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Prevention of casting defects in an aluminum alloy component

Relatore:
Prof. Paolo Matteis

Candidato:
Nicola Sassu

Ai miei genitori, che sono la mia ispirazione tutti i giorni

Ai miei nonni, che sono sempre con me

Al resto della mia famiglia

E ai miei amici

A chi, in questa tempesta, è stata la mia luce

Grazie per avermi accompagnato in questo percorso

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Abstract

This work of thesis has been developed in collaboration with the companies STCast S.r.l. and F.O.M.T. S.p.a. and it focuses on analyzing the gravity mold casting process for an aluminum casting alloy component, which is destinated for use in internal combustion industrial vehicles as an engine oil pan. The part has a moderately complicated geometry that ends up causing a particularly critical defect during its manufacturing process, which this thesis work focuses to solve.

The work prevalently consisted in experimental research, analyzing the effects of different experimental approaches to the production run of this particular product in order to solve its manufacturing problems, analyzing both at the macroscopic and microscopic level some samples from the different experimental production runs and comparing their microstructures in order to validate the different results. The modification of the mold in order to implement a compressed air-cooling system proved to be very effective in solving the occurrence of hot spots in locations where it was not possible to set a proper directional solidification due to the part's geometry.

The thesis is divided in two parts, with the first part constituting the ensemble of notions required to build a theoretical background in order to better understand the choices behind the experimental research performed on the second part of the thesis.

Introduction

This work of thesis focuses on a production run defect occurring on an aluminum alloy gravity mold casting product made by the company STCast S.r.l., which is destinated for use in internal combustion industrial vehicles as an engine oil pan.

The part has a moderately complicated geometry that ends up causing a particularly critical defect during its manufacturing process, which this thesis work focuses to solve. The thesis is divided in two parts, with the first part constituting the ensemble of notions required to build a theoretical background in order to better understand the choices behind the experimental research performed on the second part of the thesis.

The first chapter opens the theoretical background part by introducing the properties of aluminum (Al) first as a pure metal, then as a casting alloy, describing in detail the role of each major alloying element in cast aluminum alloys, the effects of each on the microstructure, and the resulting intermetallic phases.

The second chapter focuses on the different possible casting technologies, classifying them depending on the different results each of them can achieve and their limitations, while highlighting the pros and cons of each different technology.

The third chapter explores in detail the gravity die casting technology, specifically for aluminum casting alloys, explaining the properties that are possible to achieve with this technology, and comparing them with the properties achievable with other technologies. Particular focus is put on explaining the design behind a gravity casting mold, the casting principles to follow, the materials used, and all the components that are part of a gravity mold casting machine.

Chapter four concludes the theoretical background part by providing a classification for all the different possible defects that may occur during a casting cycle, dividing them in three different categories depending on whether they're internal, surface level, or geometrical, describing their causes and their solutions.

Chapter five opens the experimental research part by introducing the part displaying the manufacturing defect that this thesis focuses on, by first quickly introducing the company where the work of thesis took place, then explaining in detail the manufacturing process for this specific part, from the melting operations of the aluminum ingots in furnace, to the casting cycle, followed by the post-casting operations, inspections, and testing.

In chapter six the part is analyzed further, by first displaying its geometry and the main manufacturing problem that occurs during its casting, then analyzing the mold in which it's manufactured to understand whether the mold's shape may have an influence on the defect or not.

Chapter seven focuses on analyzing the casting cycle of the part as it would normally occur, in order to find any correlation between the casting parameters and the defect occurrence. Twelve sample products were taken throughout a normal production run while recording and analyzing their casting parameters, such as mold temperature, casting time, the alloy composition and density. A micrographic analysis has also been performed on the samples displaying the defect in order to identify its source.

After hypothesizing the source of the defect to be due to the high mold temperatures, in chapter eight an experimental corrective measure has been taken in order to see whether cooling down the mold locally where the defect occurs would prevent the defect from happening or not. An experimental run of 14 parts was planned where, during the casting cycle, the critical area would be cooled down locally with a nebulized water spray. After getting positive results, a more stable, consistent design has been adopted by modifying the mold to allow for internal cooling trough a compressed air circuit.

