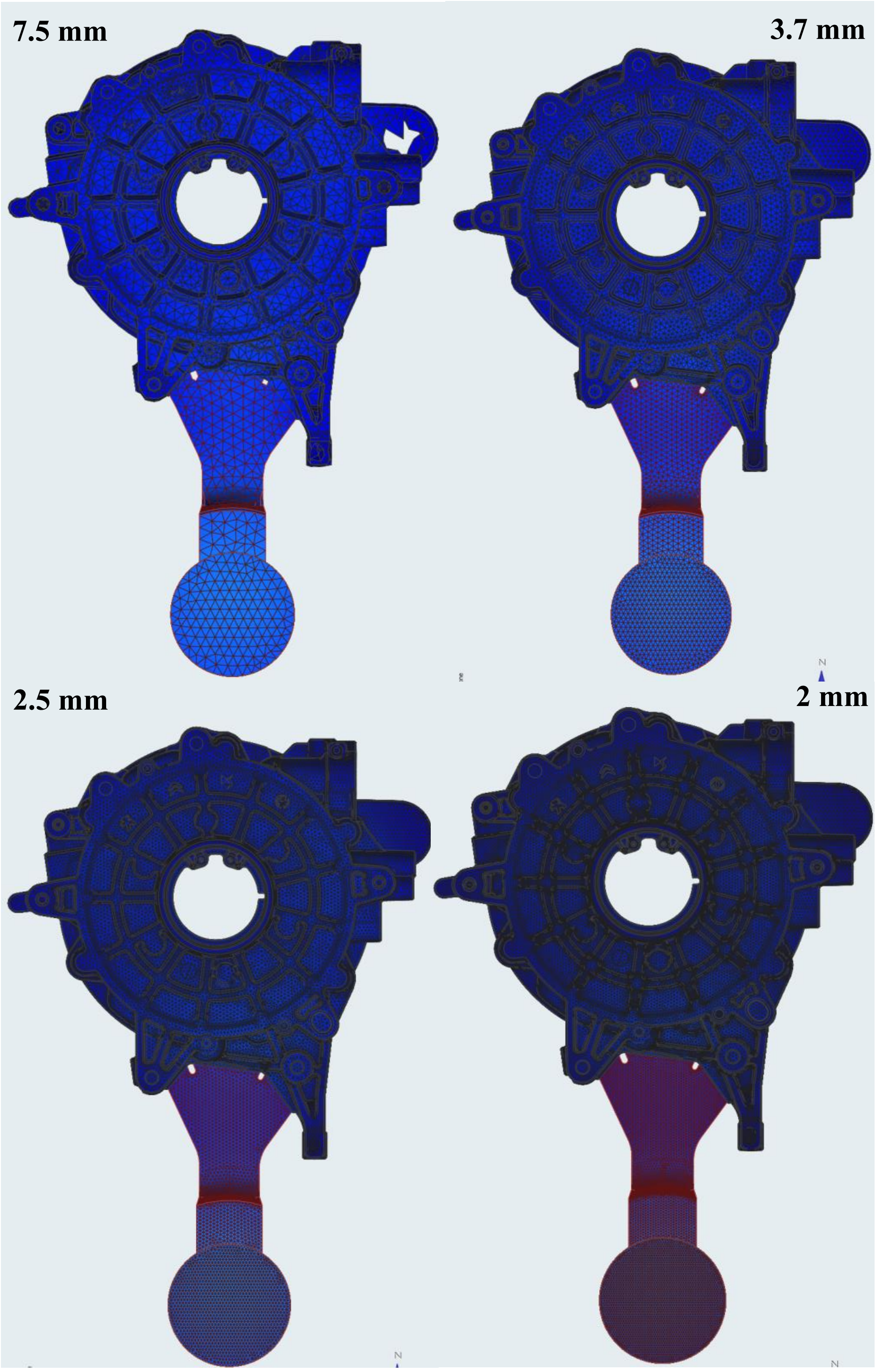


Figure 29: geometry approximation plan view

We have tested four mesh dimensions 7.5 mm, 3.7 mm, 2.5 mm and 2 mm, in the following we can see how the component is approximated by the computer. These imagines show how the program “sees” the geometry of the model when elaborating, in fact in this phase the calculations are performed no more on the CAD model imported but on the geometry created with the mesh. For each mesh dimension we have two different views, one of the geometry in plan and another representing one of the most complicated zones from the point of view of the geometry to see how well the mesh approximate it.

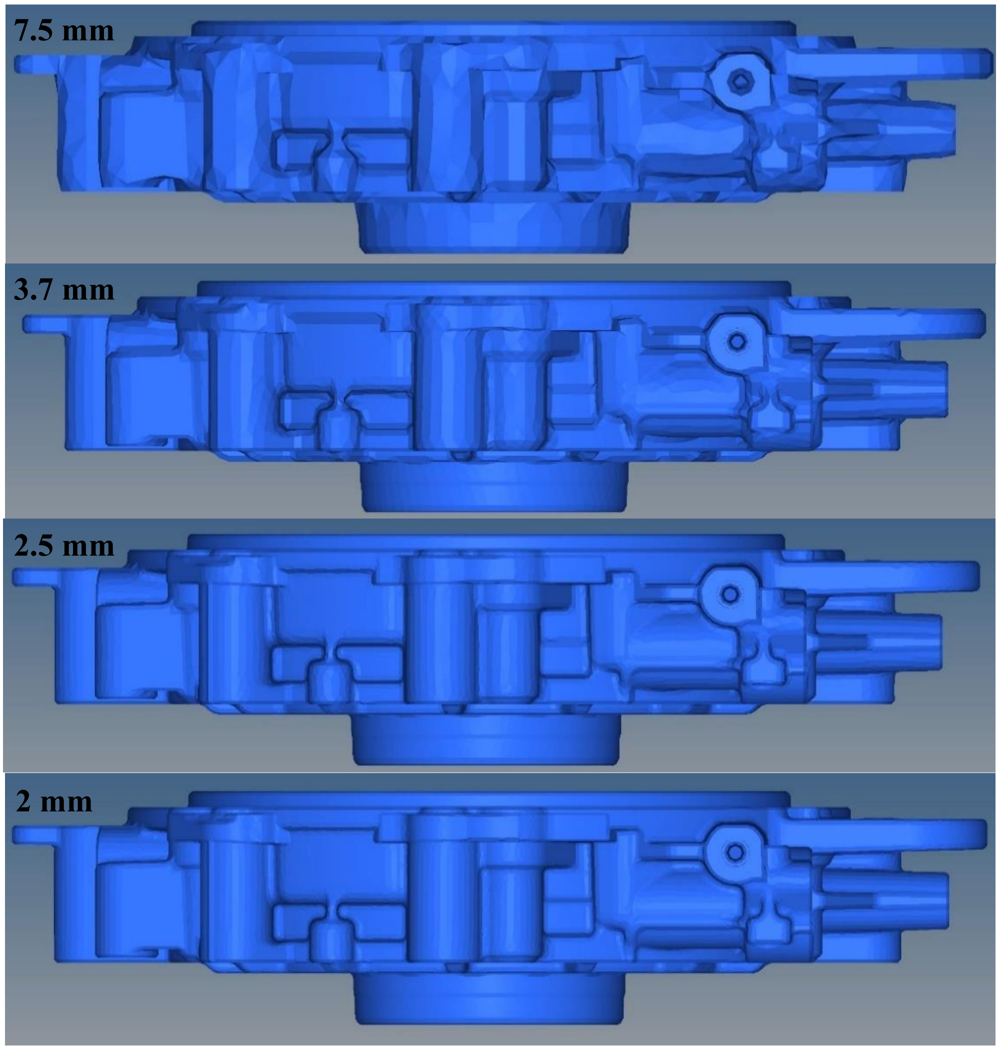


Figure 30: intricate geometry approximation

In figure 29 we can see the mesh pattern on the component and we can appreciate how the element density increase with the reduction of the mesh dimensions. Considering the figure 30 we have a substantial difference between the 7.5 and the 3.7 mm mesh. An important difference can be seen also between the 3.7 and the 2.5 mm, while the 2 mm mesh will give an advantage with respect to the 2.5 mm on the approximation of the circumferences and on the more intricate edges. Observing these results we can say that simulations with 7.5 mm mesh are not reliable. From the mesh point of view the best trade off seems to be the 2.5 mm because using the 2 mm mesh we have a small improvement with a more than triplication of the computational time.

This consideration is confirmed by a widespread guideline that suggests using a mesh dimension that is one third of the mean thickness of the part, in this case just 2.5 mm.

5.2.2 Temperature

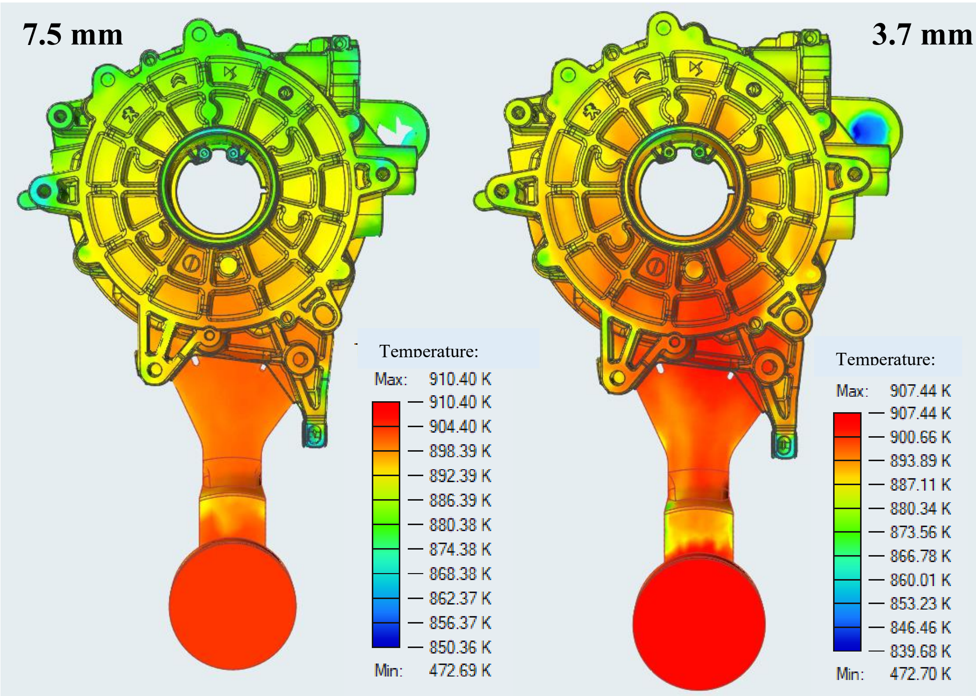


Figure 31: temperature results with various mesh dimension part 1

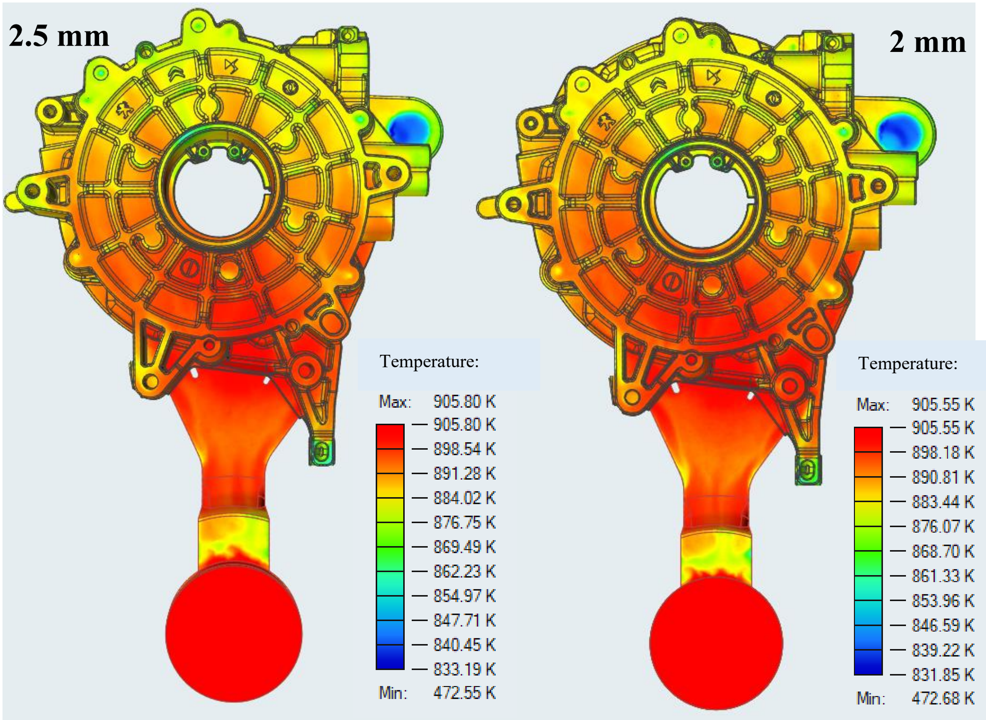


Figure 32: temperature results with various mesh dimension part 2

In figures 31 and 32 we can see the temperature distribution during the filling phase. With the reduction of the mesh dimension we can notice that the maximum and minimum temperatures remain practically unchanged. Obviously increasing the number of elements of the analysis we have a more varying temperature evolution in each zone with the reduction of blocks of the same temperature that characterize the coarser simulation. Considering the 2.5 mm mesh simulation we can see that we have many more temperature transient conditions with respect to the two coarser simulations which means a better approximation of the actual condition. Passing from a mesh of 2.5 mm to one of 2 mm we practically cannot see many differences. The higher temperature is at the exit of the injection cylinder and in the zone near the gate where we have the restriction before entering the cast and so the temperature increase due to frictions in the fluid. The colder points are on the opposite side with respect to the gate, in fact when the melted metal has reached this zone it has already passed through all the die losing a part of its thermal content. In all the simulations we can see a very cold zone but it is an error in the CAD file so it can be neglected.

5.2.3 Velocities at the gate

For what concerns the velocities at the mold entering we do not have significant differences between the 3.7 and the 2.5 mm mesh. Obviously the simulation with a smaller mesh dimension will have a higher number of vectors describing the melted alloy movement, being the computation performed on a higher amount of elements. Also in this case using a mesh dimension below 2.5 mm seems not to change much the results obtained. Inserting the imagines of the analysis was not useful because they will not be explicative. In fact to better understand the velocity of the flow a video is needed but for obvious reasons it cannot be inserted here.

5.2.4 Air remained

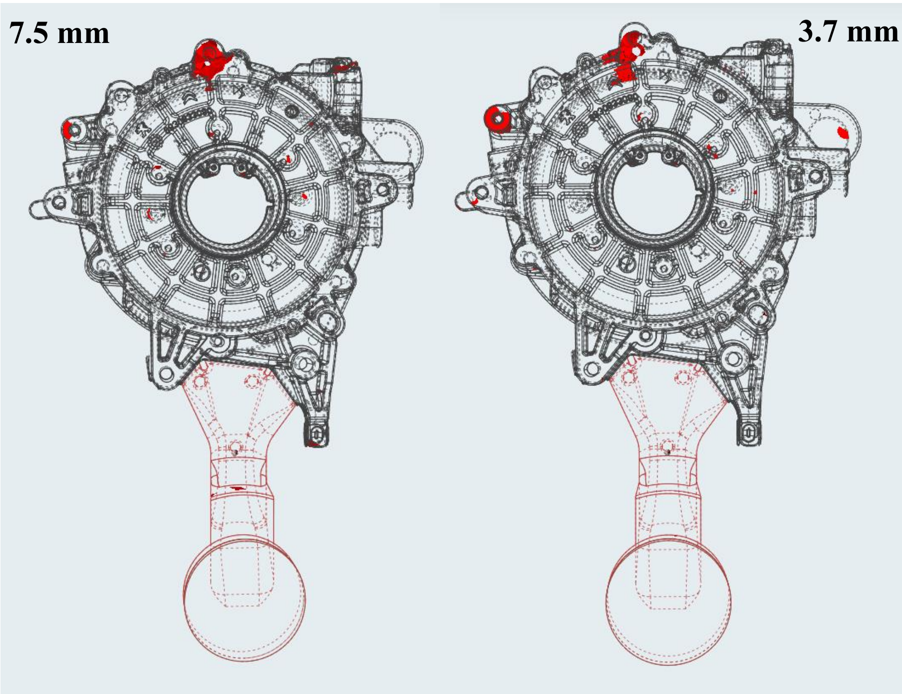


Figure 33: air trapped with various mesh dimensions part 1

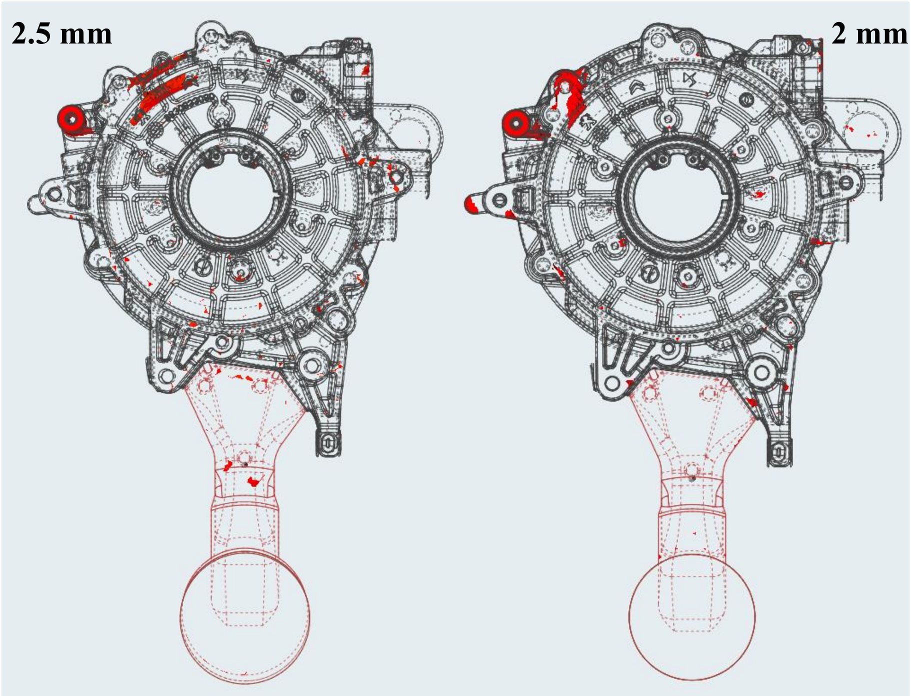


Figure 34: air trapped with various mesh dimensions part 2

Here we have one of the more evident differences between the all four simulations (figure 33 and 34). In fact while the first two simulation highlight a remaining of air in the two holes in the upper part of the cast, in the 2.5 mm simulation the air entrapped in the left hole is confirmed while the other one is moved from the top hole to the zone between the two top holes. Reducing the mesh dimension we have a gradual rapprochement of the two sacks of trapped air. In principle both positionings can be correct in fact with this geometry of the cast it is expected to have the trapped air on the opposite side of the melted alloy entering, where the two fronts rejoin as in this case. We have also to consider that here we have only the representation of the macro amounts of air trapped, we have not considered all that small amounts of air that can lead to porosities. As we can see in the following when analyzing the positioning of overflows the situation will be not so easy as it may appear from the previous images and it will not be limited to these two zones.

5.2.5 Die erosion

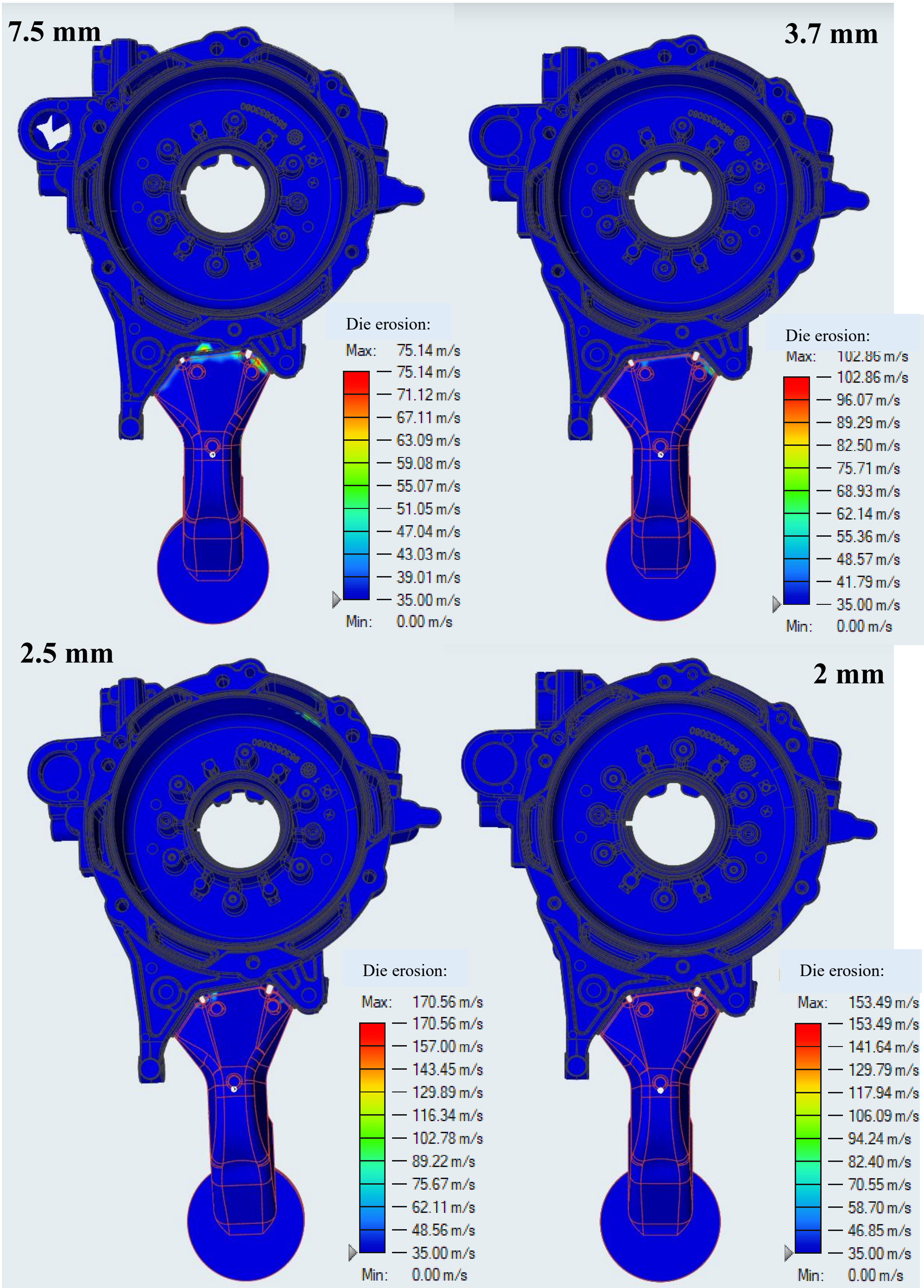


Figure 35: die erosion with various mesh dimensions

The analysis of the die erosion (figure 35) takes into consideration the speed of the melted alloy in the mold, in fact too high speed can cause premature wear of the die. Not considering the velocity peaks that may be due to some error in the CAD or in the mesh geometry we have that the speeds are more or less equal in all the simulations as in the case of the velocities at the gates. The higher speeds are found at the interface between the runner and the mold cavity, being this the thinner section.