In chapter nine a micrographical analysis is performed on three samples, one representative of each production run (normal, water cooled, air cooled) in order to actually quantify the benefits of the adopted solution. The secondary dendritic arm spacing is measured for each sample, and the porosity distribution % for each sample is measured, proving the beneficial benefits of the localized cooling.

Theoretical background

1 Aluminum

Aluminum is a silvery gray metal with a very high specific strength and remarkably good technological properties. Produced for the first time in 1825, throughout the years its alloys have found use in the aerospace industry, automotive field and transportation, industrial applications, in construction, and in other fields where a high strength-to-weight ratio is required [1], such as sportive goods and consumer goods in general.

1.1 Aluminum's characteristics

Aluminum (chemical symbol: Al, atomic number 13) is the most abundant metal in earth's crust. It's found in the form of aluminum silicates (such as bauxite and cryolite), which are turned into pure aluminum with either the Bayer process or the Hall–Héroult process.
Although these processes can be quite resource intensive, once it's been produced this metal does not degrade and can be easily recycled.
Pure aluminum by itself lacks strength and doesn't have good mechanical properties, it must be alloyed usually with silicon, copper, magnesium, and manganese in order to greatly improve its properties.

At parity of volume, a part made out of aluminum would weigh a third of the same part made from steel, but it won't be as strong. It's possible to achieve the same mechanical strength or performance of a steel component, but the weight reduction will be lower than a third, yet still significant in most cases [1]. Aluminum's low density make it the preferred choice in many applications where high strength at light weight is required. In the automotive industry it's starting to see wider use compared to steel, as the lower weight of aluminum translates into fewer CO_2 emissions and higher fuel efficiency.

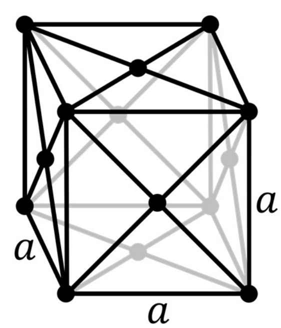


Figure 1: Unit cell of a face-centered cubic crystal structure

Aluminum has a face-centered cubic crystal system FCC (see Fig.1). This structure has a very high atomic packing factor (APF) of 0.740, with many dislocation planes that give this metal a very high malleability and ductility, even at lower temperatures (resiliency stays constant, no cold embrittlement) making it easy to machine, draw and extrude.
It is also a very good thermal and electrical conductor. Although it has around 63% of the electrical conductivity of copper, it is often used in electrical transmission lines as it's both cheaper and lighter. Aluminum having 30% of copper's density makes it the best option for long distance power transmission [2].

Aluminum has a very high resistance to corrosion. Aluminum passivates, meaning that its oxide structure is slightly bigger than the alloy's structure, when exposed to air the metal reacts with the oxygen in the atmosphere to form a thin oxide layer that protects the metal underneath from further corrosion [3] . This makes of aluminum a very good choice as a building material when corrosion resistance properties are deemed significant.

Pure aluminum displays the properties listed in Table 1 (data from [4]):

Property	**Value**
Atomic number:	13
Melting point:	660.32 $°C$
Density:	2.70 $[g/cm^3]$
Thermal expansion:	23.1 $[\mu m/(m \cdot K)]$
Thermal conductivity:	237 $[W/(m \cdot K)]$
Electrical resistivity:	26.5 $[n\Omega \cdot m]$
Young's modulus:	67 $[GPa]$
Shear modulus	26 $[GPa]$
Poisson ratio:	0.35

Table 1: *Pure aluminum properties, in standard conditions*

1.2 Cast aluminum alloys

Depending on the processing used to obtain them, aluminum alloys can be categorized into two major groups: wrought aluminum alloys and cast aluminum alloys [5].

Wrought aluminum alloys are ideal for shaping and machining after heat treatment, the components are obtained by processes of mechanical working, such as extrusion, rolling, and forging.
Cast aluminum alloys are used in casting technologies for their good castability, the components are obtained by the pouring the molten aluminum in dies which give shape to the part. Compared to wrought aluminum alloys, parts made through casting methods are cheaper to produce, but they'll display worse mechanical properties.