5.2.6 Solidification times

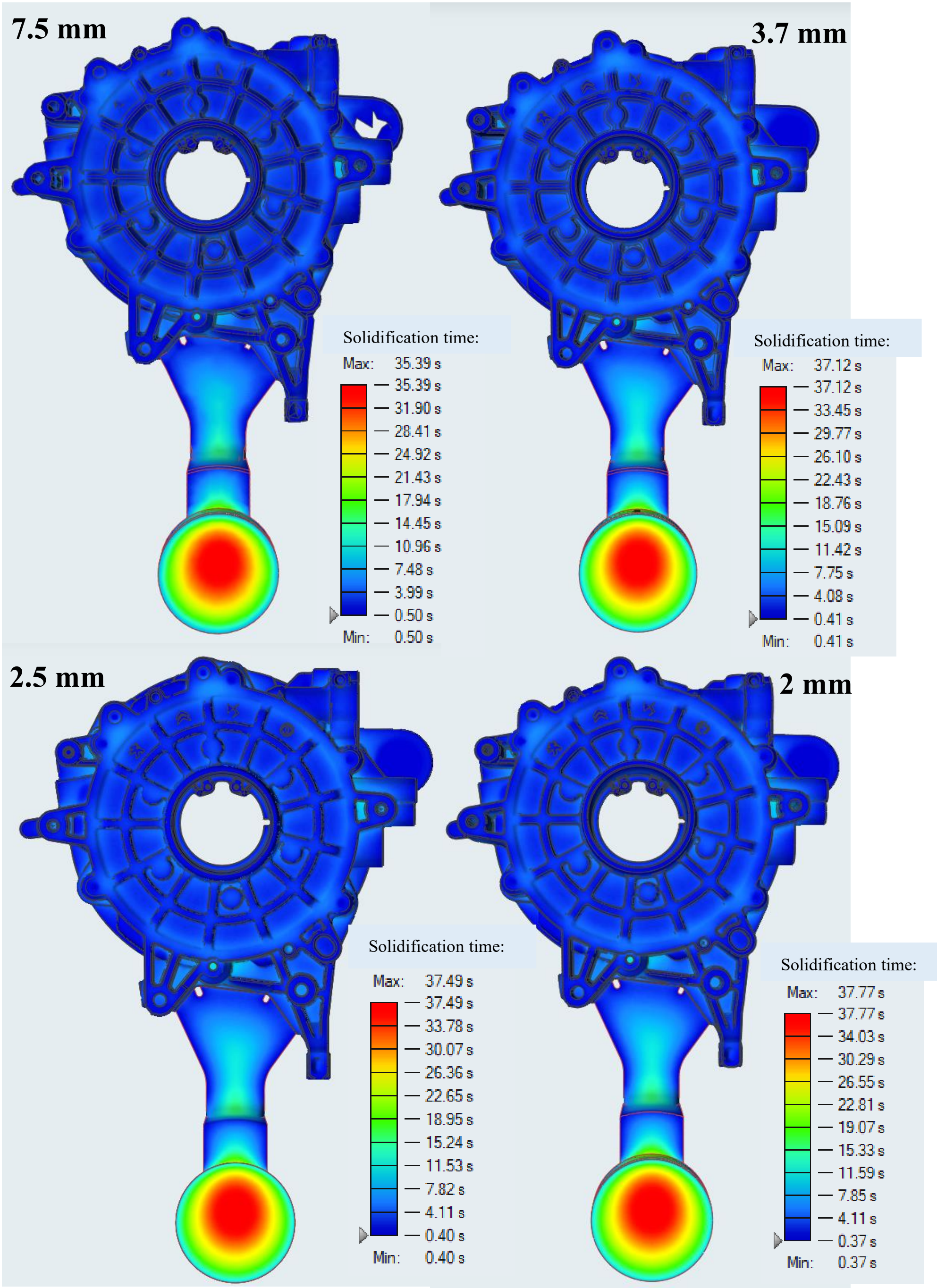


Figure 36: solidification times with various mesh dimensions

This is the time employed by the casted part to cool down (figure 36), it mainly depends on the temperature of the zone at the end of the filling, its thickness and the cooling system that in this case has not been simulated because it will be analysed in the following. All the simulations show the same situation, with the reduction of the mesh dimension we have a slight increase of the maximum cooling time and a reduction of the minimum. As we can see the last part to solidify is correctly the so-called biscuit that has to remain liquid longer than the casted part to feed eventual shrinkage due to material retirement during solidification.

5.3 Simulation software used

In the following we will use Flow-3D Cast, Inspire Cast and PIQ2 Castle for the casting simulation. We have decided to use three software because we are working on a particular component that is outside the standard production, so having a broad view of the results we will be able to see the behaviour of the programs when dealing with something that is not a “traditional component”. The software are very different for costs, completeness and ease of use. Flow-3D Cast is the costlier and the more complete, Castle was the one bought by the company and the less complete while Inspire Cast has been obtained thanks to the academic license of the Politecnico. All the software have more or less the same base features: they can perform the die cycling till the steady state, the filling considering also the motion of the alloy in the injection cylinder, and the solidification. The only important lack that we have found is on the die thermal simulation with Castle, where the die is “simply” considered at a constant temperature set by the operator.

5.3.1 Software characteristics and peculiarities

To analyse the characteristics of the simulation tools we can divide the simulation in five steps that are: model manipulation, mesh generation, thermal die cycling, filling and solidification. For each of these phases we can consider the peculiarities of each software.

Regarding model manipulation (figure 37) Flow-3D Cast and Castle that is based on Visi have a good interface but the one of Inspire Cast is the easiest to use. For the model closure and the elimination of the geometric errors of the CAD file, all the systems have pretty good methods. It is noteworthy that Castle has an integrated tool to automatically evaluate the thickness of the cast, this value becomes useful in the phase of mesh generation.

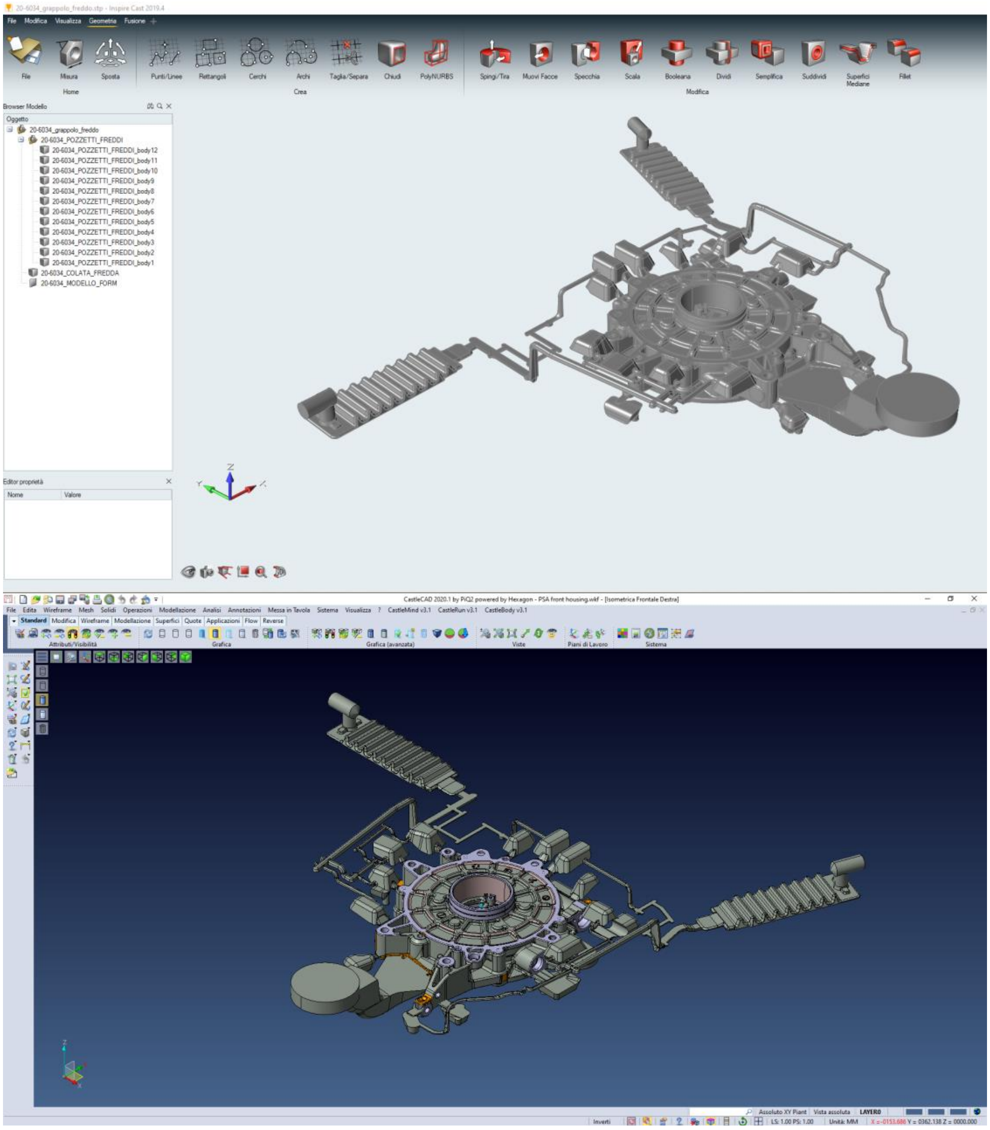


Figure 37: Inspire Cast and Castle modeling interface

The mesh generation is very delicate in Inspire Cast where you have very limited possibilities of choice of the mesh refinement regions. A second problem linked to this software is that you cannot have a preview of the mesh before its generation and this can lead to the mesh process failure with generic errors that do not allow you to understand where is the problem without the use of external post processing tools. The last problem encountered with meshing in Inspire Cast is the too high sensibility of the mesh generation process to small errors in the geometry. Considering this last point the other two software can tolerate a much higher number of errors in the CAD file still leading to a correct result.

As mentioned before for the thermal die cycling Castle should not be considered because lacks of all this feature. Now in this case Flow-3D Cast is able to simulate what happens in the real process (figure 38).

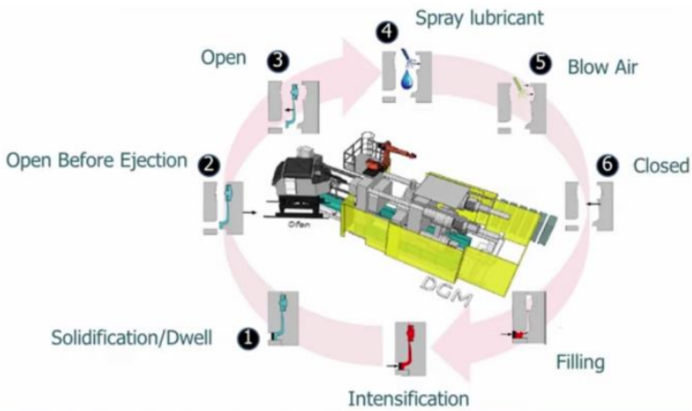
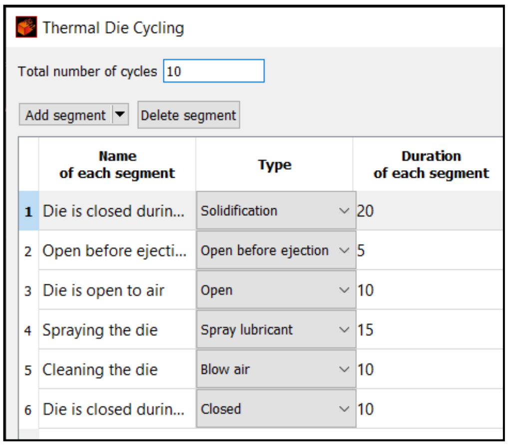


Figure 38: Flow-3D Cast thermal die cycling

First you can directly import the complete die with all its sub components like the cooling channels and the squeeze pins. The software has integrated algorithms that directly evaluate all the heat transfer coefficient (for the die, the cooling channels, the piston, etc...). The cooling channels can be opened or closed individually and you can choose if keep them always on or simply till a certain temperature of the mould. The lubrication and the


Thermal Die Cycling

Total number of cycles 10

Add segment Delete segment

	Name of each segment	Type	Duration of each segment
1	Die is closed durin...	Solidification	20
2	Open before ejecti...	Open before ejection	5
3	Die is open to air	Open	10
4	Spraying the die	Spray lubricant	15
5	Cleaning the die	Blow air	10
6	Die is closed durin...	Closed	10

Figure 39: Thermal die cycling length (Flow-3D Cast)

following air blowing (figure 39) can be precisely set according to the motion of the arm of your real robot and you can see in real time how the die temperature change according to the lubrication cycle chosen. On the opposite in Inspire Cast you cannot import the real die, it is automatically created by the program as a negative of the casted part. In this case the cooling channels must be drawn in the program so the precision is lower and you cannot simulate the squeeze pin and the lateral dowels. The inserted cooling channels in this case cannot be commanded they are always on kept at the indicated temperature. During the thermal cycling in Inspire Cast you can only simulate the time with die open and with die closed not considering the spraying and the air blowing.

Also for the filling simulation (figure 40) Flow-3D Cast is the most complete, consider that with this tool you can also simulate different geometries of the ladles to see their effect on the amount of oxides incorporated before the pouring of the alloy in the injection cylinder. All the three programs obviously simulate the injection cylinder. Both Flow-3D Cast and Castle work with the PQ^2diagram aiming at optimizing the system (HPDC machine plus the mould). Both software have also a complete simulation of the air extraction systems allowing to simulate both the vent and the vacuum system, and this leads to a better simulation of air motion with respect to Inspire Cast that is without these functions. Regarding the afore mentioned oxide evaluation on the base of the ladle geometry, both Castle and Flow-3D Cast can evaluate the oxide formation due to the difference in temperature between the injection cylinder walls and the melted alloy and its subsequent incorporation inside the cast. The last useful feature of Flow-3D Cast is the possibility of analyse separately the flow coming from each gate and track it across the cast. This can be used to highlight the contribution given by each single gate to the filling of the cast.

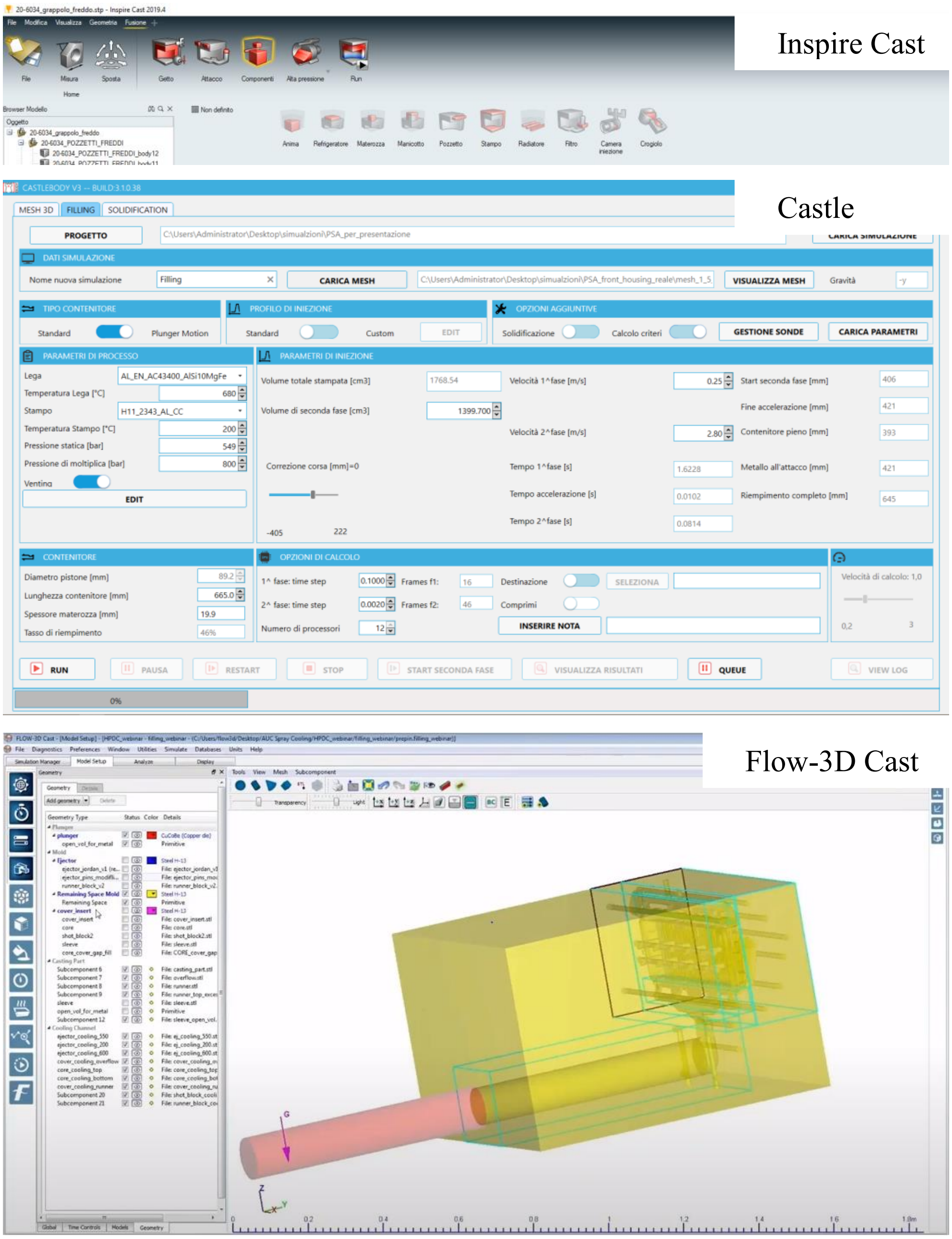


Figure 40: Filling setup with the three software

For the solidification all the programs have more or less the same analysis that means that they are able to evaluate the cooling time, the solid fraction, the temperature variation, porosities, volume net defects and the die temperature. The main difference is that Flow-3D Cast importing the complete die can consider also the squeeze pin whose work is really important to prevent voids during the cooling phase. Flow-3D Cast is also the only one among these three that can perform a stress analysis on the cast once extracted from the mould to evaluate the residual Von Mises stresses and the displacements during the cooling phase.

These were the main characteristics of each software now we can briefly see the main differences in the user interfaces.

5.3.2 User interface

The three tools present extremely different interfaces, Inspire Cast has the modelling and the simulating tools that are integrated in the same program while for Castle we have that they are two distinct software. Inspire Cast can be considered an all-in one tool because also the viewer of the results is integrated while in the other two cases it is a third party program. Despite the possibility of having all you need in a single program seems a good facilitation, this is the real big limit of this software interface. In this case, you can only perform the simulation steps in a sequence always starting from the mesh and ending with the solidification. With the other programs from a single mesh file you can launch n filling simulations or n cooling simulations, saving the time lost each time to mesh the cast. Talking about the simulation process Flow-3D cast and Castle allow to pause, stop and restart the simulation while with Inspire Cast this cannot be done. The fact of having the result viewer integrated in the software is still a limitation because if you want to see the results on different computers you need more licenses. Here comes the advantage of Castle that uses an open source result analyzer that can be easily installed on many pc.

Overall the three interfaces are quite intuitive with the software that guides you step after step to the complete setup of the process parameters. Regarding the parameters to be inserted Castle considering also the injection machine used, has more parameters for the simulation while Inspire Cast needs only the injection cylinder dimensions and the injection velocities.

The two programs that use the PQ^2diagram allows you to try different combinations of process parameters with very fast computation that lasts about 30 s and once you have found the most suitable you can insert them in the final simulation (figure 41). This will avoid the loss of time connected with performing simulation with wrong parameters that can happen with Inspire Cast.

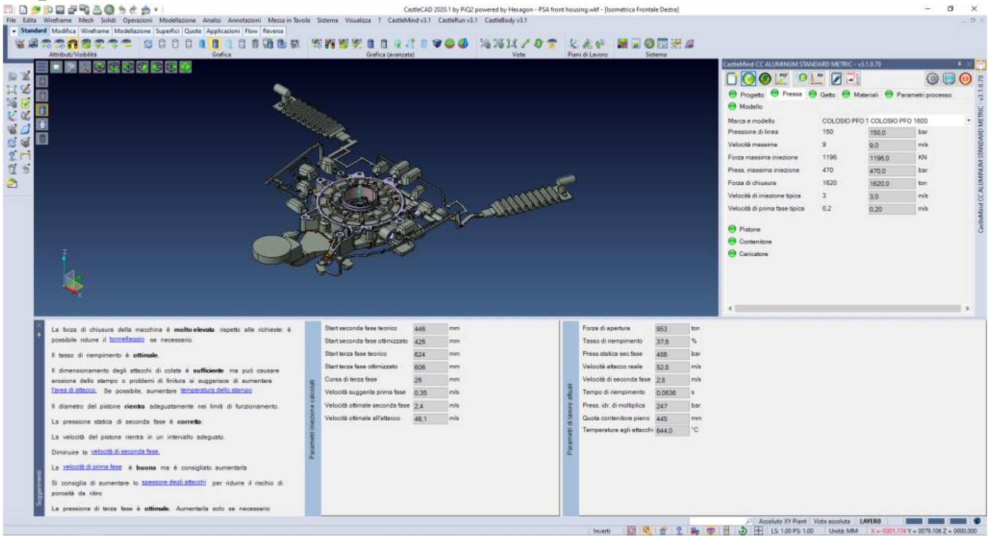


Figure 41: Rapid evaluation of the best machine parameters

For what concerns the computing time Inspire Cast and Castle take about the same time, with the first that is slightly faster. Flow-3D Cast is the fastest and can also parallelize the work on as much as 160 cores. Inspire Cast uses maximum 20 cores and Castle 12 cores.

5.4 Simulations with Flow-3D Cast

A first simulation was performed with flow 3D cast by the mold manufacturer with the same base parameters used in the simulation for the mesh evaluation. Flow-3D Cast has much more functionalities and is more complex than Inspire Cast. The result obtained with this simulation will be considered as a starting point to check the correctness of the simulation by Inspire Cast. Once we have established a correspondence between the two results we will use Inspire Cast to find an optimization of the geometry and of the casting parameters.

With Flow-3D Cast we have many advantages:

- The auto detection of the best mesh dimension on the base of the geometry of the component to be simulated. This can save a lot of time in the preparation phase;
- Very precise simulation of melted alloy-air interaction that can lead to even more accurate results;
- Simulation of the lubrication process, so we will have a precise identification of the mold temperature.

The obvious disadvantages are the by far higher costs, the need for a costly system dedicated to simulations and the longer computing times.

In figure 42 we can see the temperature during filling. In this case we have that the temperature of the alloy in the cast is above the solidification limit at the end of the filling, this condition should always be verified to prevent the formation of solid material that can prevent alloy from flowing during filling. We must also check that there are not very hot spots that can damage the die or create defects on the part.