This thesis work focuses on casting technologies, therefore from now on only casting aluminum alloys are considered. Good casting aluminum alloys must have good castability, meaning it must display the following characteristics [6]:

- Good fluidity: the material must be able to flow easily to fill the die, while keeping uniform composition and properties
- Resistant to hot tearing: Aluminum can shrink volumetrically up to 6.5% of its volume during its solidification, and the geometry of the cast may
- Low melting point: the lower the melting point, the faster the solidification.
- Low solubility of gasses (oxygen and hydrogen)
- Good surface finish

1.2.1 Designation system for aluminum cast alloys

The Aluminum Association (AA) has developed specific a nomenclature for cast aluminum alloys. The first digit indicates the main alloying element, while the second and third digit identify the specific alloy in the series. The fourth digit, after the decimal point, indicates whether the alloy is a casting or an ingot.

The main alloying elements for each aluminum casting alloy are listed in table 2:

Alloy Series	**Principal Alloying Element**
1xx.x	Aluminum (≥99% minimum)
2xx.x	Copper
3xx.x	Silicon, with Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other elements

Table 2: Cast Aluminum Alloy Designation System

Within the series mentioned, only some of them are heat treatable. The heat treatable alloys reach their optimal mechanical properties after a thermal treatment subsequent to the casting. Out of those mentioned, heat treatments can be applied to the 2xx.x, 3xx.x, and 7xx.x series.

1.2.2 Major alloying elements

Pure aluminum by itself lacks in strength and doesn't display good mechanical properties, it's usually alloyed with different elements [2], such as silicon, copper, magnesium, and manganese, in order to vastly improve its technological and mechanical properties.

1.2.2.1 Silicon

Silicon (Si) is the main alloying element for cast aluminum alloys. The silicon content in commercial aluminum casting alloys ranges between 5 to 20% in weight percentage, the faster the solidification rate of the casting technology used, the higher the Si% possible to have in solution.
Depending on the Si concentration it's possible to distinguish three main categories:

- hypoeutectic alloys (Si% content in weight <12.7%)
- eutectic alloys (Si% content in weight =12.7%)
- hypereutectic alloys (Si% content in weight >12.7%)

In Fig. 2 the binary Al-Si phase diagram is displayed:

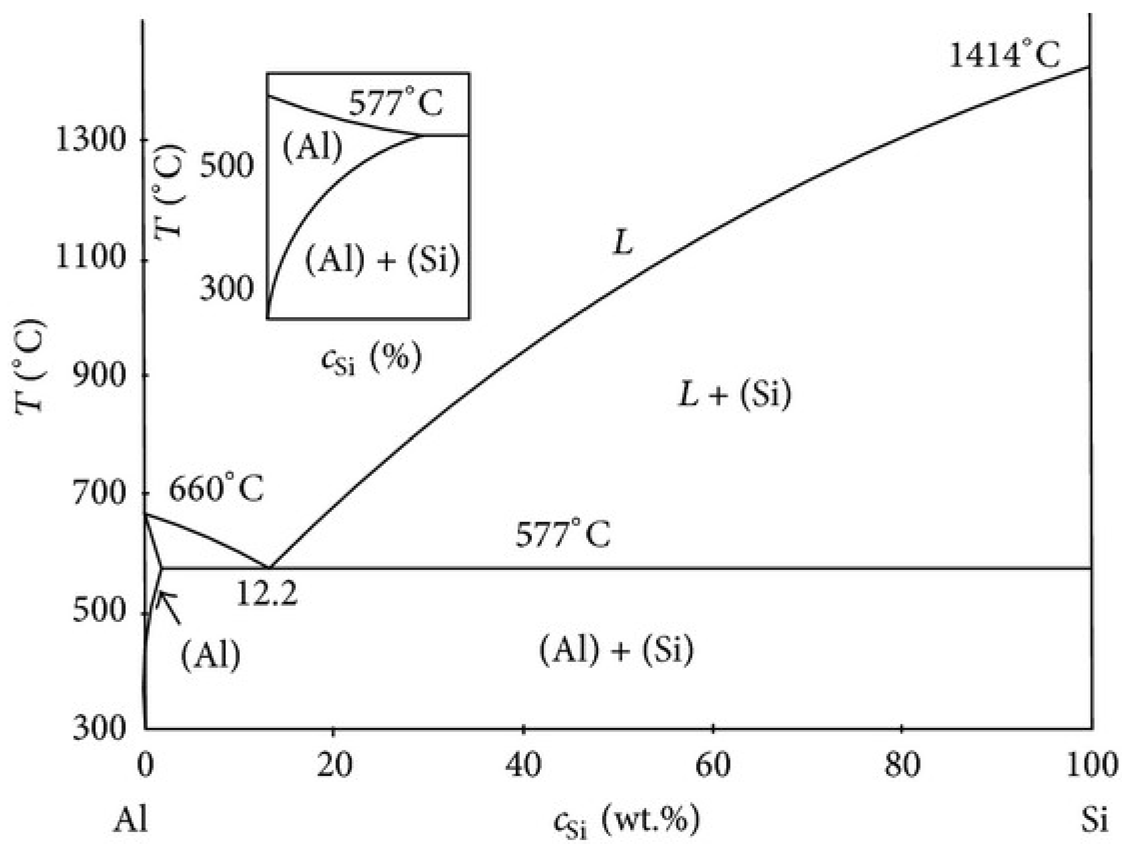


Figure 2: The Al-Si phase diagram. It's possible to see how aluminum has no solid solubility in silicon at any temperature, meaning that there's no β phase, but only pure silicon precipitates

The benefits of silicon in alloy are the following:

- increases mechanical properties: with an increase of Si% in alloy it's possible to observe an increase in hardness and in ultimate tensile strength (see Fig. 3), with the highest UTS recorded for values of 12% of Si in volume [7]
  Ductility and resilience instead decrease with Si%, with their values being mainly correlated to the shape and distribution of the silicon particles
  Resistance to corrosion is not influenced.
- improves castability: lower viscosity and lower surface tension allow to cast thinner parts and finer details.
- increases resistance to hot tearing: the eutectic liquid lowers the risk of hot cracking [8]
- lowers melting point.
- increases resistance to abrasive wear.