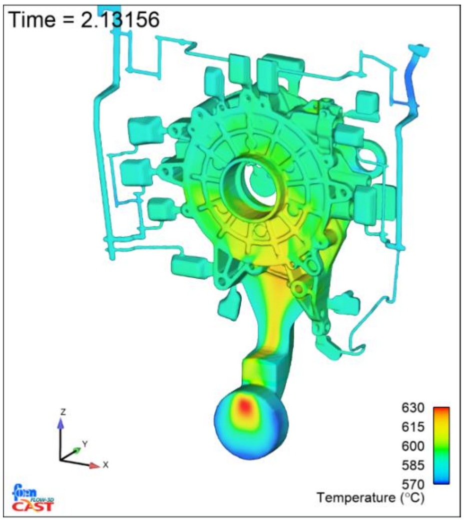


Figure 42: temperature during filling

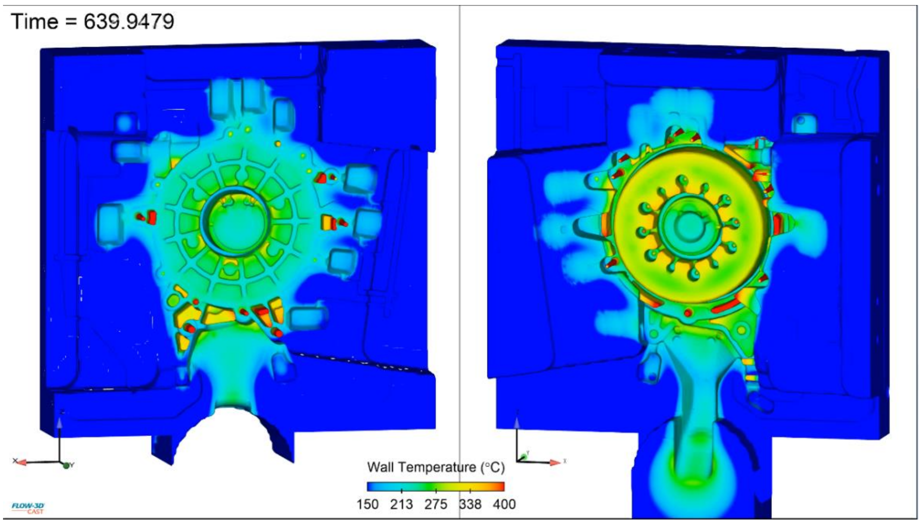


Figure 43: die temperature before lubrication

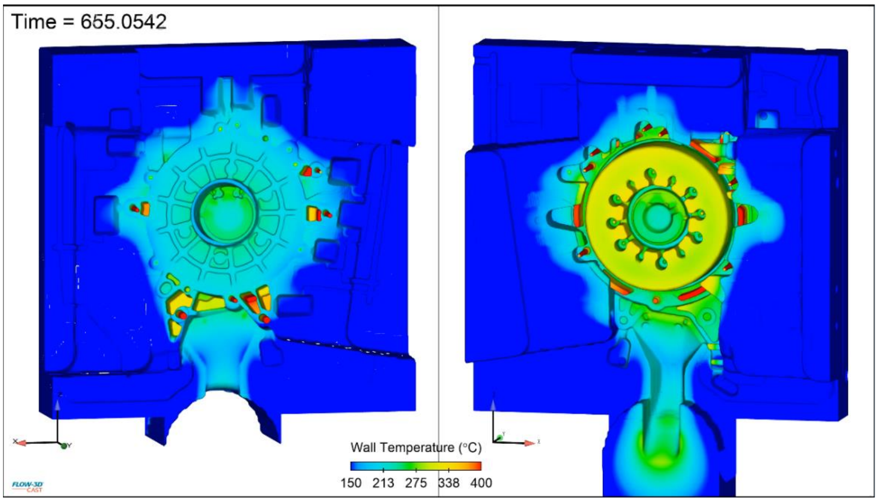


Figure 44: die temperature after lubrication

In figure 43 and 44 we can see the die temperature before and after the lubrication considering both fixed and mobile part. To perform this analysis the die undergoes ten complete thermal cycles till it reaches the steady state. This analysis is very useful because in this way we can use a more probable temperature distribution during the filling simulation. It is noticeable that the temperature is no more the 200 °C that we have set at the start but we have colder zones in the periphery and hotter in the center that will influence the filling. We can also see the important temperature reduction given by the spraying of the die with the lubricant. In figure 45 on the left we can see the air trapped at the end of filling, in this case all the overflows seem to work well. There are only some areas with a worrying amount of air. In the end we will try to add some overflow and adjust their geometry to be able to take away more air from the critical zones in the cast. On the right side we

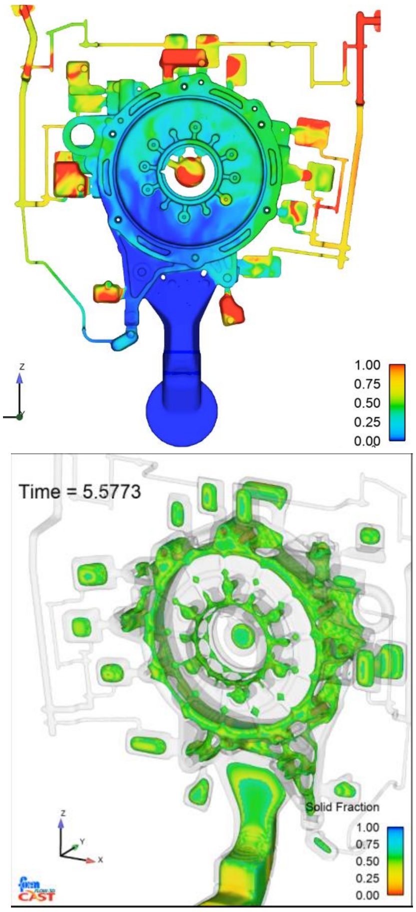


Figure 45: air trapped at the end of filling and solid fraction

can see the solid fraction, here we can notice a problem because while the gate is solidified a big area (the thickest one) of the cast is still not fully solid. The solidification of the gate will prevent the feeding of material and these zones can originate porosities due to lack of shrinkage compensation. Figure 46 indicates the net defect volume that is linked to the solid fraction picture. Also in this case we have the thickest zones that are highlighted as possible critical areas due to lack of material compensation during shrinkage.

In this simulation as can be seen in figure 43 and 44 the die was analyzed considering only the matrix, in the following when using inspire cast we will consider a die measure that is in between the matrix and the complete die one. To check how the results vary with the mold dimensions we have performed three simulations. The first was with the mold dimensions equal to the matrix while the second with the dimensions of the complete mold and the third that has been taken as reference was in between. Analyzing the three simulation we found that for what concerns all the parameters that we have analyzed in this chapter nothing changes even the solidification time remains unchanged. For what concerns the temperature of the die itself the only observable difference is that the complete die has the temperature of the core that is about 90K lower during the solidification, but the periphery remains more or less the same. From the perspective of the computation, the main differences are shown in the table below.

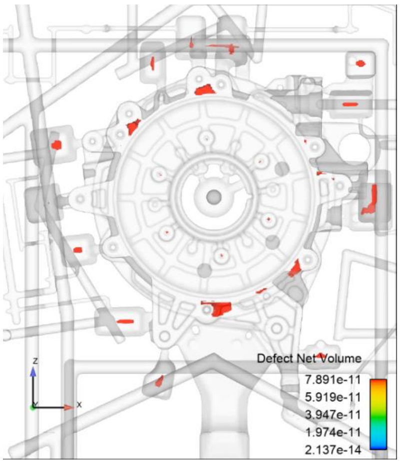


Figure 46: defect net volume

Table 4: die dimensions comparison

PART CONSIDERED	ELEMENTS [MILLION]	COMPUTING TIME [HOURS]	DELTA TIME	DIE DIMENSIONS W X D XH [mm]
Only matrix	1.45	08:47	-5%	500 x 520 x 227
Reference	1.2	09:15	NA	427 x 584 x 220
Complete die	1.75	09:39	4%	900 x 910 x 490

5.5 Simulations with Inspire Cast

The main part of the simulations has been performed with Inspire Cast, a tool of the Altair suite that has a good and reliable level of precision and an affordable computing time. This tool is used both by academic institutes and foundry so it seemed to be a good choice for the simulations.

We will consider the results of five different simulations, starting from the simplest one that is the same used for the mesh evaluation. Simulation by simulation we will add components to reduce the defects and increase the correspondence between what is simulated and what happens in the foundry. Every time a component is added the relative settings parameters will be enlisted together with the expected function.

Being this discussion linked to the application of the obtained result to the foundry process in order to reduce the formation of defects, all the simulations in the following will be based on a mesh dimension of 2.5 mm. Based on the considerations of the previous paragraph, 2.5 mm seems the dimension that reconciles better accuracy of the results and computing time.

5.5.1 Base simulation

In this case as seen previously we have only the part to be produced and the runner. This simulation is useful in the preliminary phase of the process design to see if the chosen point for the material entering in the cavity will generate macro defects or castability problems. Once determined the material entering point with this simulation we can also verify the good rheology of the designed runner.

The main objectives of this phase are:

- Assessing the correctness of the gate positioning from the point of view of material temperature, velocity at the gate, die erosion, filling of the cavity, cold joint and filling time;

- Modelling the shape of the runner;
- Setting the injection velocities.

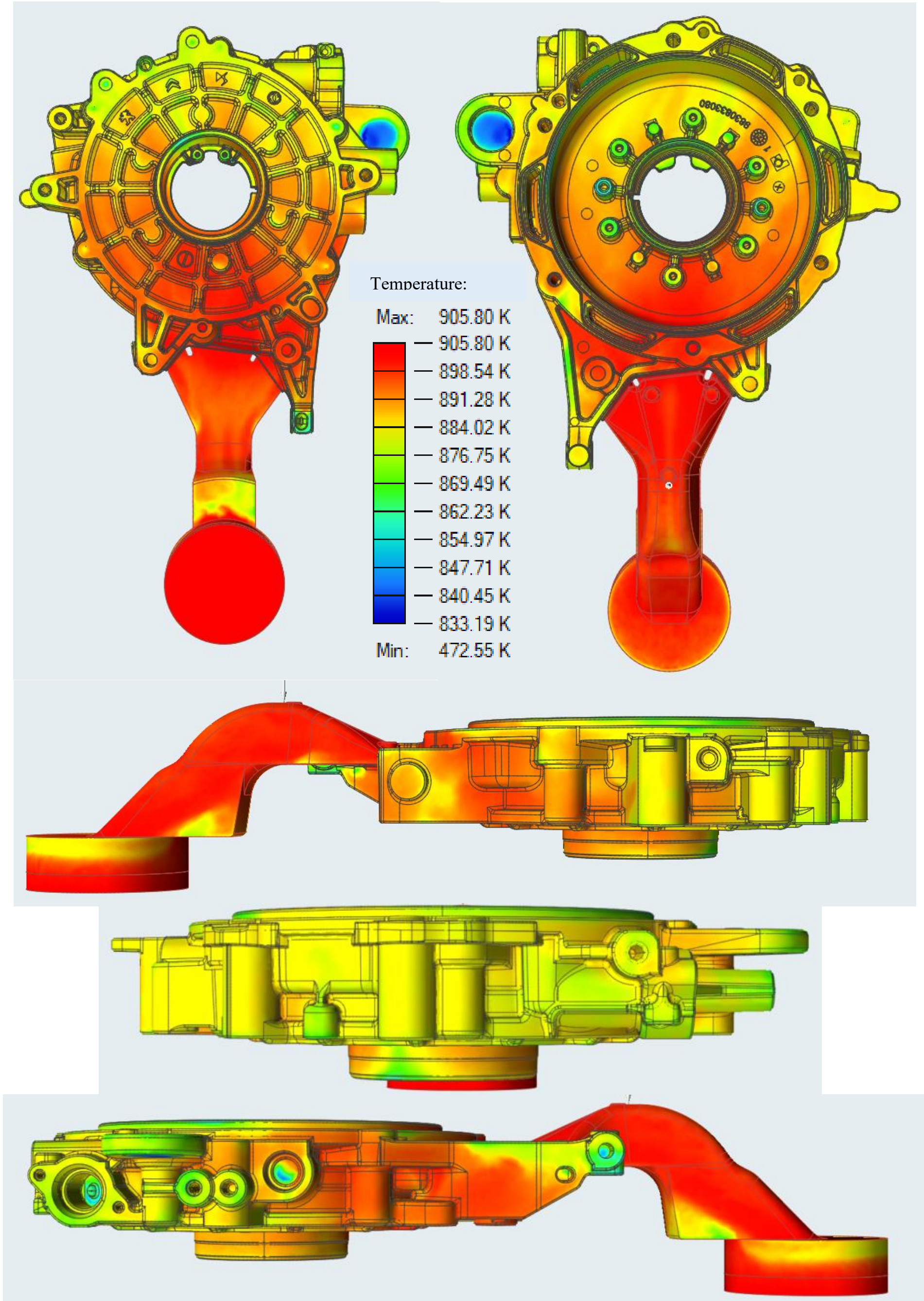


Figure 47: temperature distribution at the end of filling

For what concerns the temperature distribution during filling (figure 47) there is not anything different to mention with respect to what was mentioned before in the mesh dimensioning chapter. All the five views have been inserted for completeness. We can see that the flow temperature is above the aluminum melting point, as it should be. With the following simulation and the introduction of the cooling system we have to check if this is confirmed.

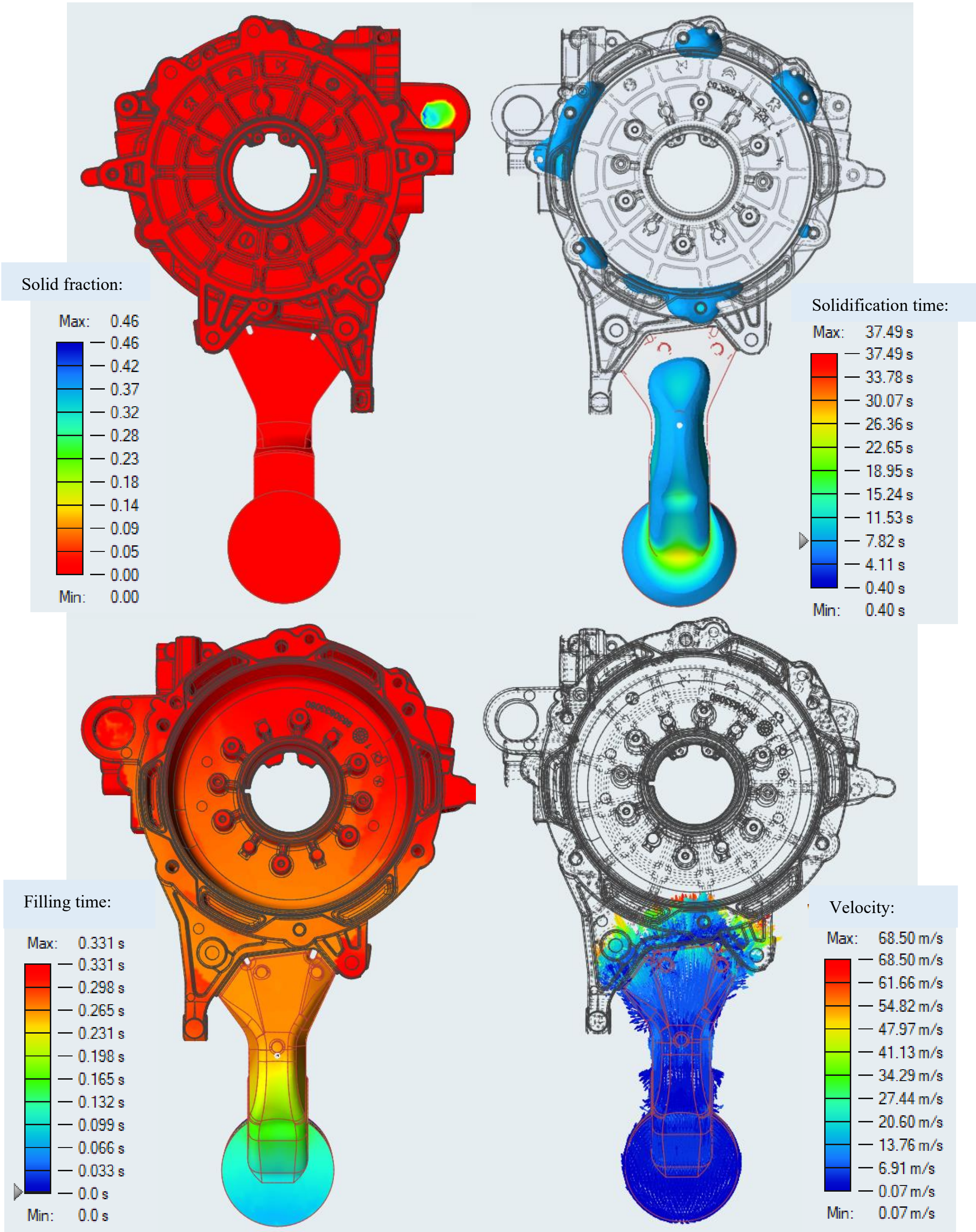


Figure 48: various results of base simulation

From the solid fraction representation (figure 48) we can see that we do not have zones that solidify before the end of the filling, which would have caused many problems. A problem can be seen in the solidification time. In this case we have the zone at the gate that solidifies before some zones in the cast. This can lead to cavities due to retires. The other two pictures show a plausible filling time, even if not considering the injection cylinder lead to a shorter total injection time. For what concerns the velocities at the gate we can see that they are set according to the guidelines mentioned in the second chapter.

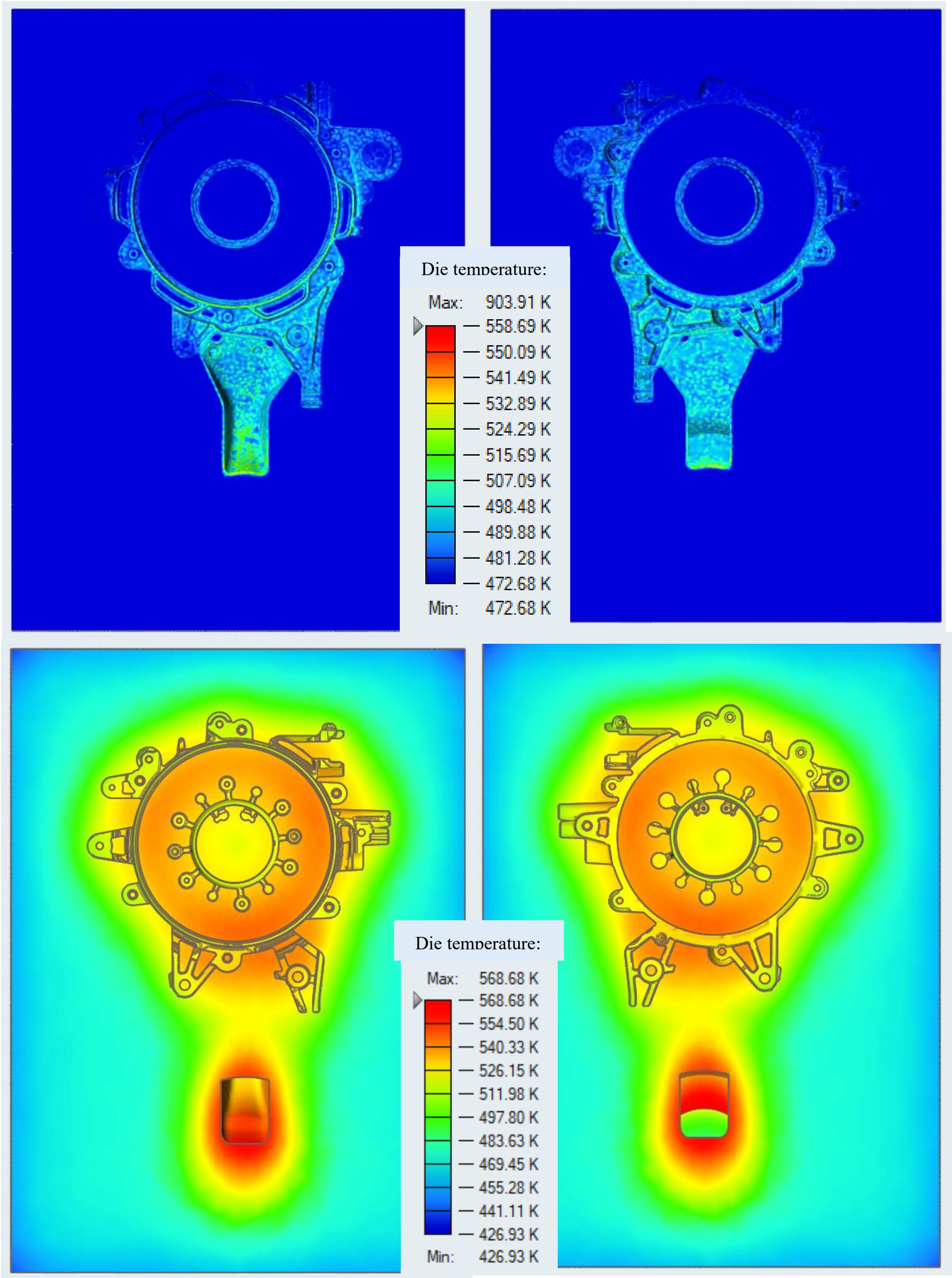


Figure 49: mould temperature during filling and solidification

In figure 50 in red we can see the remaining air at the end of the filling. These points are where the two fronts of melted alloy meet. Obviously in the next simulations we will add overflows to eliminate this defect.

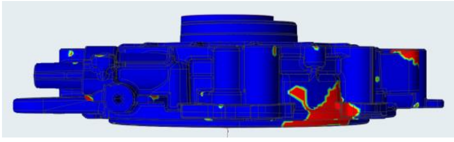


Figure 50: air trapped

In figure 49 the mold temperature values at the end of the filling and during solidification are shown. This is only an approximation, in the following for a higher precision we will add the cooling channels that will have a great influence on the die temperature.

5.5.2 Injection cylinder

The previous simulation does not take into consideration the injection cylinder and this leads to two main problems: first the transition point between the v1 (speed at which the piston moves till the melted metal is at the gate) and v2 (speed at which the piston moves during the real filling of the cavity) is set with very low precision, second we do not consider the possible air bubble formation in the injection cylinder that can then be transferred in the cavity. In the foundry the cylinder dimension is given by the injection machine chosen on the base of the clamping force needed. To set the parameters for the simulation we need to know the position alongside the cylinder at which the piston switch from v1 to v2. This point can be evaluated considering the volume of the injection cylinder and the filling percentage.

$$cylinder\ volume = \frac{piston\ diameter^2 \times \pi \times cylinder\ active\ lenght}{4}$$

$$= \frac{9^2 \times \pi \times 67}{4} = 4135.1\ cm^3$$

$$cylinder\ empty\ space = (1 - filling\ parcentage) \times cylinder\ volume$$

$$= 0.54 \times 4135.1 = 2233\ cm^3$$

$$volume\ filled\ at\ v1\ speed = cylinder\ empty\ space + runner\ volume$$
$$= 2233 + 370.02 = 2603.02\ cm^3$$

$$piston\ stroke\ with\ v1 = \frac{volume\ filled\ at\ v1\ speed}{piston\ area} = \frac{2603.02 \times 4}{9^2 \times \pi}$$
$$= 40.9\ cm$$

In our simulation the piston will switch from v1(0.2 m/s) to v2(2.8 m/s) after having covered 40.9 cm.

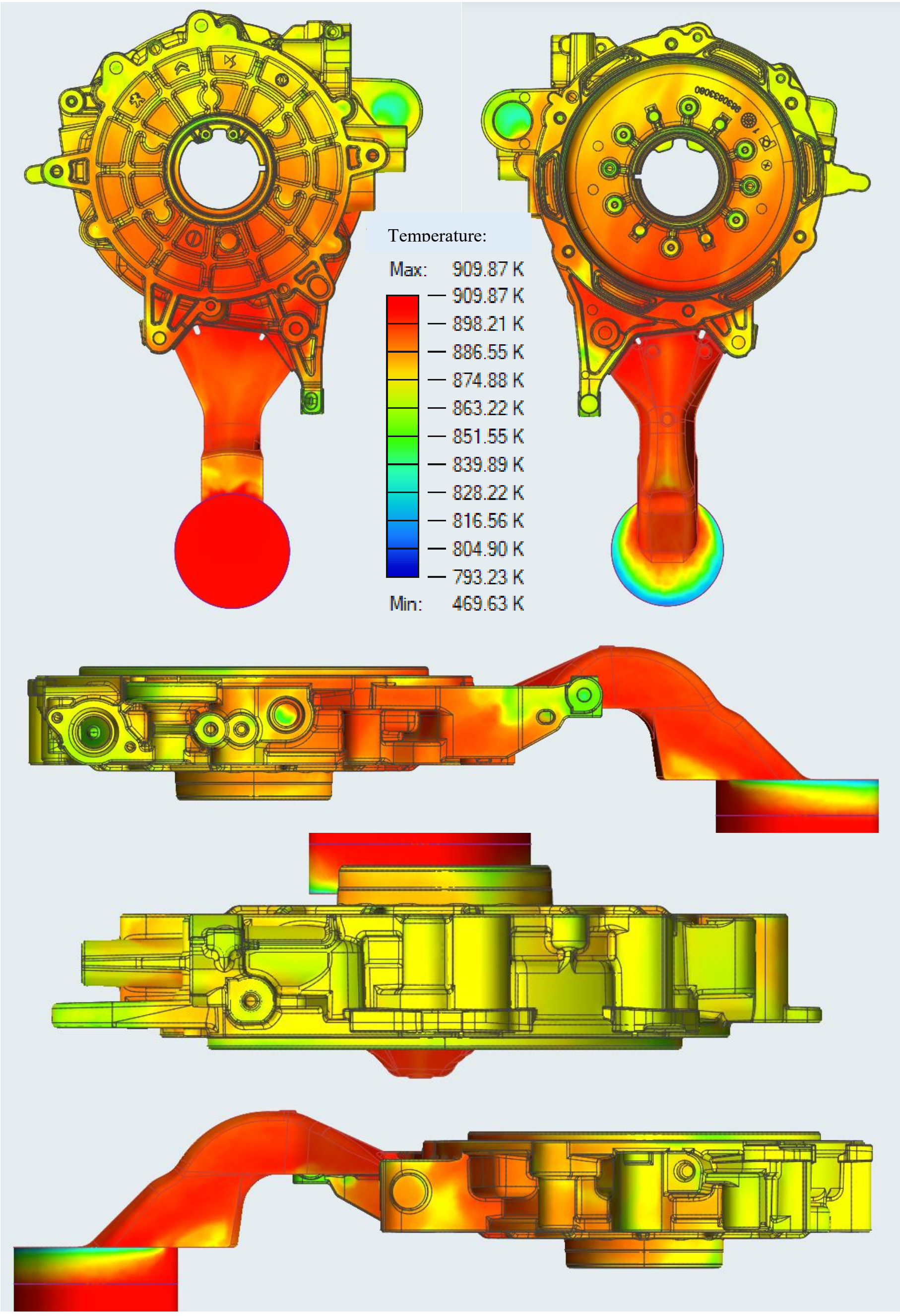


Figure 51: temperature distribution after filling

In figure 51 we can see that there are not significant changes in the temperature of the cast, the only small change is in the runner temperature. We have also a small increase of the maximum temperature and a slight reduction of the minimum.

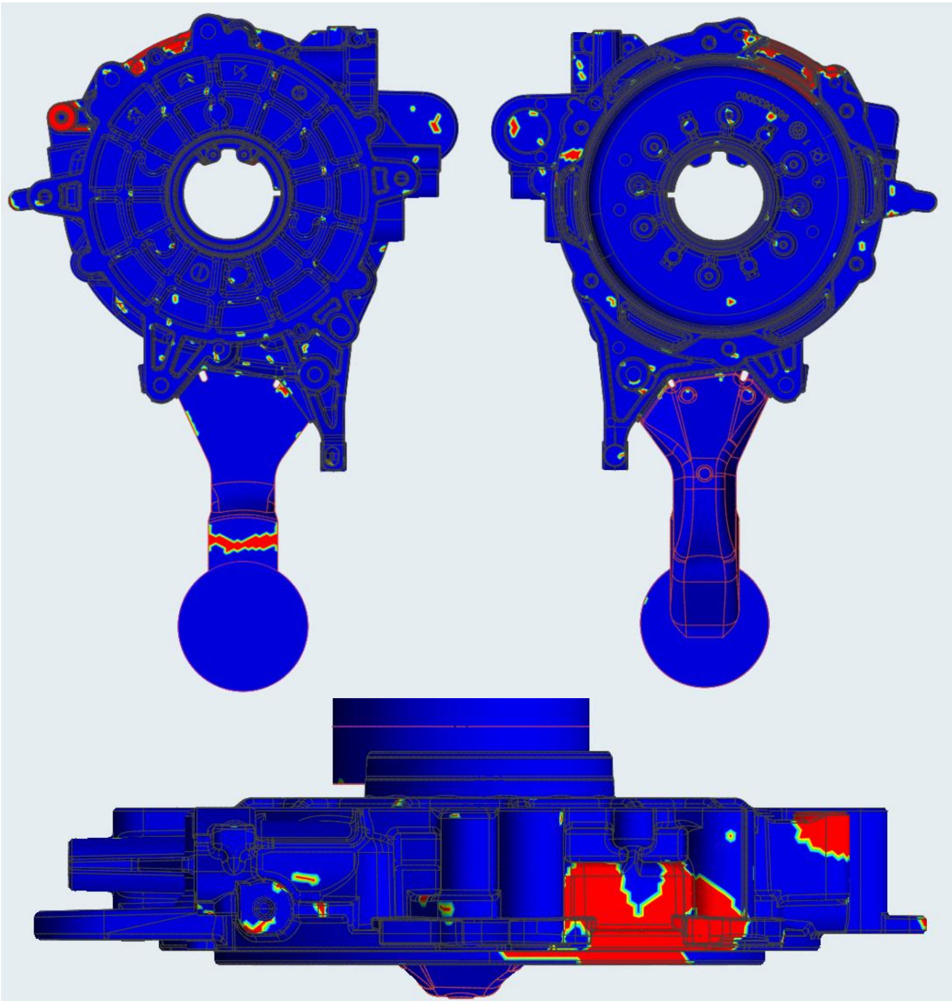


Figure 52: air trapped simulation

In figure 52 we find an enlargement of air trapped, probably created by the motion of the piston and then pushed in the cavity. From the point of view of the solid fraction as in the previous case we do not have material that freezes during the filing. The velocity at the gate remains practically the same of the previous simulation. We have a change in the evaluation of the filling time (figure 53) that now with the adding of the injection cylinder should be more precise. We can see that we have a much more longer filling time, this is since now we are also considering the motion of the injection piston that in the previous case was neglected. Nothing change for what concerns the solidification time that is still like the previous simulation.

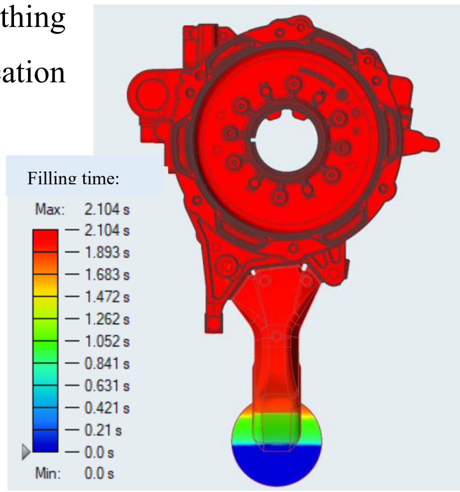


Figure 53: filling time

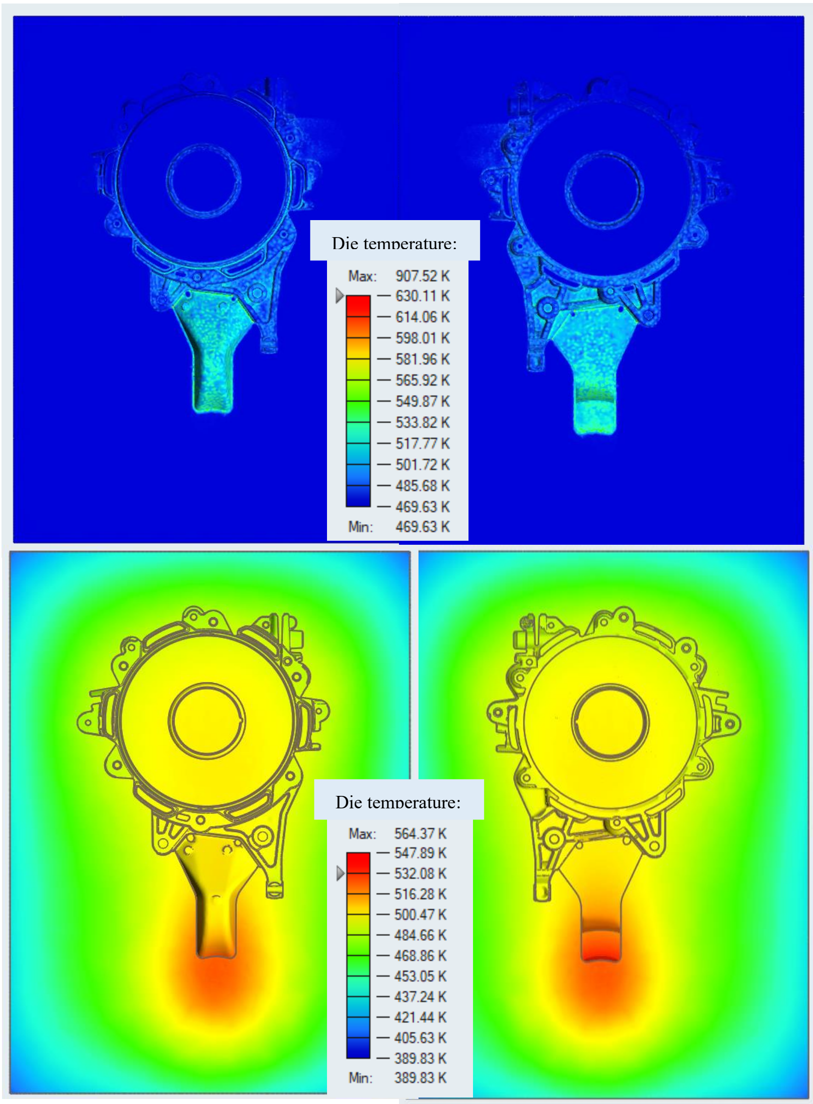


Figure 54: mould temperature during filling and solidification

From figure 54 we can understand that with the introduction of the injection cylinder we have a hot mass of metal (the biscuit) that remains in contact with the die at the end of the filing. This lead to an increase of the die temperature in the zones near the runner and the biscuit.

5.5.3 Cooling circuit

At this point, we can focus on the cooling system (figure 55 and 56). In the die we have channels that are used to cool the mould and if properly placed the critical zones of the casted part. We have to remember that the reduction of the cooling times helps not only to reduce the cycle time and so increase the number of moulded parts per hour, but it also increases the mechanical and aesthetical properties of the cast. In fact as said in the previous chapters a fast cooling will lead to finer grains structure with an increase of the mechanical properties. The cooling channels helps also to redistribute the heat over the die avoiding the presence of hot spots. In this case, we have two separated cooling circuits one with water at 303.15 K (in blue) and the other at 393.15 K (in red). The diameter of both channels is 14 mm.

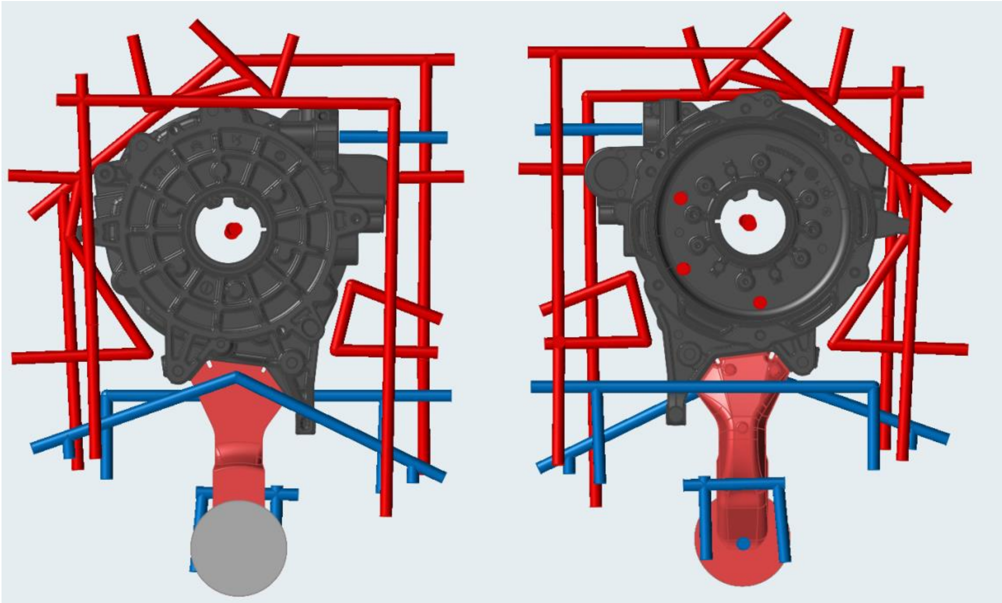


Figure 55: cooling system layout

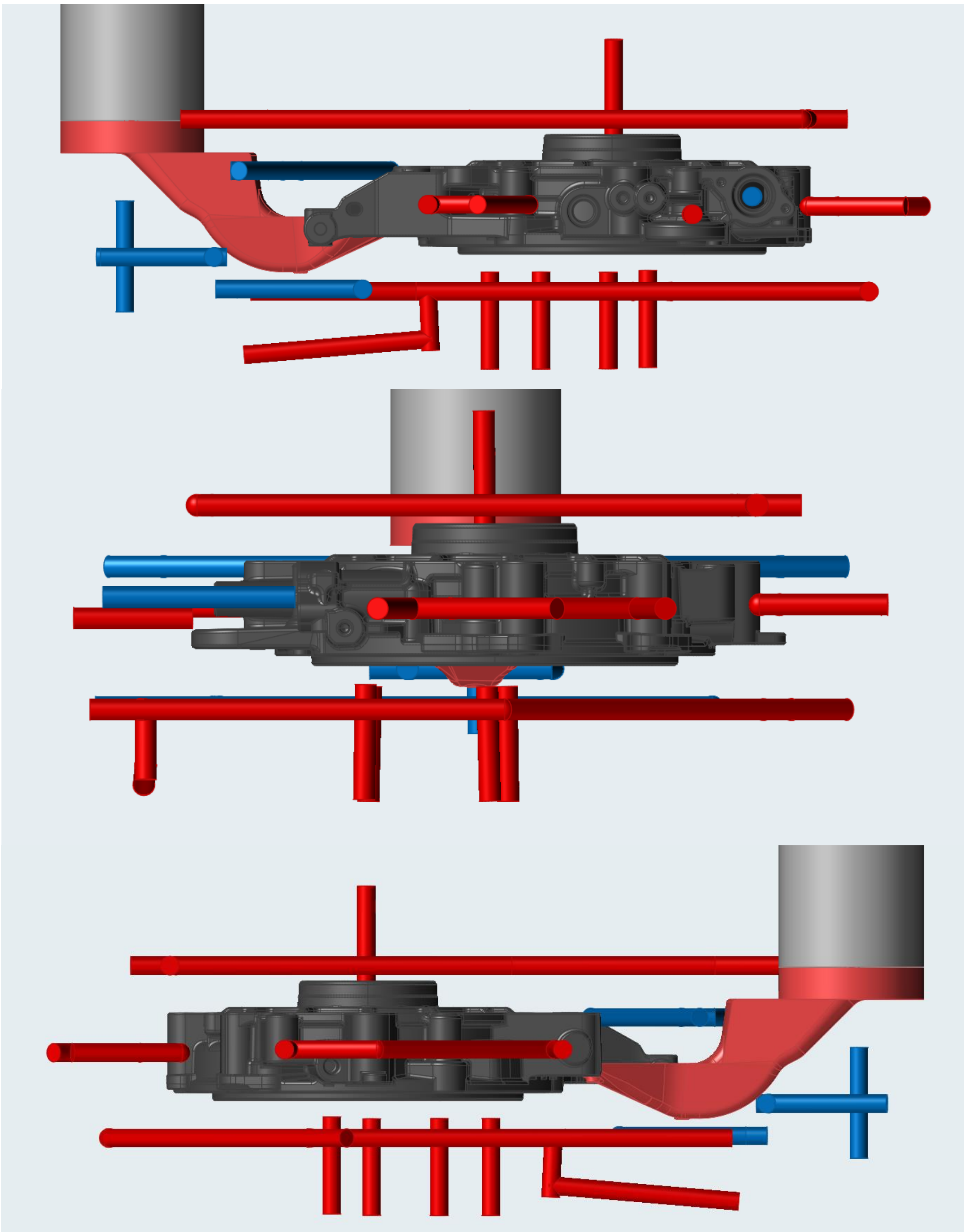


Figure 56: cooling system layout, lateral views

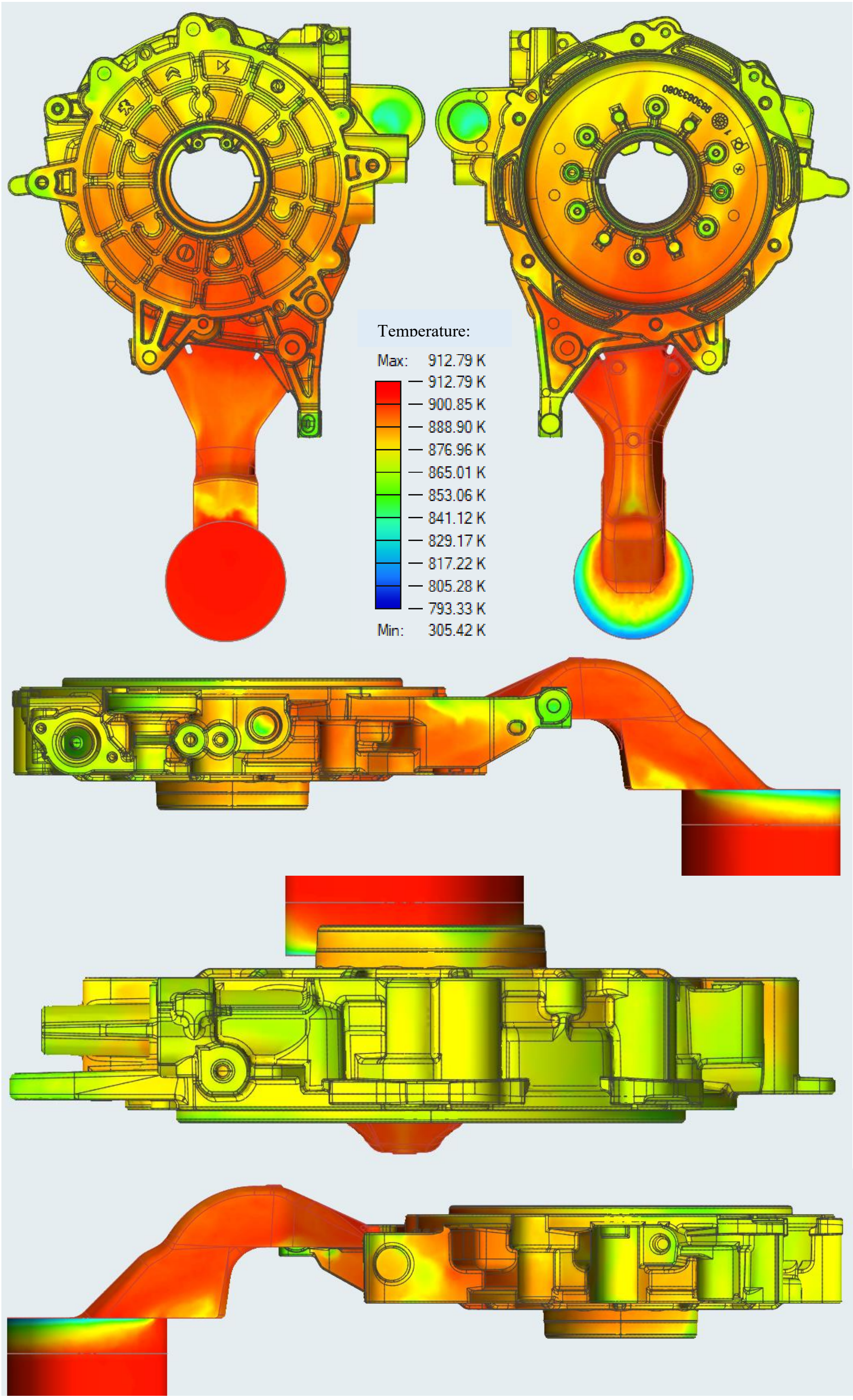


Figure 57: temperature distribution during filling

For the temperature distribution during filling (figure 57) the situation does not change too much. What we can see is a slight reduction of the temperature of the runner and of the part area near the gate. The temperature reduction however is limited to a couple of tens of degrees. The very low influence of the cooling system in this case may be given by the short time over which the injection takes place, this fraction of time can be too short to have a consistent thermal exchange between the cooling channels and the entering alloy. This low variation of temperature however still does not lead to the formation of solid fractions during the filing phase.

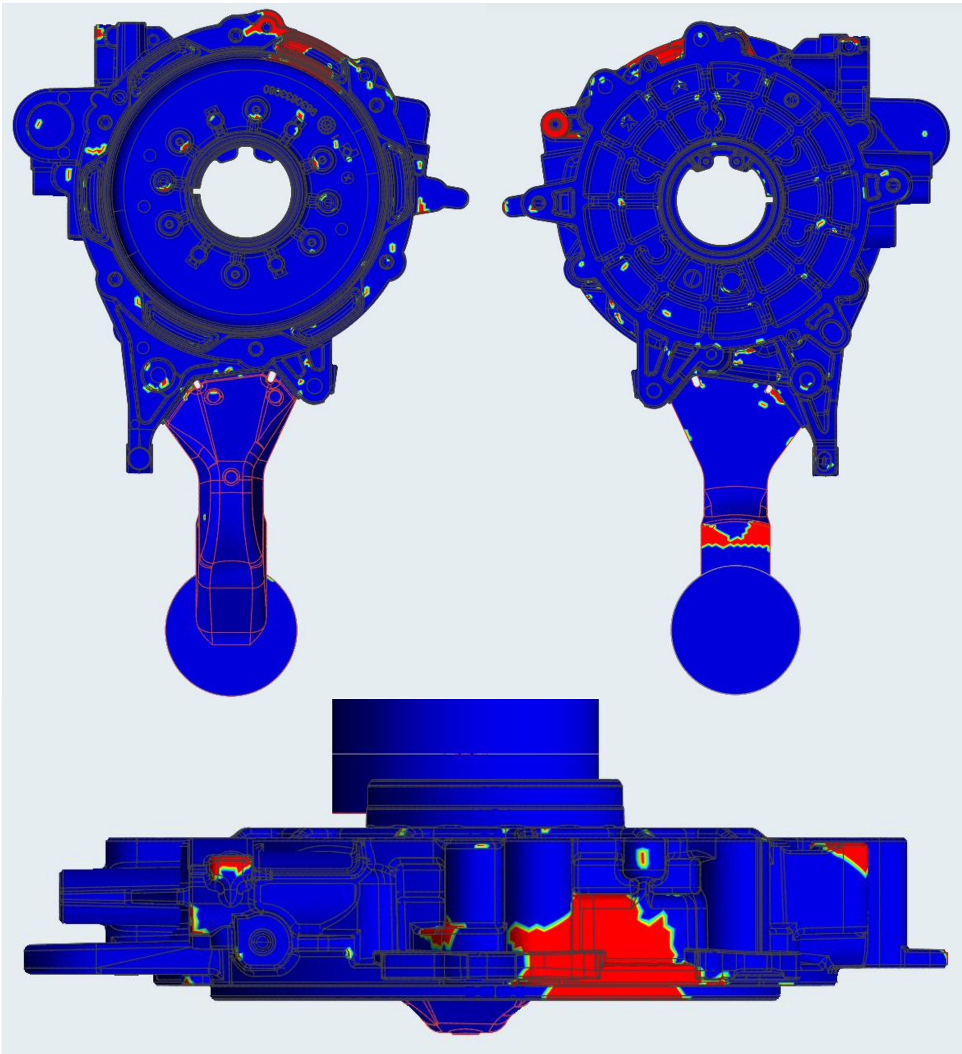


Figure 58: air trapped

Considering the trapped air we can see from figure 58 that there is an increase of air concentration in the top zone and generally an expansion of all the other small sacks of air.

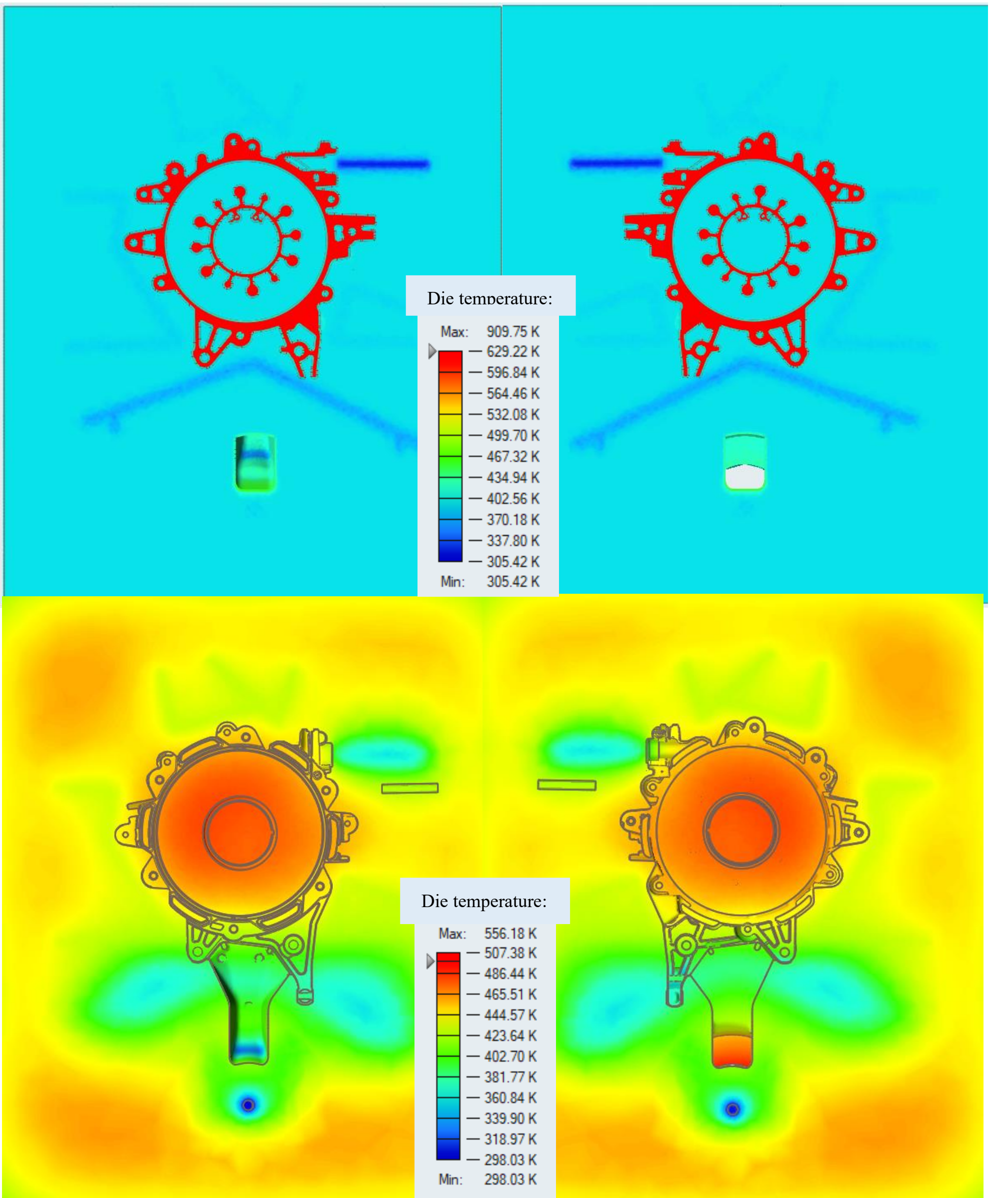


Figure 59:mould temperature during filling and solidification

The velocity at the cavity gate remains unchanged with respect to the previous simulations and being these linked to the die erosion also this does not change. Also the filling time and the solidification times are unchanged.

In figure 59 we can see a great reduction of the die temperature at the end of the filling, about 80/90 K. We have also the same temperature reduction in the die temperature during the solidification, in particular we can see a reduction of the very high temperature in the zone of the injection piston. The overall temperature distribution is more homogeneous avoiding the passage from high temperature in the middle to very low on the die periphery.

In the end we have to consider that the simulated mould about one half of the real one. This was done mainly because using the correct dimension will have led to an increase of the computing time. So the real temperature will be lower due to the thermal inertia given by the higher die mass, but the temperature distribution will remain unchanged. This consideration has been verified in chapter 5.3 where we have simulated three dies with different dimensions.

5.5.4 Cycling opening and closing of the mold

This simulation has the task to reproduce what happens to a mould during real functioning from the thermal point of view. The parameters that we must insert are the number of cycles for which we want to iterate the procedure and the time for which the die is opened and closed for each cycle. As we have said in the previous chapters the thermal conduction between the environment and the mould will be very different if the die is open or closed. After a certain number of casts the die will reach a steady state temperature. This is what we want to reach at the start of the filling simulation. For our simulation we will use ten cycles. For each iteration the die is closed for 30 s and open for 40 s. One of the limitations of this program is that it cannot simulate the spraying of the cavity so in the end we will obtain mould temperatures a bit higher than the real ones. In figure 60 we can see the mould temperature at the end of the filling, the one before the part ejection and the one before the die reclosing.

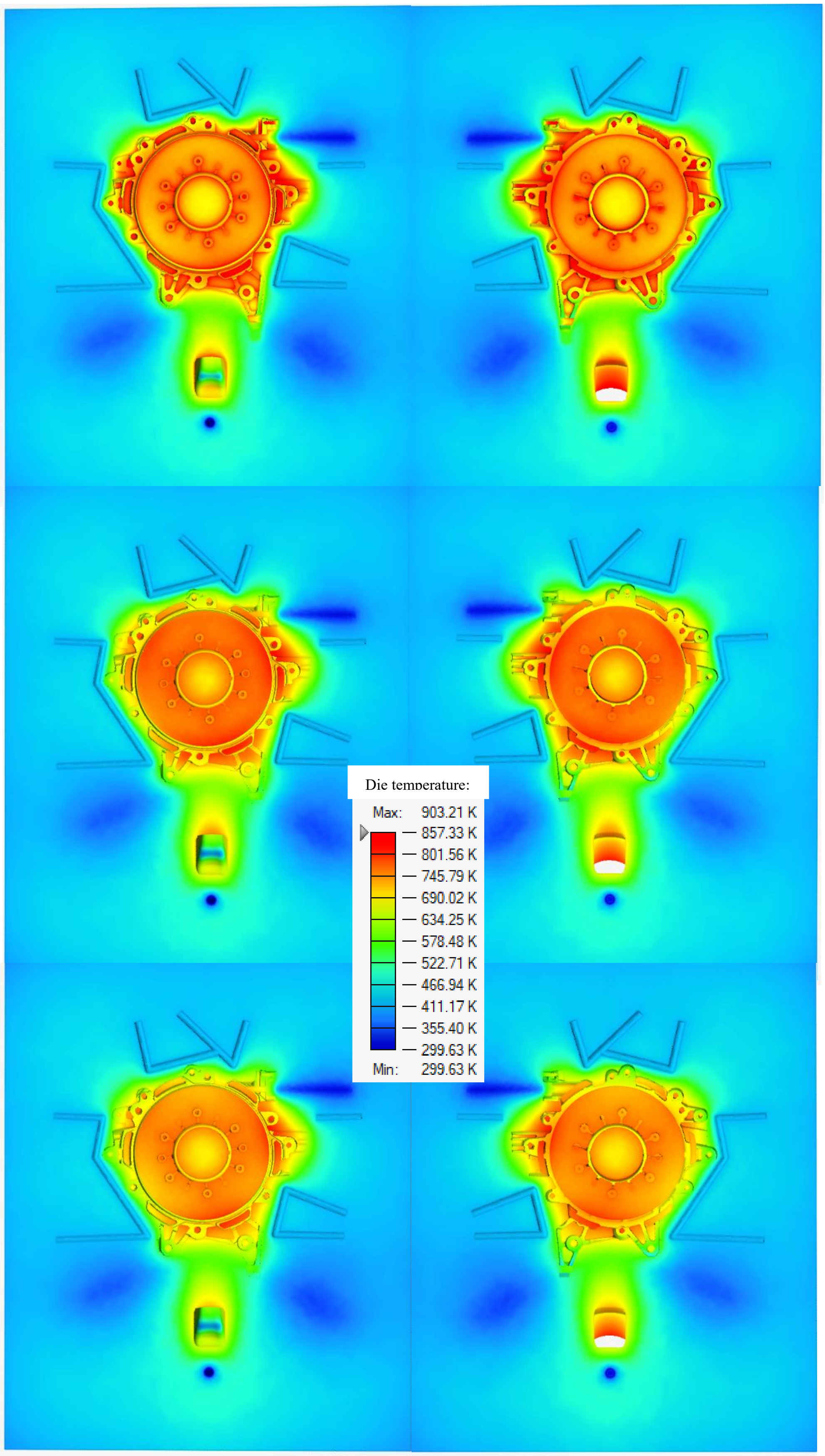


Figure 60:die temperature at filling end, before part extraction and die reclosing

As we can see from the picture, once reached the steady state the die temperature remains more or less the same during the all cycle. This is very important to avoid thermal fatigue due to continuous change of temperature. The only part with a variation of some degrees is the center of the cavity, where we have the thickest part and so the higher temperatures. Overall the die temperature is about 450 K and the temperature at the centre of the cavity is 150 K higher then before.

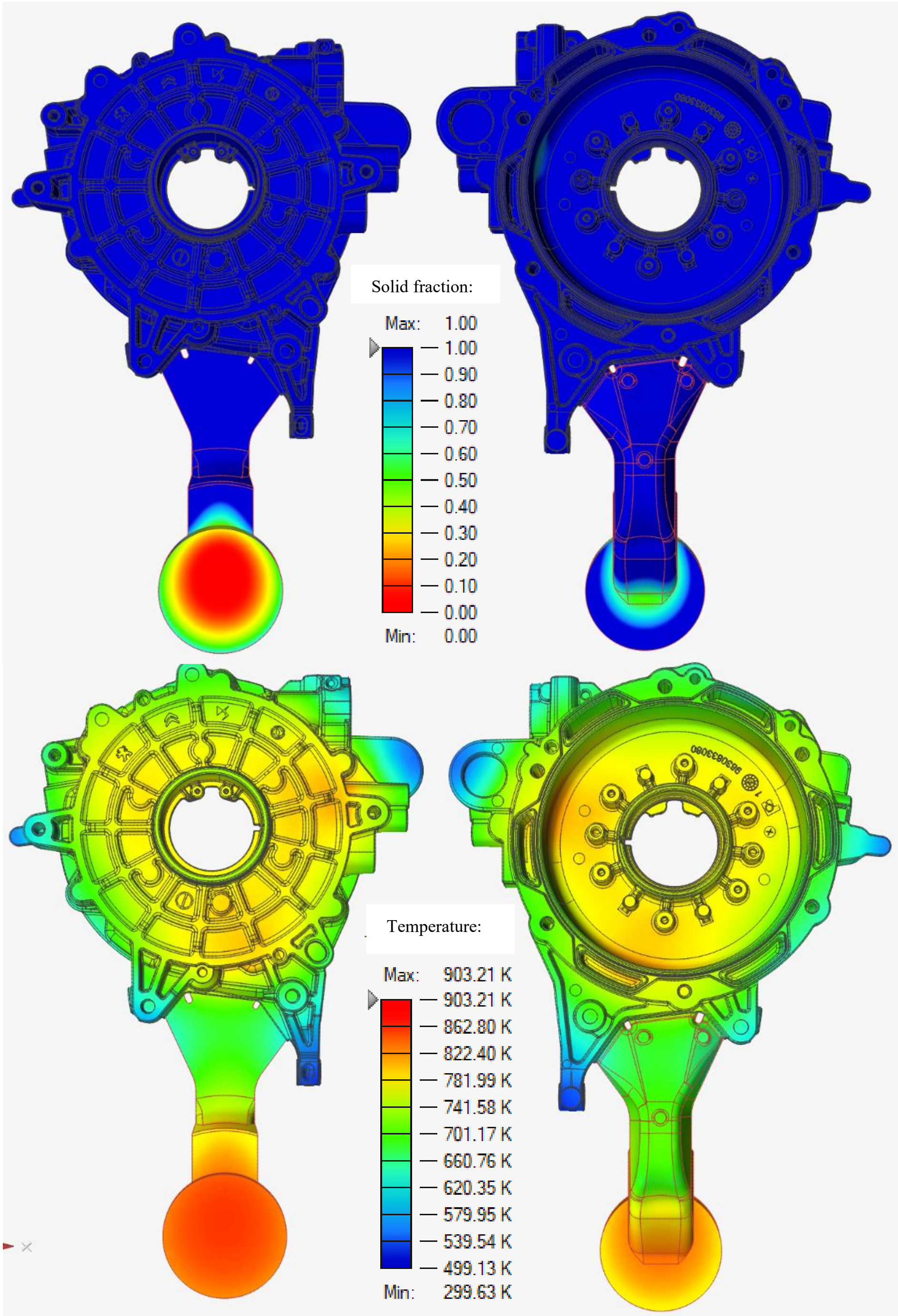


Figure 61: solid fraction and temperature at cast extraction

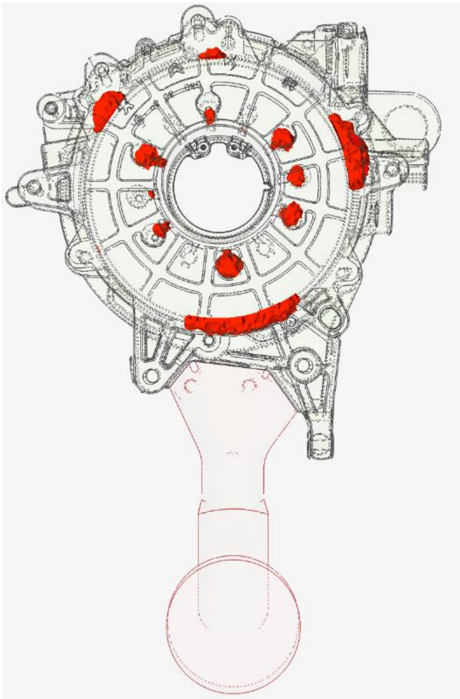


Figure 62: porosities risk

The upper part of figure 61 shows that at the time at which we have the extraction of the casted part from the die cavity all the part is at the solid state and this is very important to avoid deformations and cracks. In the second part of the picture we can see the corresponding temperature at the same time instant. On the left (figure 62) we can see the remaining porosities, in the following we will consider how to deal with them. For what concerns the air trapped inside we have a general reduction of the small diffused red points distributed on the cast part and a reduction of the three big zones on the opposite side of the injection point. Also for this problem we will take countermeasures when talking about overflows. Die erosion, solid fraction during filling, filling time and velocity at the gate we have no significant changes with respect to the previous simulations.

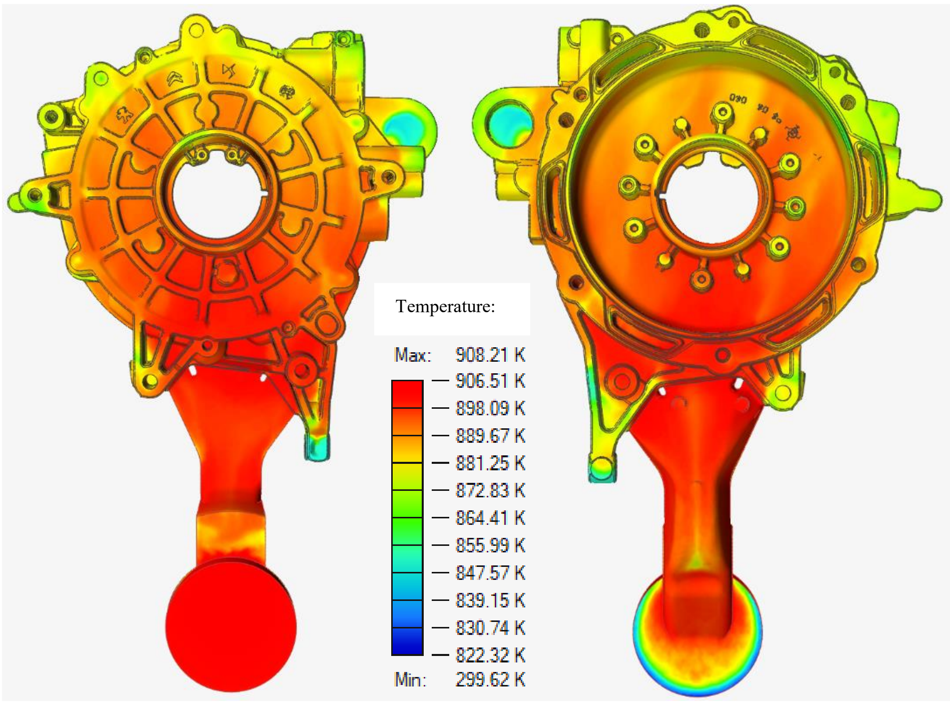


Figure 63: filling temperature part 1

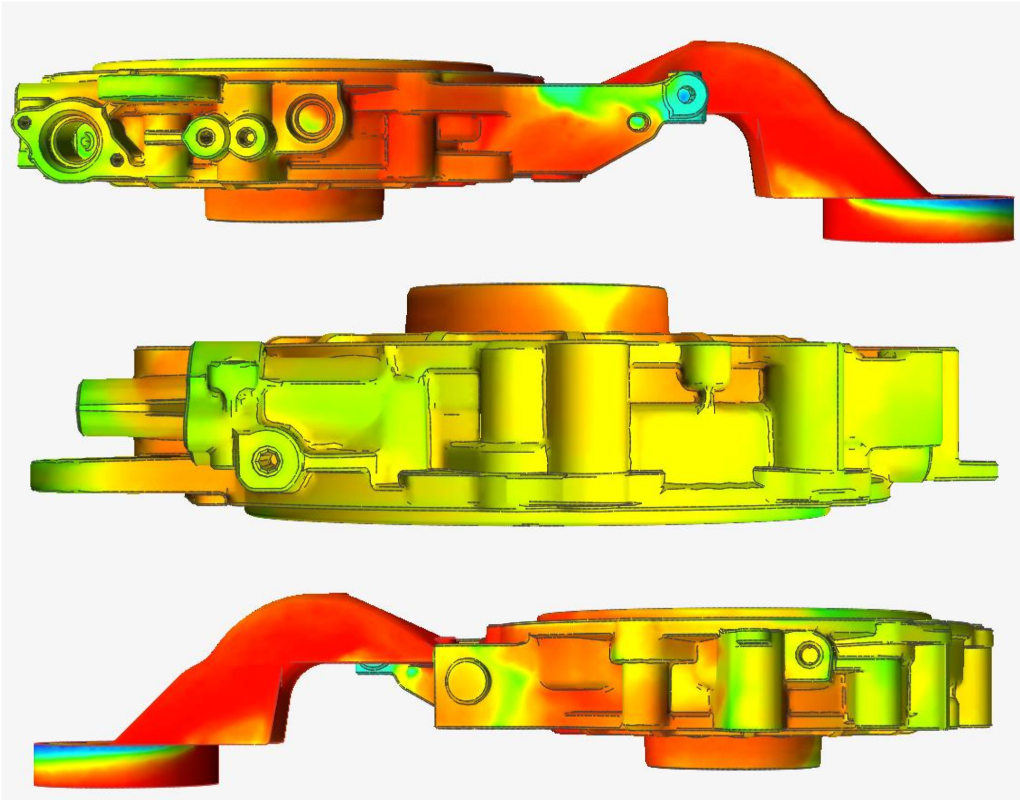


Figure 64: filling temperature part 2

From the pictures 63 and 64 we can see the filling temperature slightly higher than before (about 20 K) mainly along the runner and at the gate. The solidification time is a bit longer probably due to the higher temperatures in the centre of the mould cavity.

5.5.5 Overflows

This is the most difficult part and also the one that increases the computational time most. Regarding the computational time we have that the previous simulations last at most eleven hours, simply adding the overflows and changing nothing else we reach thirty-two hours. After having performed all the previous simulations we should be able to identify the most critical points for the air trapping that can lead to porosities. The positioning of the overflow should enable the possibility to evacuate all the remaining air in the overflows themselves. We cannot put overflows everywhere there are some guidelines to follow:

- They should be put only in an external position with respect to the figure;
- They must not be positioned on aesthetic surfaces, because after trimming a mark will remain on the surface;
- They must be connected to vents to eliminate the air;
- When more overflows are linked together at the same vent the filling time of each route must be checked. Otherwise we have the risk that filling one overflow will preclude the operations of another one;
- They must be positioned in zones where they can be trimmed away after the casting.

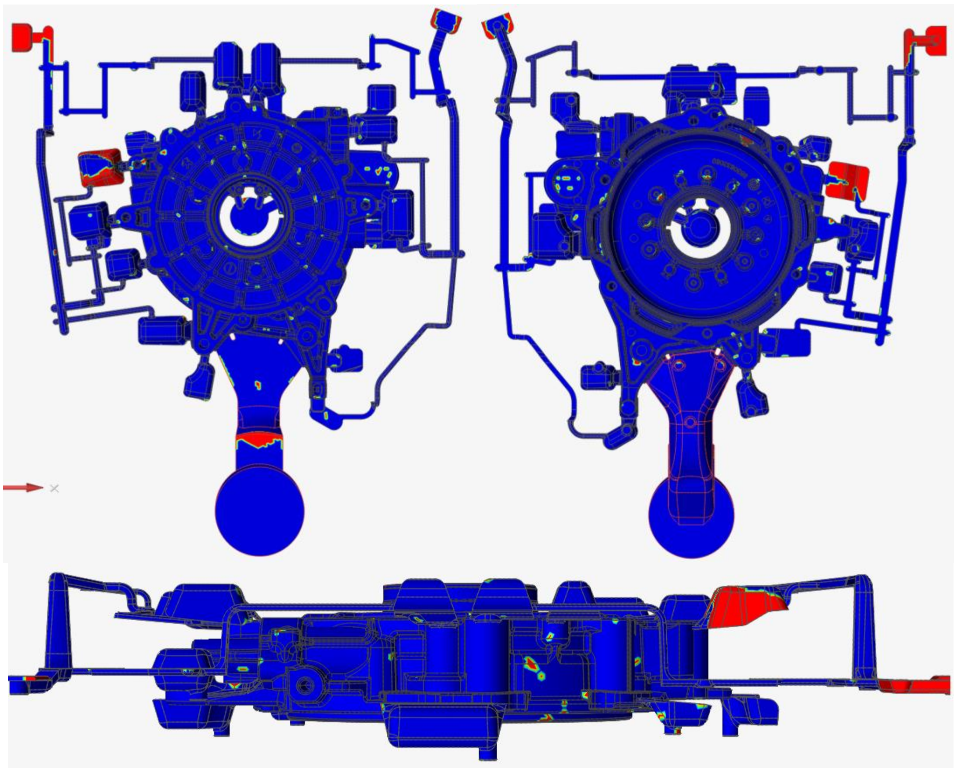


Figure 65: air trapped

In picture 65 we can see that the introduced overflows work well, in fact most red zones (air trapped) are positioned in the overflows. With their introduction we have a drastic reduction of the trapped air positioned on the opposite side with respect to the gate, this will lead to an improvement of the overall quality of the cast. In figure 66 we can see that we have only small changes in the temperature distribution and the result of the simulation have been inserted only for completeness. The changes are mainly in the zone near the entering of the alloy into the cavity where we have a slight increase of the temperature.

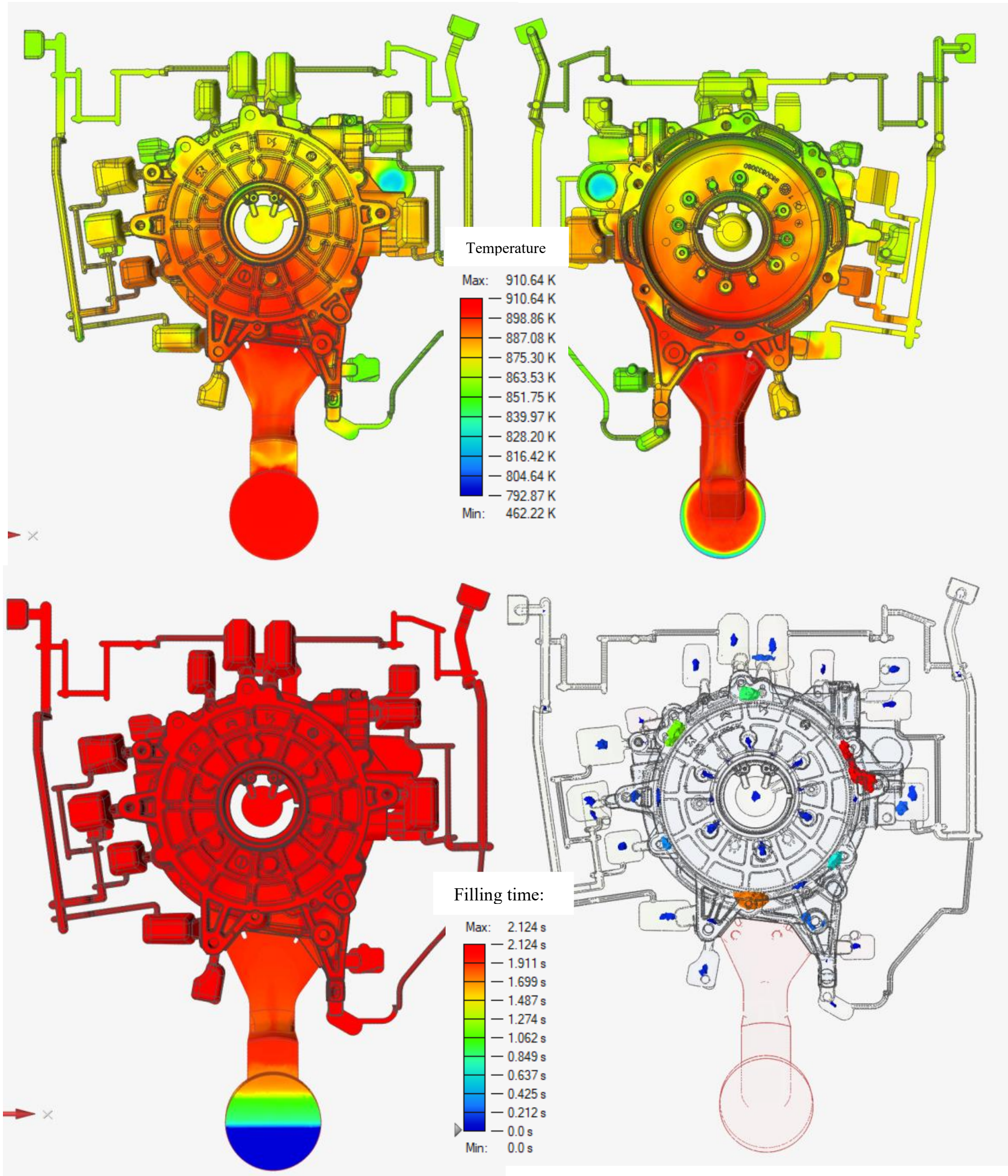


Figure 66: filling temperature, filling time and total volume restriction

The last two remarkable results given in figure 66 are the filling time that is obviously higher, having to fill a bigger volume, while on the right we can see the total volume reduction. This last highlight the zones that are more luckily to leave cavities, the severity of the risk is given by the color.

Referring to the overflows layout of the simulation performed with Flow-3D Cast to obtain a better air evacuation in this case we have introduced three more overflows in strategical areas. In reality in the previous results is possible to notice only two more overflows. The third one has given some errors due to problems with the geometry. For an easy interpretation of the results it has been removed and it will be inserted in the last simulation with Castle.

5.6 Simulations with PIQ2 Castle

As a final check we perform the simulation made with the two previous software with a third one. The software we considered is PIQ2 Castle that is used by many foundries. In table 5 are listed the main parameters used for the simulation. One of the software peculiarities is that it has a broad list of HPDC machines from which directly take the values for the simulation. As is possible to see in the table above simply selecting the machine all the parameters are inserted in the simulation.

Table 5: simulation parameters

Alloy	AC-43400
Alloy temperature [°C]	670
Die temperature [°C]	200
Static pressure [bar]	486
Multiplication pressure [bar]	800
Total casting volume [cm^3]	1768.54
First phase velocity [m/s]	0.25
Second phase velocity [m/s]	4.5
Total filling time [s]	1.63
Start second phase [mm]	391
Piston diameter [mm]	90
Cylinder lenght [mm]	675
Filling percentage	46%

We can notice some differences with respect to the parameters of the previous simulations:

- We have a higher temperature of the alloy but this value refers to the temperature of the alloy in the holding furnace, so we have set it to have the same temperature of the alloy used in the previous simulations at the point of injection start;

- The velocities of the first and second phase are higher. This has been done because these values are closer to the ones really used during the sampling. So in the end this will be the only difference with the previous simulations;
- Obviously we have a shorter filling time and an anticipated transition point between the two speeds due to the higher injection speed.

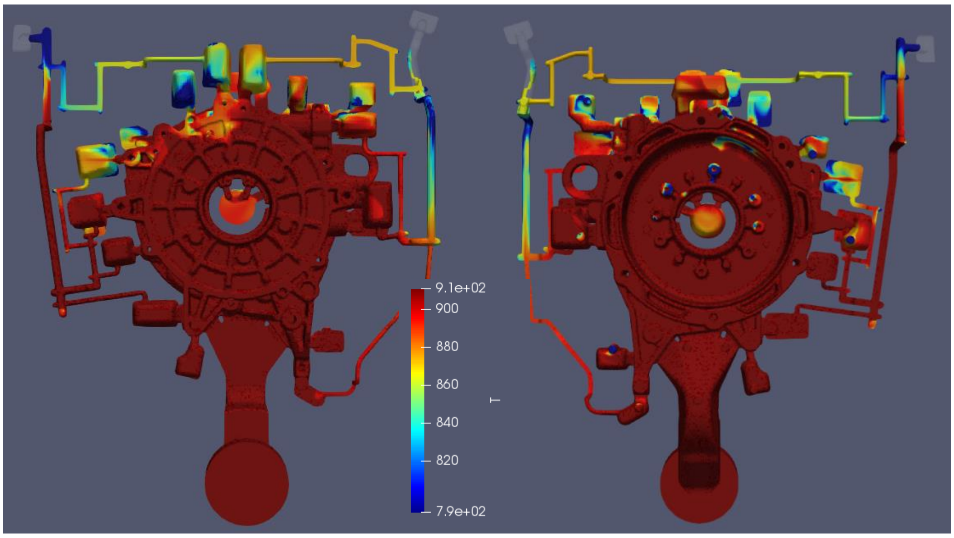


Figure 67: filling temperature

In this case we can see a higher temperature (figure 67) at the end of the filling especially in the central zone. Even if comparing the results with the previous simulation they seem really different looking at the key the difference is no more than 20/30 K. This can be due to the fact that this software does not simulate the die with the cooling system and the cycling till the steady state and this can lead to an overestimation of the temperature. Otherwise this can be given simply by the different approximation used by the two solvers during the computation.

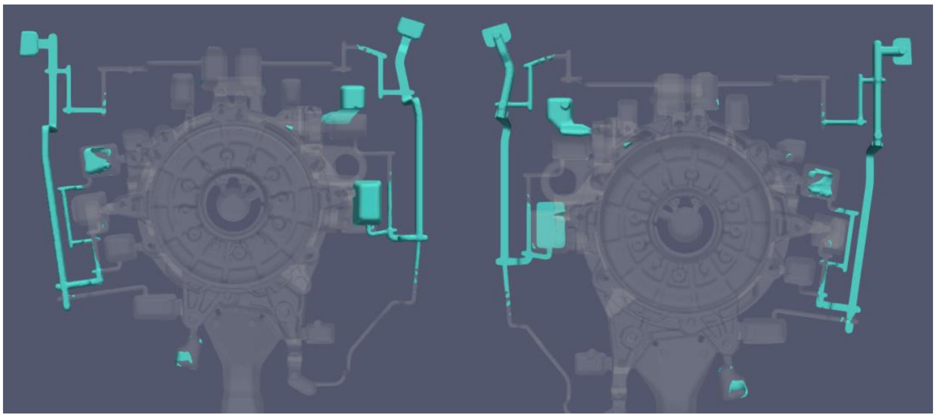


Figure 68: trapped air during filling

For what concern the simulation of the air trapped (figure 68) we have a very good evaluation fairly close in terms of completeness to the one obtained with Flow-3D Cast and surely more accurate than Inspire Cast. Obviously this results are not comparable with the first simulation performed with Flow-3D Cast due to the different number and position of overflows. On the other side they can be benchmarked with the one obtained by Inspire Cast and on this aspect Castle seems to represent better the air flowing in the die. The inserted overflows anyway work well, having all the trapped air inside them.

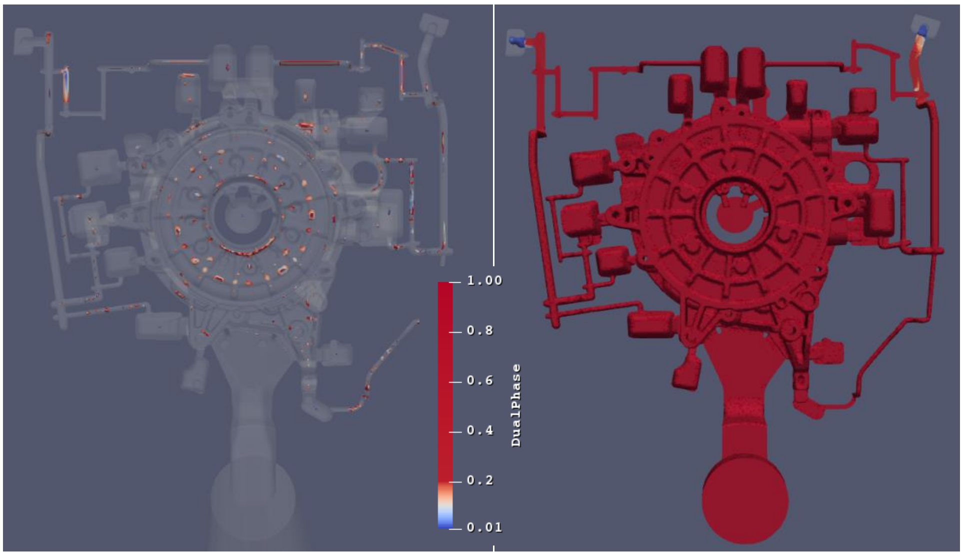


Figure 69: net defect volume and dual phase during filling

The net defect volume (figure 69) is the result where we have the major difference with respect to the other simulations. In this case while Flow-3D Cast and Inspire Cast indicate the same zones where we can have porosities due to shrinkage and the only difference is in the dimension of the zone, Castle does not highlight the same dangerous zone. In this case considering that the results of the other two software are correct the problem can be still linked to the lack of thermal simulation of the die. Considering the solid fraction during filling we can see from the results on the right of the figure that the alloy is all in the liquid state and this perfectly matches the result obtained with Inspire Cast.

The die erosion (figure 70) as usual is focused at the gate where we have the higher velocities, we have also some possible critical zones at the inlet of the overflows and in the central zone of the cast on the thinnest walls. As we will see in the following with the PQ2 diagram the die erosion will be a critical problem for this cast.

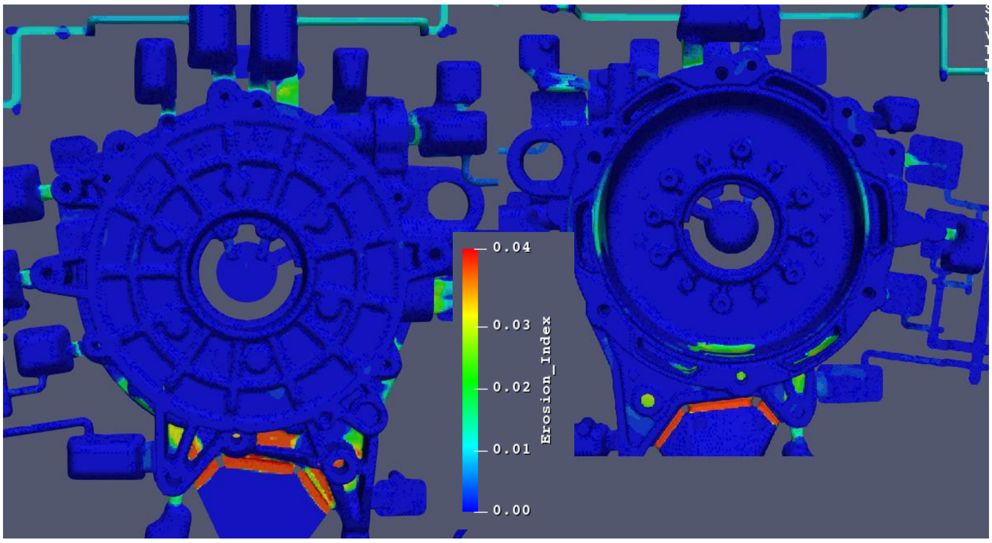


Figure 70: die erosion

Another interesting feature of PIQ2 castle is the possibility to visualize the metal flow trajectories during the filling phase (figure 71). This can be particularly useful to evaluate the flow direction once it passes the gate and hits the cast walls.

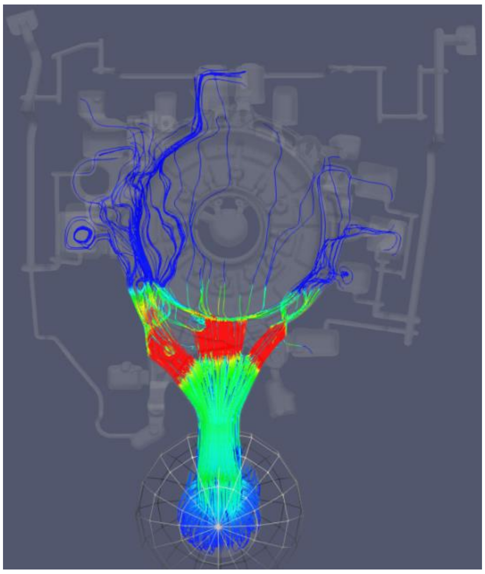


Figure 71: velocity trajectories

Last remarkable feature that is more a comfort than a real tool is the automatic evaluation of the transition point between V1 and V2 that with Inspired Cast must be evaluated by hand, nothing too complicated as shown in the paragraph regarding the injection cylinder but this feature saves time.

CHAPTER 6

Case study of a gearbox housing for electric cars transmission

The production of these components for electric motors, that are a relatively recent technology, has brought some new obstacles that must be overcome. The main problem with these types of products is that being new we have not references on how to produce them, so the first phase of industrialization can take long time with respect to "more traditional" components. In the following we will see the main problems given by these types of products and the difference with the production of parts for traditional thermal engines.

6.1 The simulation as a tool to obtain parts of the required quality

As we have already said all the technical specifications and requirements for the casted component are inserted in the STL file. STL means laboratory technical specifications and is how the PSA group calls the technical requirements sheet, however independently from the name each customer has a file with technical specifications to which we must stick during the production. When looking at the simulation results we must analyze the defects highlighted by the tool looking for the parts that are not in accordance with these requirements. Every modification of the process parameters in the subsequent simulations must aim at obtaining the requested quality in the indicated areas. In fact as said it is hardly impossible to have a cast without defects, what we can try to do is to move these defects from a sensible zone to a non-sensible one. To save time and cut costs is not useful to reduce a defect that is already within the limits given by the customer. In this optic we must try to have the result of the simulations that stick as much as possible to the STL prescription, every further improvement of the cast will only mean an increase of the cost without tangible benefits. The types of defects in the specifications file are divided in two macro groups one called internal soundness where defects can be found with the radiography and the other group includes failing revealed after machining.

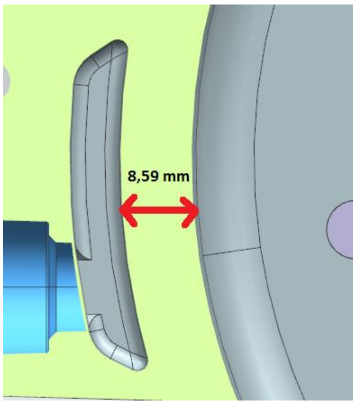


Figure 72: channels thickness

In our component we have two special zone with particular quality requirements, one being the housing of the bearing has to sustain relevant mechanical loads and the other is where is installed the gasket that seals the water and oil channels. All the other parts of the component are classified as standard zones and have less tight quality requirements. For each of these zones we have prescriptions in terms of diameter, spacing and number of porosities. Obviously a strong limitation of the porosities presence and dimension is fundamental to have a good mechanical strength of the component and to prevent leakages. The following or not of these prescriptions by the cast will be one of the main indicator of how well are set and optimized our process parameters. In our case we have also the distinction between normal porosity that can be inside the cast and pinholes that are normally on the cast surface. Other critical areas are the hole to be threaded (tapings), the requirements are no defects on the first three threads and then we have limitations on the number and the position of defects on the following thread. The first three threads are very important because they are fundamental for the correct positioning of the screw and the following screwing.

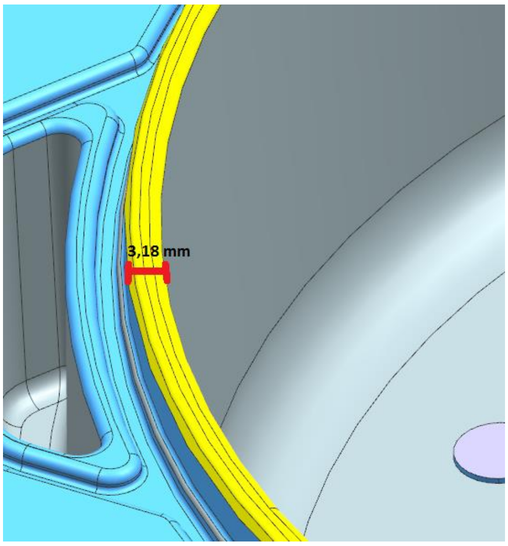


Figure 73: sealing wall thickness

6.2 guidelines for the sustainable production of electric transmissions components

Having channels with water and oil in pressure creates the possibility of drawings. As an example we can look at the two pictures on the previous page, figure 72 represents the typical thickness of the walls that separates the water in the peripheral channels from the oil that is inside where the rotor is. In figure 73 we can see the minimum thickness of the walls that is in correspondence with the joining of the two half housing of the motor where a seal is interposed. From these two images we can understand that in some zone on the cast the distance between the two channels is very short and the eventual presence of porosities can easily lead to mixing between water and oil with catastrophic effects on the motor.

6.3 casting of transmission for endothermic and electric engines

One of the main differences between the casting of the two types of components regards the oil and water channels. In thermal engine transmissions we have that the channels are external with respect to the casting and the oil that remains inside for the lubrication of the gears is not in pressure, being in this case the lubrication entrusted to the spraying given by the gear when impinges on the oil in the gearbox.

Another difference that can be easily spotted is the dimension of the two components, the electric motor housing is much smaller but with thicker walls while the gearbox housing is bigger but with thinner walls.

One of the main problems in the gearbox casting are the high velocities of the flow being the walls thin, this will lead to die erosion. Having a very big casted part and injecting on one side there is also a problem where the two fronts of the melted alloy rejoin.

On the other side considering the electric motor housing having a thick central part will likely create porosities or voids due to retirements during shrinkage. In the end having two completely opposite structures of the cast lead to the formation of different defects.

In the images below we can see a simulation of a “conventional” transmission housing from Ftp Industrial. This simulation has been performed with the same mesh dimension of the previous ones (2.5 mm) without the cooling system and the overflows to underline all the defects that the casting of this type of products can generate.

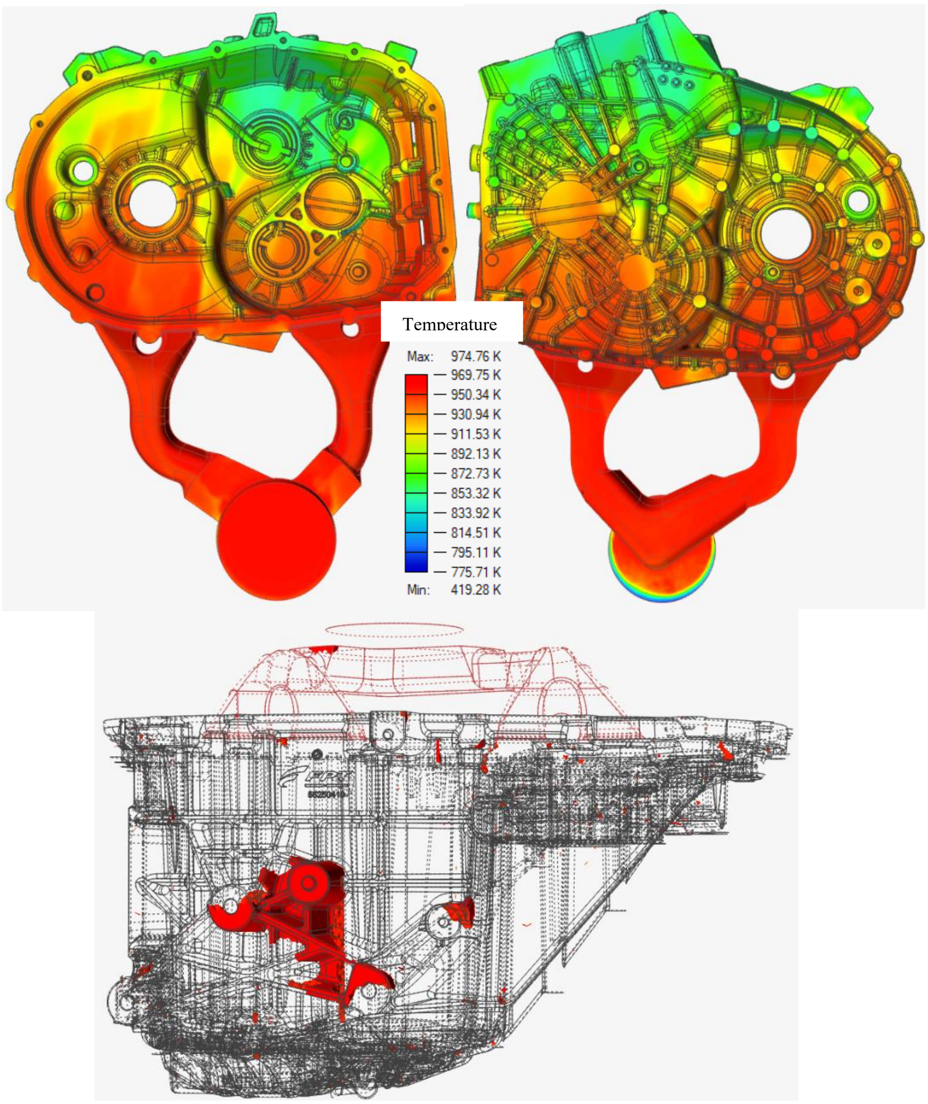


Figure 74: example of simulation of thermal engine transmission part 1

Comparing this result with the one in the section 5.4.1 we can see many substantial differences. First of all looking at the filling temperature (figure 74 top) apart from the higher initial temperature of the alloy we can see a much bigger decrease in the metal temperature while flowing through the cavity, in this case we have a variation of about 80 K while for the front housing we have about 25 K, this is probably due to the dimension of the casted part.

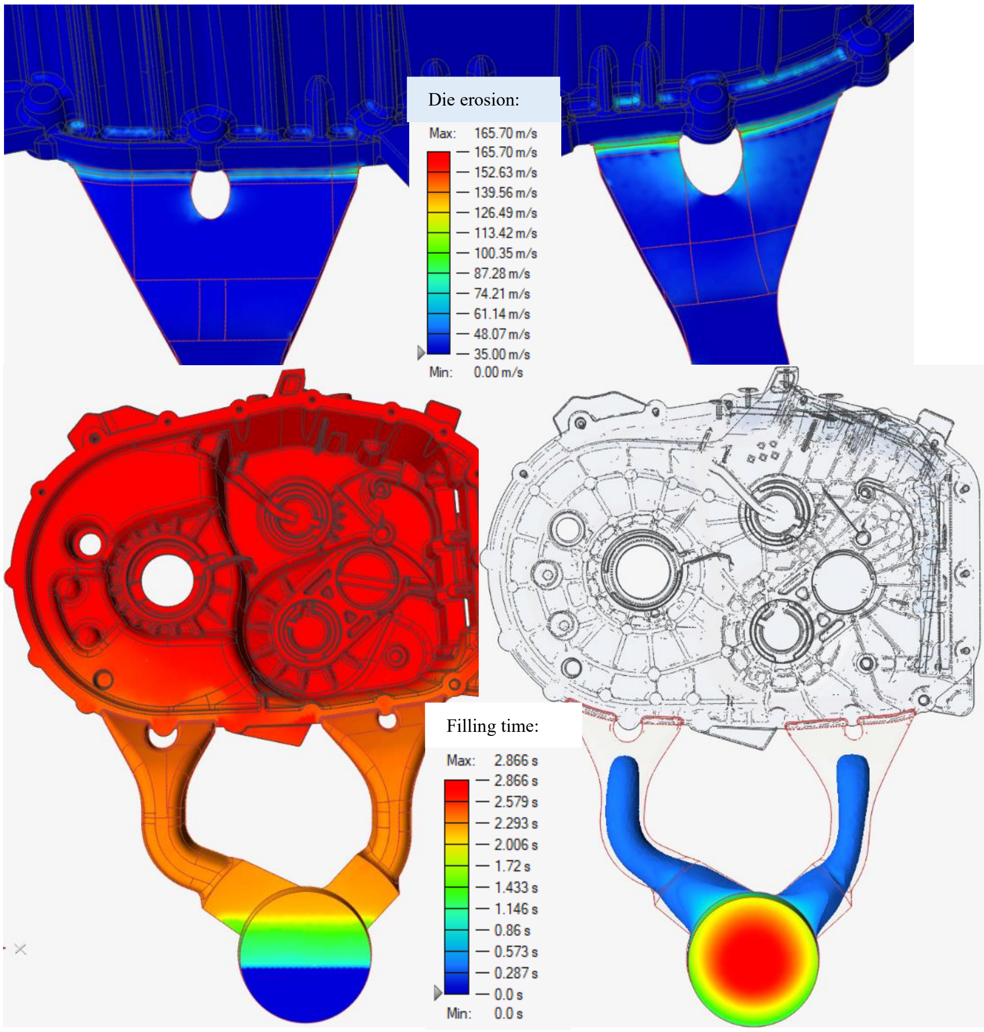


Figure 75: example of simulation of thermal engine transmission part 2

The trapped air is only at the rejoining of the two melted fronts and in this case is concentrated in one zone (figure 74). As we have mentioned before at the gate we have by far higher velocities due to the lower thickness of the casted part (figure 75 upper part). In figure 75 we can see by far higher filling time that is a consequence of the bigger volume of the part and on the right we can see that this component has, as will be described after, already undergone an optimization of the thickness in fact on the contrary with respect to the front engine mount once the gate solidifies all the parts after this has already solidified this will reduce the risk of retirements, voids and porosities.

In the end the main differences that we can see in the two types of components are due to the different periods for which they have been in production. For what concern the thermal engine transmission the same components have been produced for over twenty years, so they have sustained different optimization process. These optimizations have led to minimum and constant thickness of the walls (figure 76) that is exactly what we desire for a good castability. Thanks to this long year experience and the collaboration with the suppliers nowadays also the car producers have developed knowhow on the design of components for a good castability. On the opposite side these parts linked to the electric vehicles are young and have not reached the maturity stage that characterizes the components for thermal engines. Moreover automotive OEMS do not directly design these parts but they outsource to other companies like (Bosch, Continental, Siemens). These suppliers have not the knowhow that the car manufacturer has developed over years on the high-pressure die casting process.

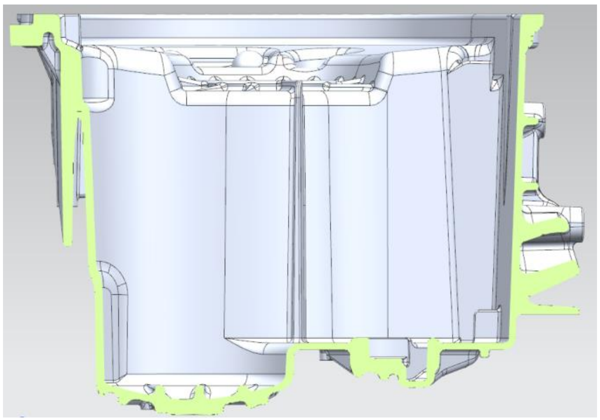


Figure 76: wall thickness

CHAPTER 7

Mold sampling

Once the mold arrived (figure 77) we start with the sampling. This is a procedure performed with every new mold to verify the correspondence between the prescriptions given to the mold supplier, the simulations performed and the obtained results. The same process is followed with the trimming machine (figure 78) to check if the cutting of the overflows and runner is correct or leave some bad marks on the cast surface.

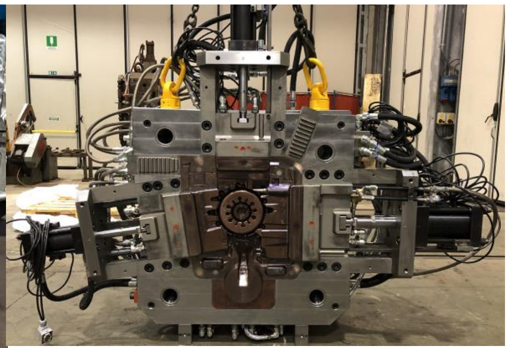


Figure 77: die before sampling

7.1 The procedure

The mold is installed on the designated high-pressure die casting machine and the parameters are set according to the ones of the casting simulations. After the production of some waste casting the die goes to the steady state temperature and the theoretic productions of good quality products should start. In reality we have to deal with the fact that as mentioned before die casting can be considered in some way an art and we must rely on the experience of the technicians, we have also to consider that the simulations are an approximation of the reality so there is always a small error. In this phase usually few adjustments are performed to the machine parameters to obtain the desired quality.

The quality of the cast is checked at first looking at the surface searching for potential defects then we have the X-ray analysis to see eventual porosities inside the cast and we also check if the dimensions of the cast are in accordance with the tolerances.

In our case the first good parts produced were already of a fair good quality and only minor changes have been performed to the original parameters. In reality it is not always like this, for this product, given its particularity, we have performed much many simulations than usual and when setting the machine parameters we have strictly attained to the obtained results.

After the good results obtained with the mold we passed to the trimming machine. We installed the cutting die on the trimming machine and performed the trimming. Also in this case the machine works fine and only some minor abrasion or edge smoothing on the cutting die where necessary.

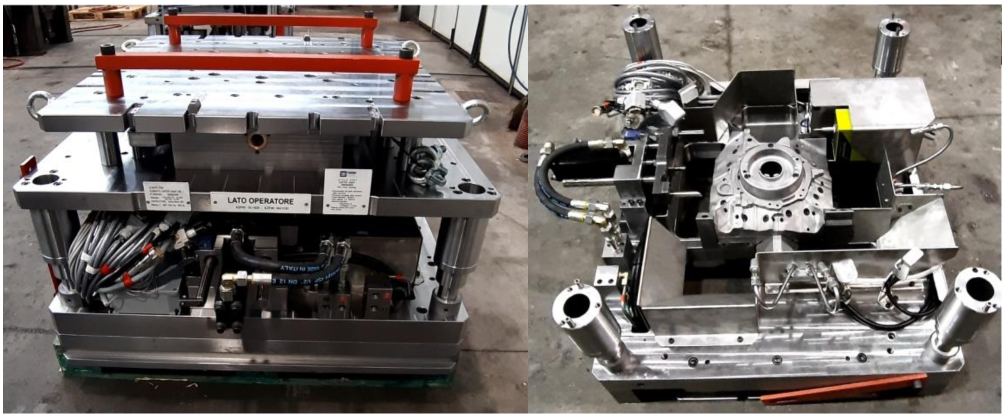


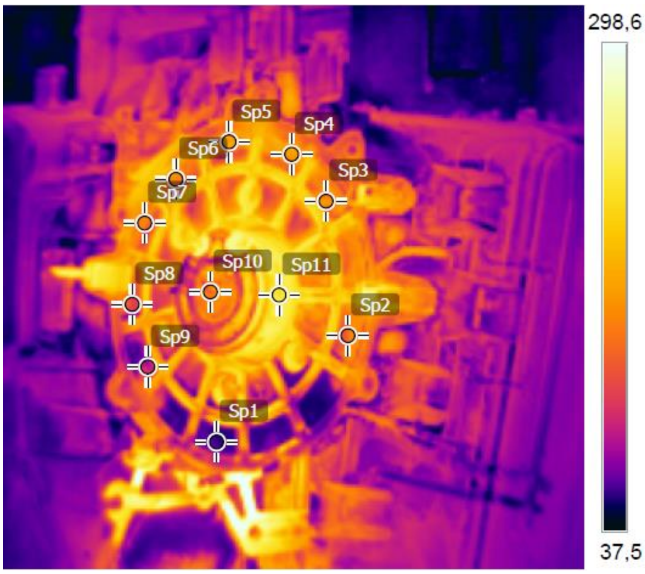
Figure 78: trimming machine mould before installation

The results obtained with our sampling allow us to already go into production, even if in the original planning were taken into account two samplings as usual. This proves once more the usefulness of the simulation in fact thanks to the deep work of analysis we are in advance of three weeks with respect to the planning, this means saving money and a reduction of the lead time.

We have also to consider that no modifications to the original design of the die have been performed because all the possible changes have already been taken into account and simulated before the finishing of the die. This last part is very important for money saving, as an example considering a simple cooling channel if it must be added when the die is still in construction it will cost a couple of hundred Euros because can be simply obtained by drilling. Otherwise if the channel must be added once the die is finished and has been tempered the hole can be performed only by erosion and it will cost thousands of Euros.

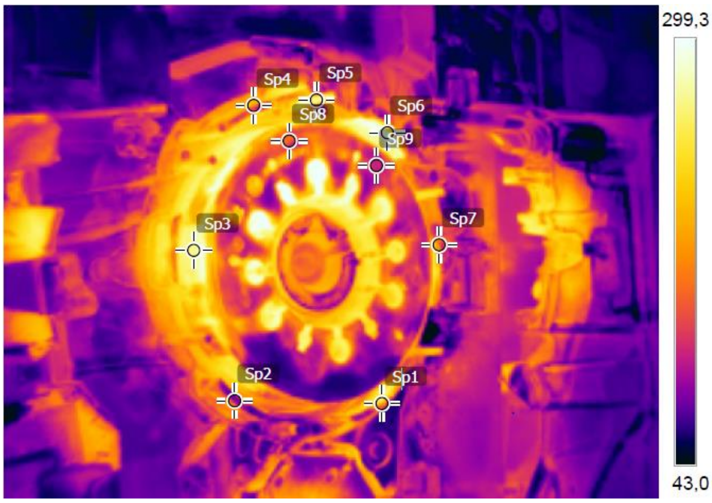
7.2 Thermographs

Once the parameters are set and the products obtained with the desired quality, using a thermocamera we have recorded the die temperature before and after the lubrication. This was done mainly to store, for the following application, the optimal die temperature once it has been reached. Having this data we can compare them with the predictions of the simulations to see if there is any significant difference. In the following we will consider only the Flow 3D Cast simulation having seen in the previous paragraph that is the more complete for what concerns the die temperature.

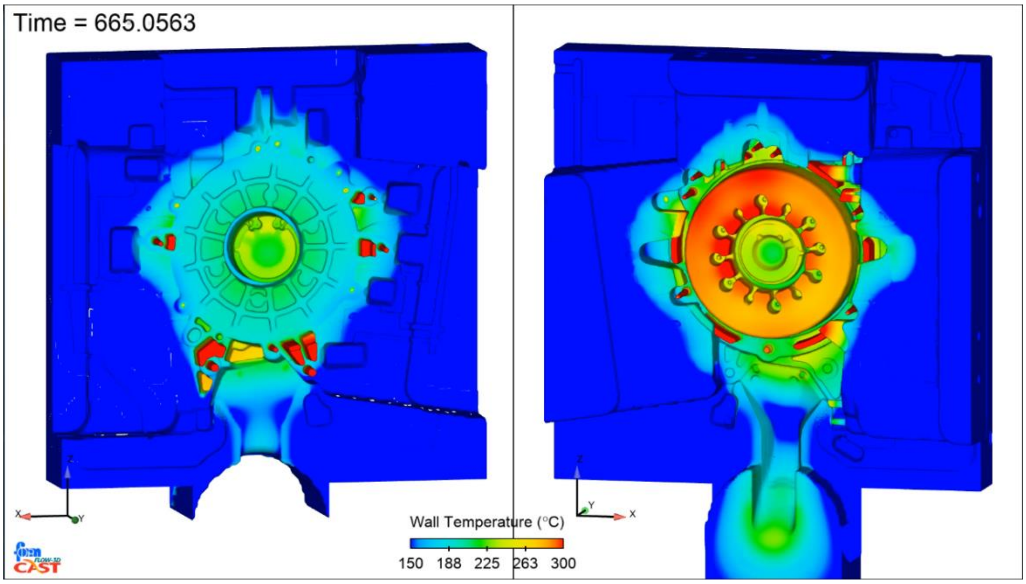


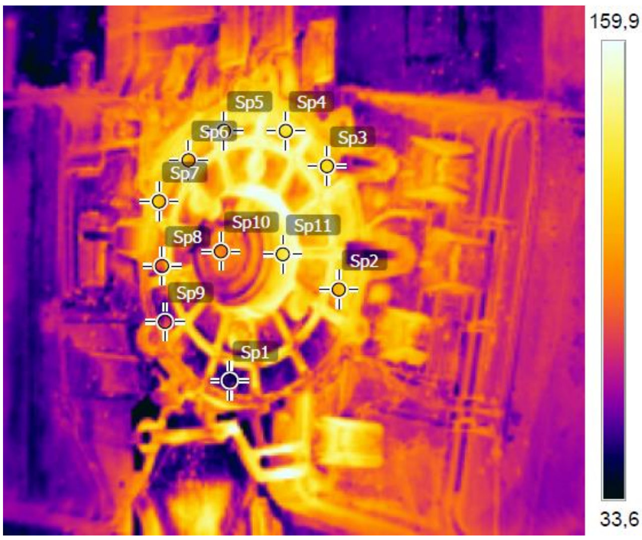
Measures	°C
Sp1	71.2
Sp2	164.0
Sp3	198.0
Sp4	193.1
Sp5	197.6
Sp6	180.1
Sp7	184.1
Sp8	140.6
Sp9	114.1
Sp10	158.8
Sp11	239.8

Figure 79: thermograph fixed side die open



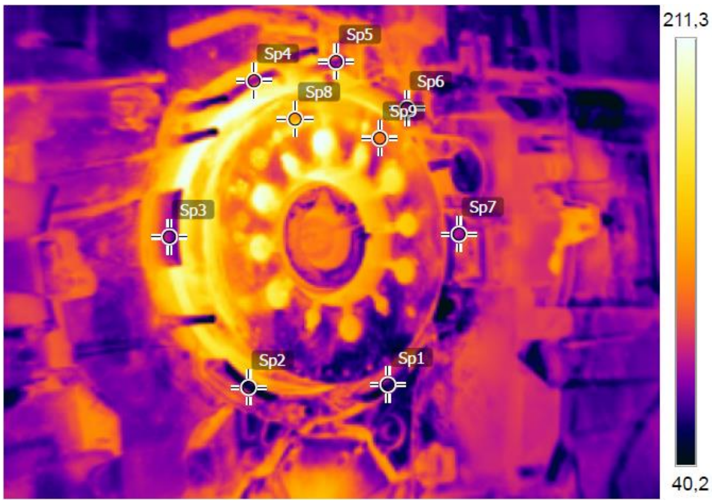
Measures	°C
Sp1	209.3
Sp2	110.5
Sp3	273.7
Sp4	201.9
Sp5	273.3
Sp6	285.8
Sp7	183.5
Sp8	174.6
Sp9	136.0





Measures	°C
Sp1	47.0
Sp2	119.8
Sp3	128.3
Sp4	134.6
Sp5	130.9
Sp6	118.3
Sp7	123.5
Sp8	94.8
Sp9	87.6
Sp10	105.3
Sp11	136.4

Figure 80: thermograph and simulation results part 1



Measures	°C
Sp1	64.4
Sp2	51.0
Sp3	92.9
Sp4	87.9
Sp5	82.1
Sp6	96.0
Sp7	95.6
Sp8	138.3
Sp9	127.9

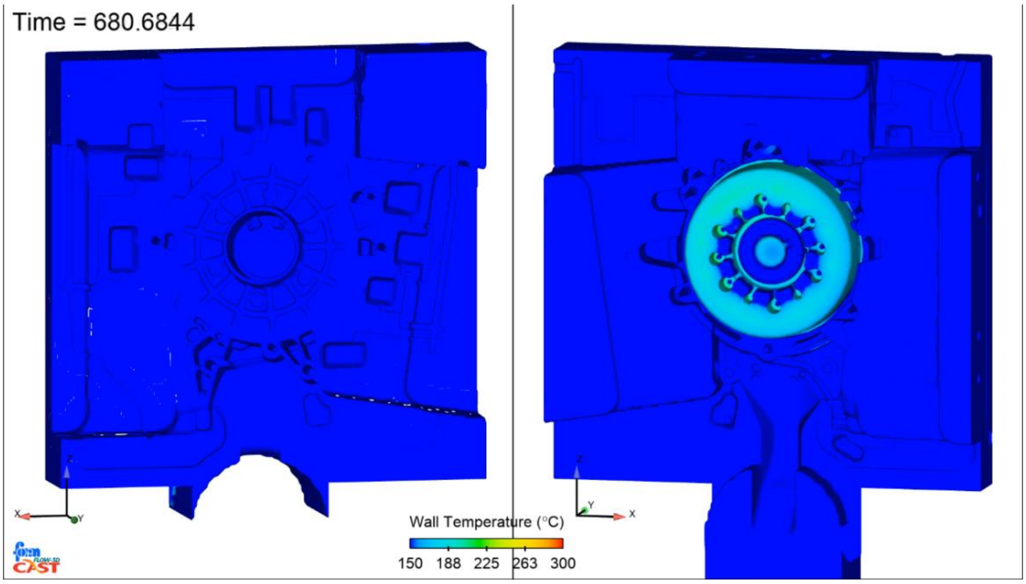


Figure 81: thermograph and simulation results part 2

Looking at figures 79, 80 and 81 that represent the die temperature before and after the lubrication, we can see that the average measured temperature is lower with respect to the simulated one. This is not a surprise because we have to consider that for measuring the die surface temperature the machine should be stopped and left open for a given amount of time in this condition the thermal exchange with the environment is very high. Due to this each second that passes before we take the measure the temperature can significantly decrease with respect to the original one.

Due to the contamination of the data given by the higher thermal exchange the results obtained must only be taken as an indication and we can see a good match with the data obtained in the simulation considering the higher margin of error.

7.3 X-ray analysis

As mentioned in the previous chapters the X-ray is a fundamental nondestructive analysis that is used to check if our produced cast is in accordance with the technical prescriptions given by the customer. The use of X-ray allows seeing many defects that are under the surface of the cast i.e., it is possible to check porosities, cracks, cold joints and so on. In the following we can see the X-ray of each part of the cast where the simulation highlights the possibility of porosities. For reference figure 82 represent how porosities appear at the X-ray, this photo is of a waste cast produced when the machine was still not at the production regime.

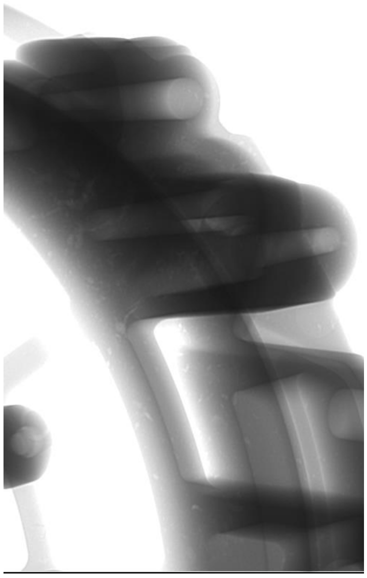


Figure 82: X-ray with porosities

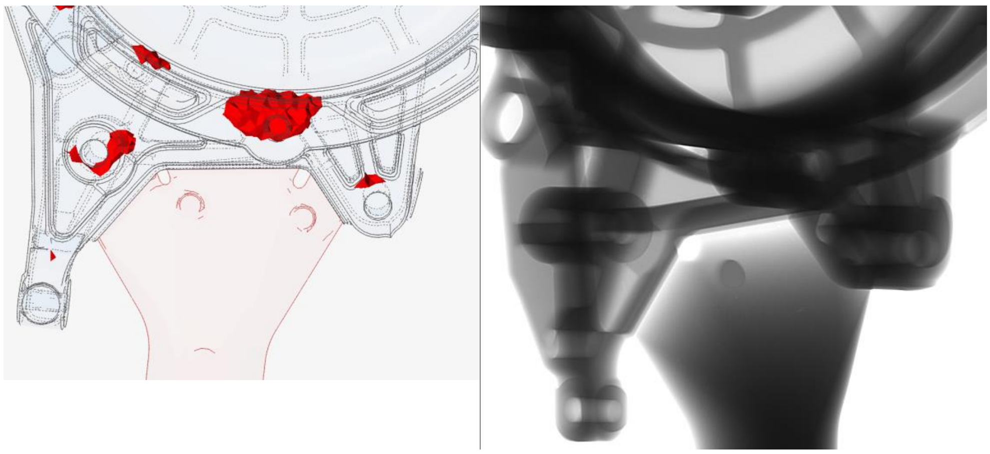


Figure 83: porosity risk and X-ray results part 1

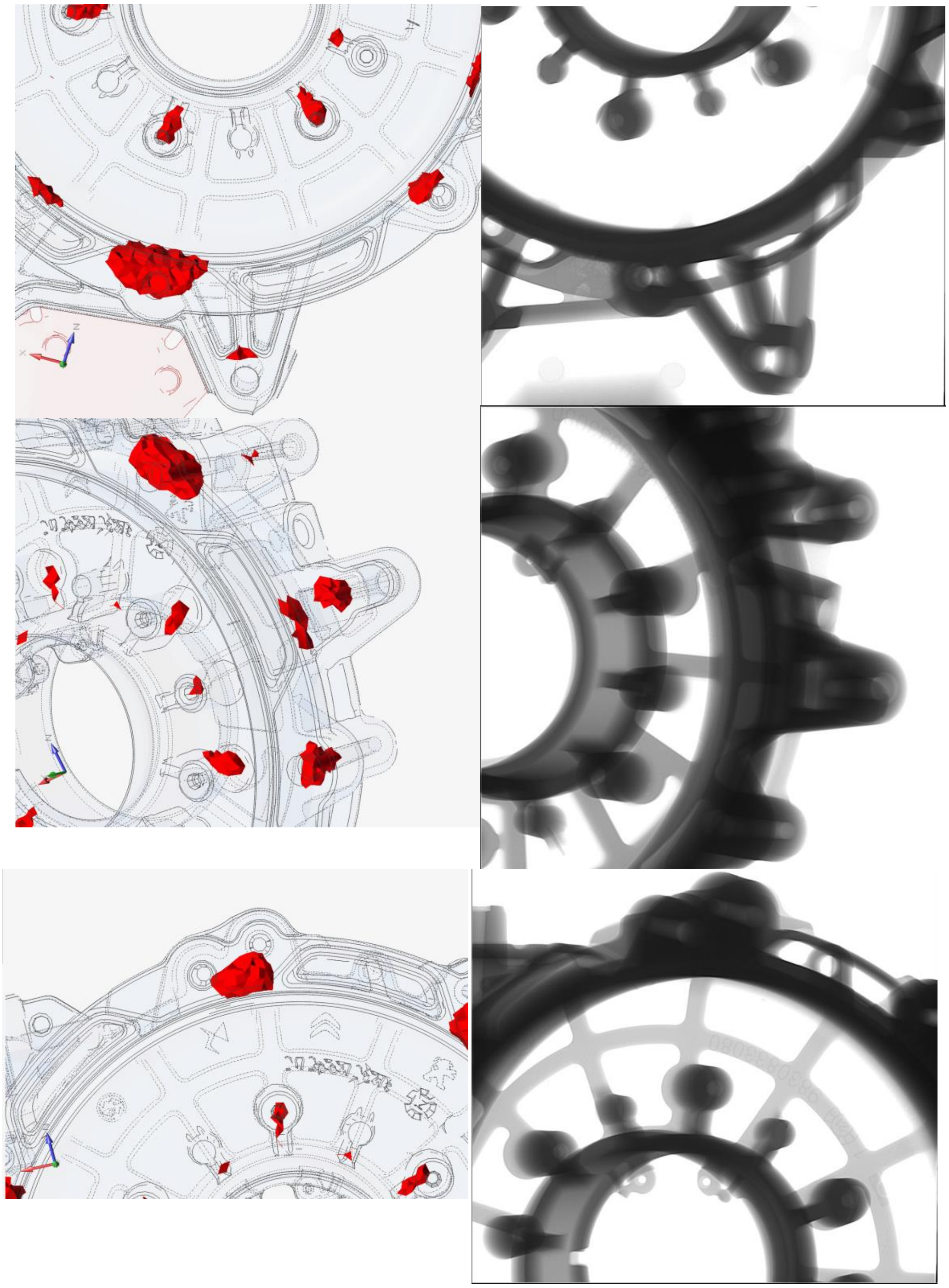


Figure 84: porosity risk and X-ray results part 2

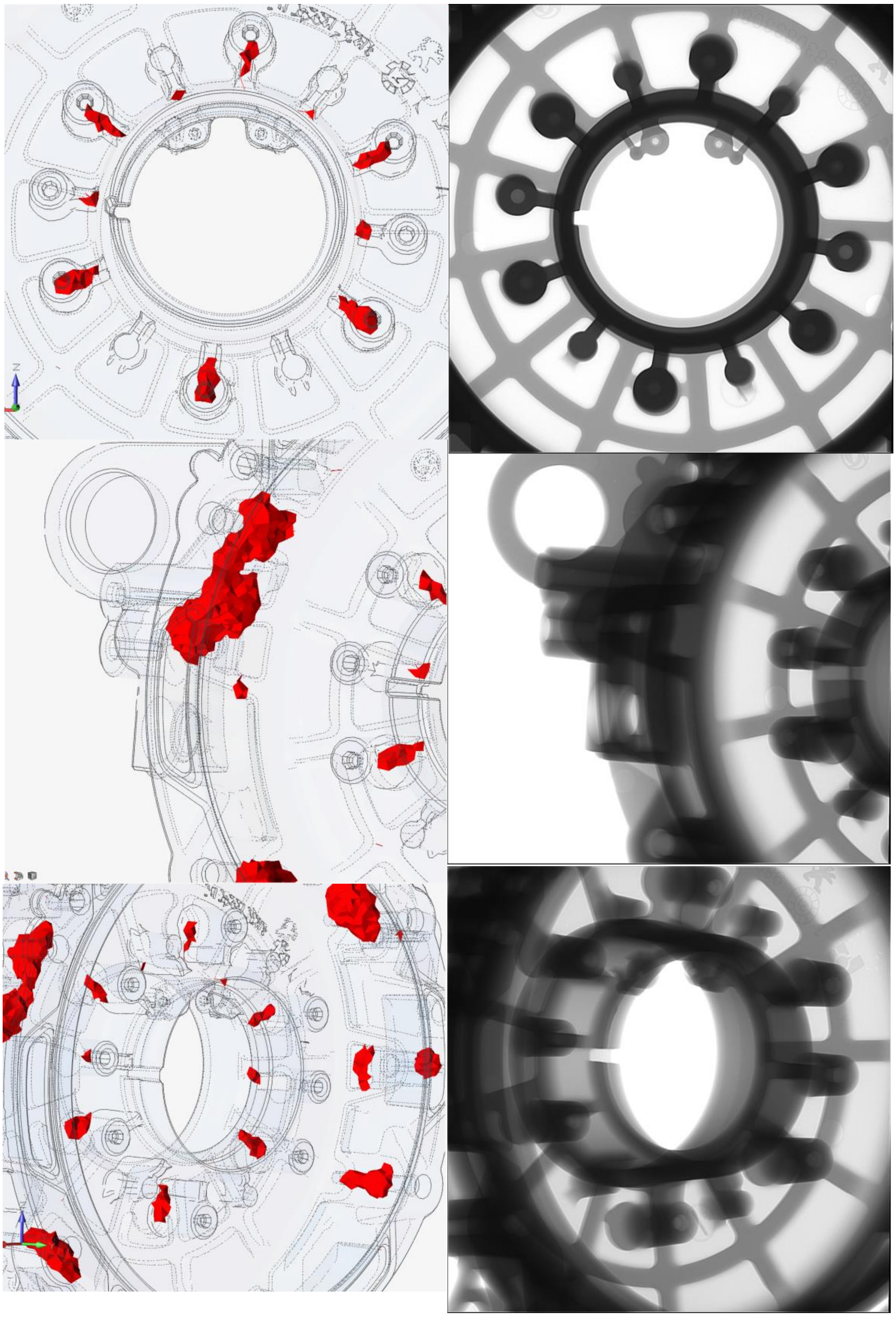


Figure 85: porosity risk and X-ray results part 3

In the previous figures 83, 84 and 85 we can see on the left the results of the simulations that highlight the possibility of porosities, while on the right we have the X-ray of the corresponding zone of the casting. The element analysed was produced at the end of the sampling once all the parameters were appropriately set. From this analysis we can see that in all the possible critical parts there is not a significant presence of porosity, with this level of quality it is possible to already go into production.

7.4 Pq^2 diagram

As mentioned in chapter 2 in the Pq^2 diagram we have two main curves: the green one for the machine and the blue one for the mould. In figure 86 we can see that the two more relevant points are the static pressure, i.e., the maximum pressure on the metal obtainable by the injection system with a determined piston at null flow rate, and the maximum flow rate, obtained with the piston at the maximum speed without the metal. In between these two points we have all the possible working positions of the machine/piston, it will never be possible to work outside this area.

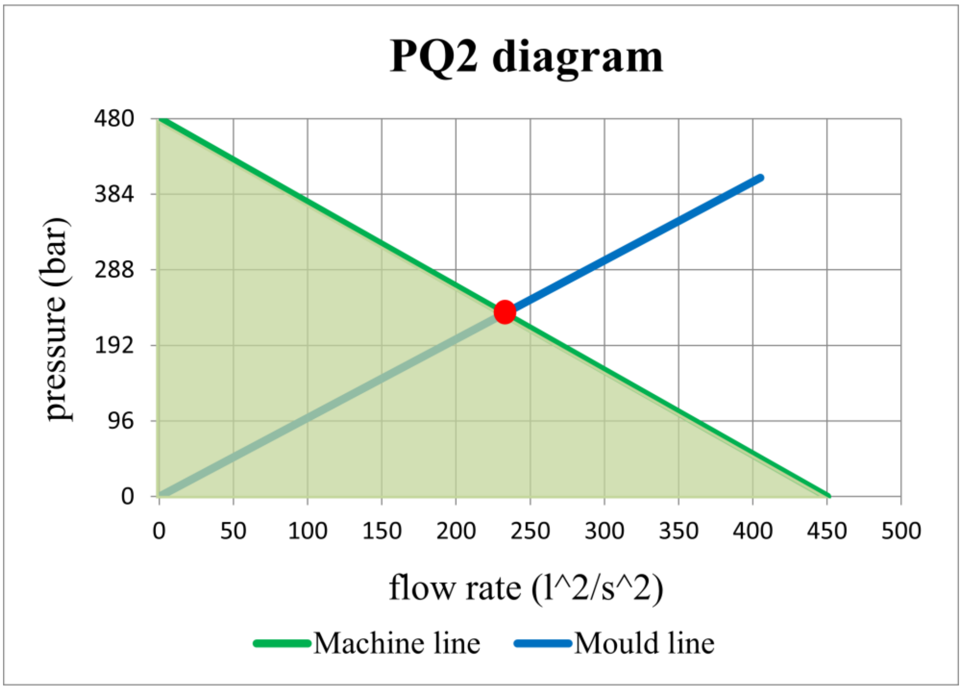


Figure 86: example of Pq^2 diagram

At this point we can see how the more common adjustments will influence the behaviour of the HPDC machine:

- Acting on the flow rate regulator of the hydraulic fluid, we could reduce the flow keeping unchanged the static pressure on the metal;
- Lowering the charging pressure of the accumulator, we have a proportional lowering both of the pressure and flow rate;
- The variation of the piston diameter acts on the two variables with inverted proportionality i.e. reducing the piston we get a reduction of the flow rate and an increase of the pressure on the metal, and vice versa.

Looking at the curve of the die resistance to the flow, the pressure and the flow rate (at the square) in the cavity are proportional. The coefficient of proportionality between the two dimensions is linked to the difficulty that the alloy will meet when flowing into the cavity. The higher this difficulty the higher should be the pressure to keep the desired flow rate.

This difficulty is linked essentially to two main factors, charging losses due to the complexity of the path that the alloy must follow to enter the die cavity and the gate sections, where smaller sections will imply higher pressures for the same flow rate.

When putting together the two lines on the same diagram the intersection point indicates the maximum flow rate achievable with that given mould on that given HPDC machine. Usually depending on the chosen parameters we will identify a point on the line of the die resistance. To have the part castable on the chosen machine this should be below the green line.

The yellow rectangular area indicates the optimal functioning zone, inside which we should find the operating point that allows the casting of parts compliant with the quality requirements. The smaller this area the higher the control on the process. The optimal condition is achieved when the working point is centred with respect to the rectangle allowing to obtain good parts also with a small variation of flow rate and pressure values.

If the operating point is outside the yellow rectangle we can identify four different problems depending on the position of the operating point with respect to it:

- Operating point on the left of the rectangle: given the low flow rates and consequently the longer filling times, we have the risk of cold joints, missed fillings and bad surface finishing
- Operating point on the right of the rectangle: excessive turbulences that lead to air trapping and consequent porosities
- Operating point under the rectangle: low pressure of the metal entering the cavity that can bring to formation of cold drops and air trapping
- Operating point above the rectangle: the filling of the cast requires too high-pressures, this can lead to erosion of gates and problems of surface finishing.

In figure 87 we can see the Pq^2 diagram of our process at the end of the sampling phase.

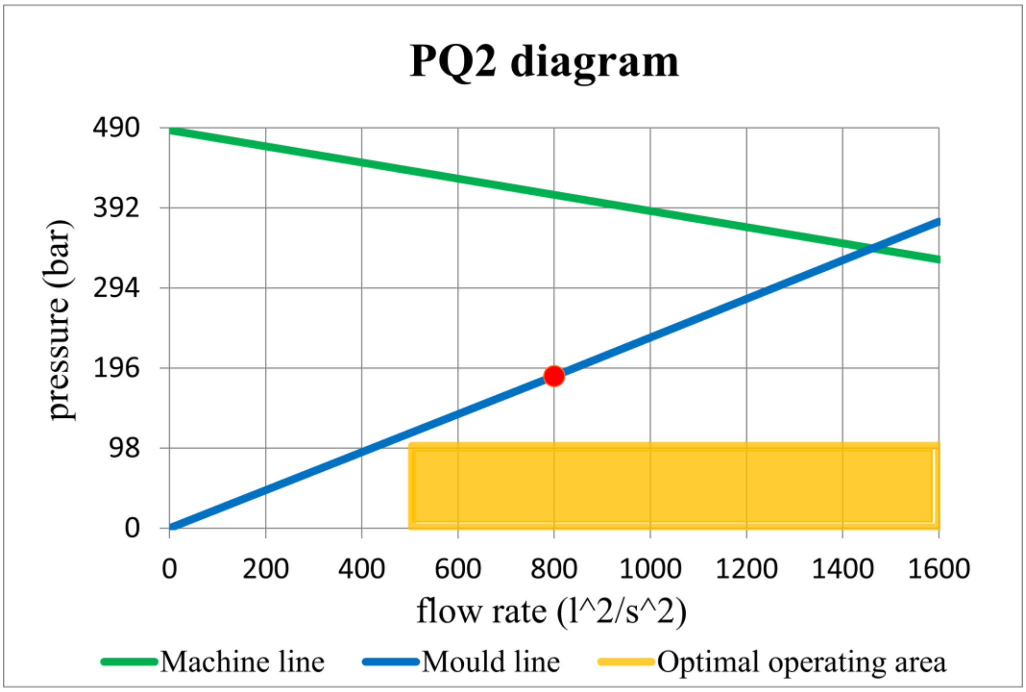


Figure 87: Pq^2 diagram actual condition

As we can see we are not in the optimal functioning zone, so even if our cast reaches the quality target fixed by the customer there is still the possibility to improve the process. The working point is above and on the left with respect to the optimal position, following the explanation given before we have the risk of missed fillings and bad surface finishing. Another problem highlighted is the possibility of die erosion due to the high filling pressure, as we have experienced in reality on the mould.

The two main causes are that the machine that we are using for the casting is over dimensioned but at the moment the most suitable one is occupied with other products. Second and more important the section of the gate is too small for the finishing quality that we need. In fact as previously mentioned this part needs a good surface finishing due to the sealing that it must guarantee. The problem is that at the actual gate we cannot increase the section due to the geometry of the cast that anyway has a limited section inside from which we can make the material flow. A possible solution could be to insert another channel laterally with an additional gate but this will lead to two other problems: first the entering flow will move the point where the melted alloy front close at the end of the filling and second we will have to create a channel on a lateral dowel that is something complicated that can generate a lot of problems.
Lastly for completeness in figure 88 we can see the Pq^2 diagram of the same mould mounted on the HPDC machine of the correct dimension. Here we are in the optimal zone but the problem linked to the too small gate section remains and this prevents the working at the centre of the optimal zone. This is something that cannot be solved because linked to the cast geometry.

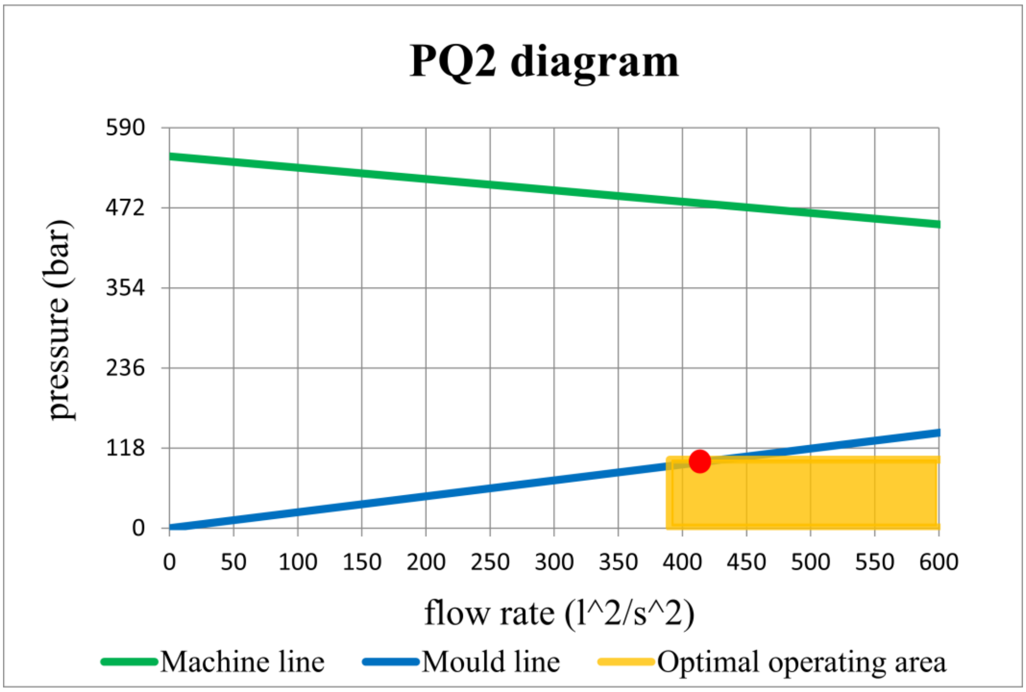


Figure 88: Pq^2 diagram on optimal machine

CHAPTER 8

Final remarks on the simulation tool and on the software used

After having used all the three software is not so easy to compare them. They have different cost, features, completeness of the simulation and depth of the analysis performed on the obtained results. Obviously each one has its strengths and weaknesses but in the end they converge toward more or less the same results.

8.1 Considerations on the software used

Flow-3D Cast can be surely considered the more complete and accurate software of the three. The only disadvantages are the by far higher costs of the license that not all the companies can sustain and the computational power needed, in fact in our case it runs on a cluster.

Considering Inspire Cast the most relevant differences are linked with the temperature of the cast and the die and are due to three limitations of the software:

- There is not a function to simulate the lubrication of the cavity that is a very important part of the high-pressure die casting process and this leads to have a higher temperature of the mold and the cast;
- It is impossible to simulate the so-called fountains, that in our simulations have been approximated by simple vertical cooling channels. In reality a fountain has a much higher cooling capacity with respect to a normal cooling channel and considering that on this mold we have five fountains in the central part we can clearly see a high temperature difference between the two simulations. The overall

a higher temperature of the mold and of the cast can lead to an overestimation of the dimension of the zones with porosities risk

- It is impossible to import the real die geometry, the programs auto create a mold that encloses the cast using the material properties and the temperature that have been inserted. Not using the real mold, the cooling lines must be redesigned inside the program, and lateral dowels cannot be integrated.

In the end Inspire Cast has proven to be a good simulation software with reliable results. What is more surprising is the identification of the zone with porosities risk that even if are overestimated in dimensions due to the above-mentioned problems (this can also be given by a slightly different timing in the two software) correspond exactly to the one identified by the more complete and costly Flow-3D Cast. Obviously the software presents all the limitations given by the not perfect evaluation of the cast and die temperature, even if the estimation of the solid fraction during the solidification well match between the two simulations. The last difference that can be observed is in the evaluation of the air motion in the die during filling that sees Flow-3D Cast having a higher-level simulation of the airflow inside the die leading to a better estimation of the air trapped at the end of filling.

The last problem that we have seen with the use of Inspire Cast that has nothing to do with the results of the simulations but is related to the hardware needs and the computing time, is the impossibility to exploit a high number of cores for the simulations. In our case the program can parallelize the calculation on at most 20 cores (between real and virtual), so considering that the workstation dedicated to simulations normally have a much higher core number the only way to exploit all their power will be to run at least two different simulations in parallel.

In the end comparing PIQ2 Castle with the other two we can say that it has many advantages, first of all is very easy to use and has a user-friendly interface that guides you step after step. As mentioned before it can directly import all the high-pressure die casting machine characteristics leading to a more accurate evaluation of the die-machine interaction. In this case the evaluation of the alloy speed seems more accurate and the results are free of the speed spike obtained with Inspire Cast that should be due to errors in the mesh. The last important advantage is that the two step mesh used by the solver allows you to work also on a bad and not fully closed surface and is by far easier to set with respect to Inspire Cast.

The main disadvantage as aforementioned is the lacking of a complete thermal simulation of the mold that saying the truth it is an add-on that must be bought separately and that was not installed on the version that we used. This is the main drawback that leads to results in some case sensibly different from the two previous software.

The last consideration regards the computing time that as said before can be a critical factor for the use in a company. The standard computing time for the simulations is slightly more than with Inspire Cast but with two advantages, firstly the program is more sensitive to the increase of the core count of the CPU allowing to have a faster computing time decrease with the increase of the dedicated cores. Secondarily it can perform a very fast simulation simply based on the geometry of the cast and the characteristics of the used high-pressure die casting machine that allows you to find the optimal parameters for the casting process.

8.2 Simulation tool facing the reality of a foundry

At this point I want to recall something said at the beginning of this thesis: “high-pressure die casting can be considered as an art”. This means that the process is so complex and with so many interacting factors that cannot be simply solved with physical law (consider that till now not all the physical interactions that verify during filling have been fully understood). This is one of the industrial activities where the technician experience still plays a fundamental role. Said that nothing surprisingly that when we perform the sampling we have noticed some difference with respect to what simulated and this is also the reason why we tolerate a certain level of discrepancies between the simulations obtained. We have also to remember that with this component we are working outside the standard of the geometry produced with the HPDC so it is completely understandable to have some minor mismatch between what simulated and the reality. As above mentioned also the working outside the optimal zone on the Pq^2 diagram can be justified in this field of view and should not generate particular worrying.

As mentioned in the chapter regarding the mesh in a company the simulation tool is used for the optimization process so in the trade-off between accuracy and computational time we can accept a bit more uncertainty in the results in exchange for less computing time.

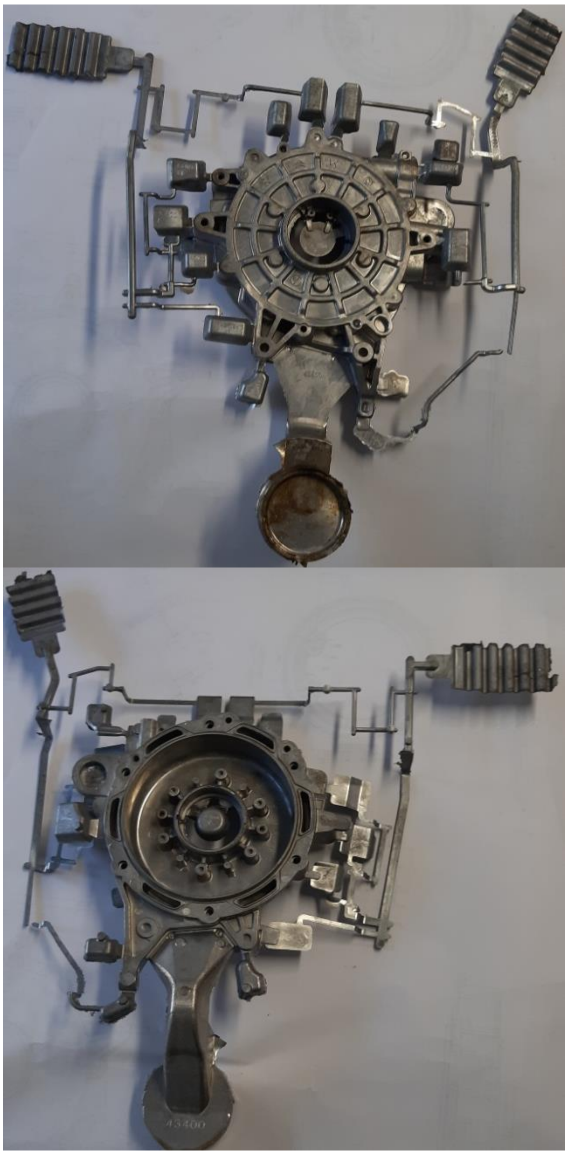


Figure 89: real component at die extraction

After the simulation results validation performed with the sampling in the chapter 7 we can see that the simulation has proved its usefulness and the obtained parameters can be used in the future as guidelines for the casting of similar products. The process simulation remains an incredibly helpful tool that especially in our case with a new product category never casted before has allowed us to obtain optimal results in terms of product quality and production standards.

Lastly I want to remark that too many times the simulation tool is seen as something useful only for research centers and that will never fit the needs of a company. Many people think that the time spent at the simulation is only wasted because at the computer we represent only an ideal model that will never fit the reality, what I have experienced during my time in the company is that once the correct parameters are set accordingly to the foundry the result obtained are very helpful to guide the optimization process. Our work on the PSA front housing can be considered as an example, thanks to our deep simulation work we were ready to go to production with three weeks of advance and this leads to two real tangible benefits: industrial competitiveness and money saved.

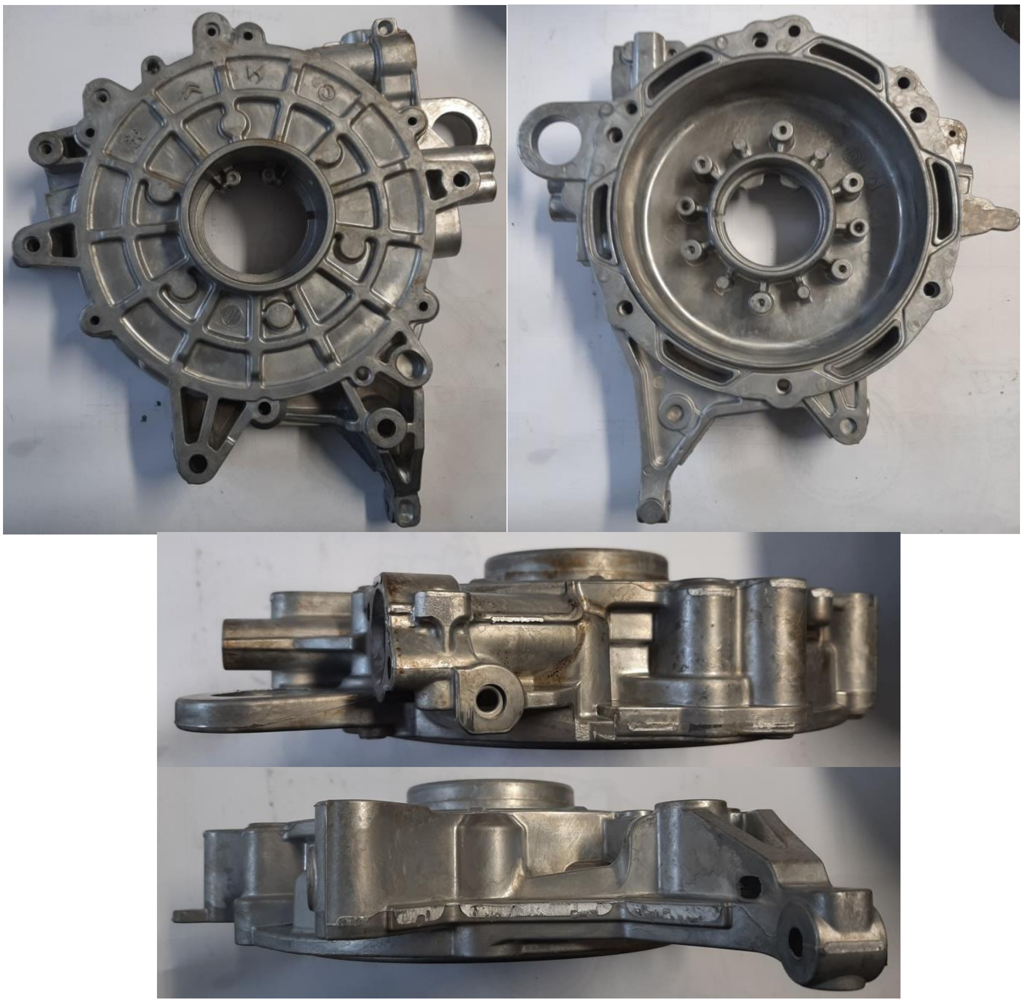


Figure 90: real component after trimming

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