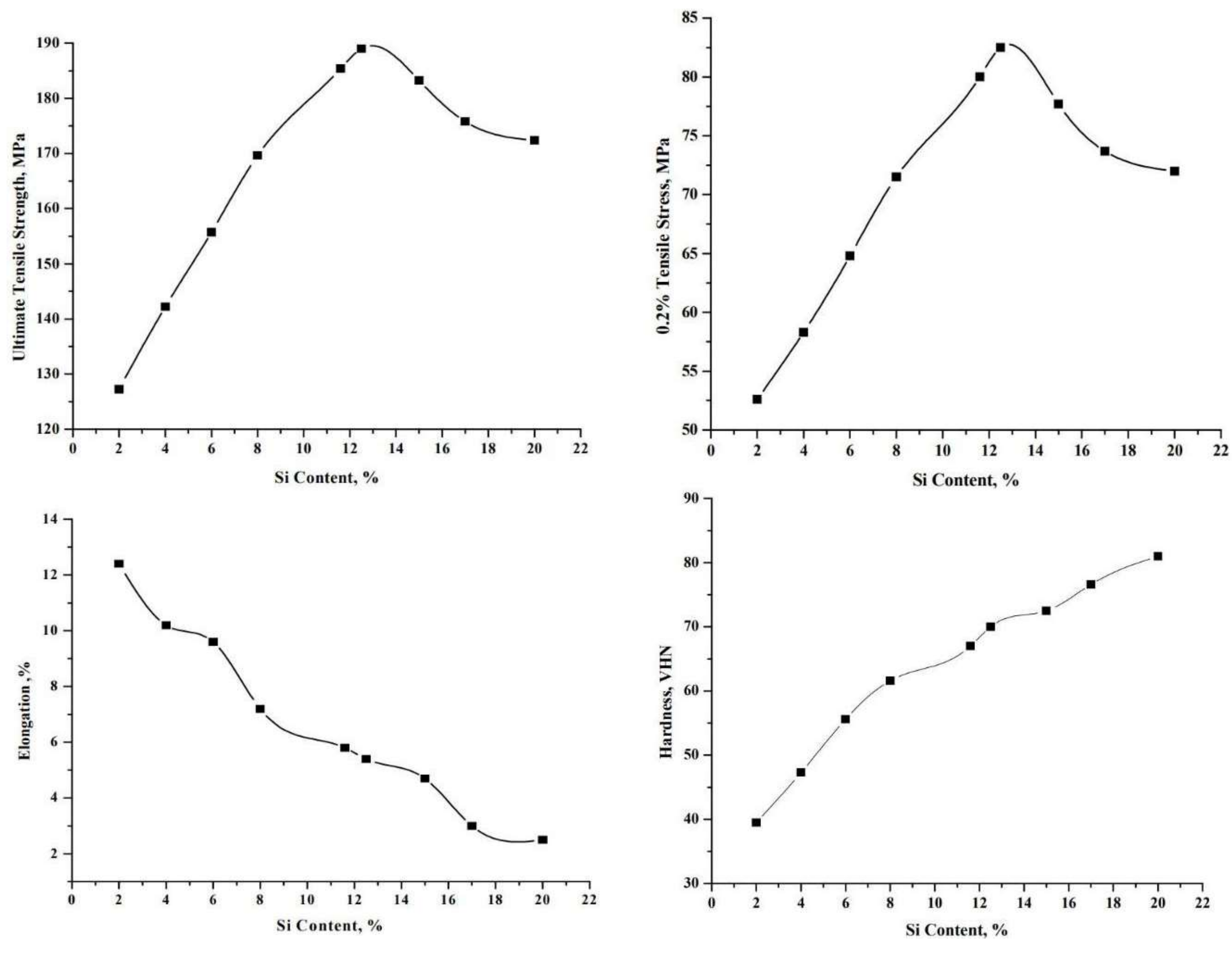


Figure 3: Effect of different Si content in Al-based alloy on the mechanical properties (image from [9]*). By increasing the % Si content it's possible to see an increase in hardness and a corresponding decrease in elongation %. Tensile strength increases up until 12% Si, after which it starts decreasing,*

1.2.2.2 Iron

Iron (Fe) presence is usually not desired, as it reacts to form several intermetallic phases (see chapter 1.3.3) of acicular form that harshly diminish the alloy's resilience and ductility. Some positive aspects of its presence are that it increases hot tear resistance and facilitates the detachment of the casted part from its die [10].

1.2.2.3 Manganese

Manganese (Mn) is usually considered an impurity, it's used in alloys rich of Fe intermetallic phases, as it reacts with them to modify their acicular structure into a more rounded phases called chinese script, which shape is less harmful to the ductility and fatigue resistance of the alloy [11].

1.2.2.4 Copper

Copper (Cu) improves strength, hardness, fatigue, and machinability for both as-cast alloys and heat-treated alloys trough solid solution hardening. Its presence can be between 1% to 6%, with alloys containing between 4% to 6% showing the greatest increases in mechanical properties post heat treatment. However, copper reduces corrosion resistance in general by hindering passivation, and reduces it's the alloy's castability [12].

1.2.2.5 Nickel

Nickel (Ni) is added as it increases the alloy's strength and hardness both at room temperature and at elevated temperatures, while reducing the thermal expansion coefficient at elevated temperatures for lower volumetric shrinkage. However, it can reduce fluidity.

1.2.2.6 Magnesium

Magnesium (Mg) allows the alloy to increase its strength and hardness in heat treated silicon alloys by forming of $Mg2Si$ which increase the strength trough precipitation hardening. Its content is kept low between 0,40% to 0,70% as it has the tendency to react with the other elements in alloy, as well with the oxygen on the surface when the alloy is molten, creating other precipitates that might negatively influence the alloy's fluidity and properties in general [10].

1.3 Structure Control

For an aluminum cast alloy, the microstructural characteristics that mostly affect the macro mechanical properties of the cast are the following:

- Grain size and shape
- Eutectic modification (primary phase refinement)
- Intermetallic phases

1.3.1 Grain size and shape (dendrite arm spacing)

Aluminum cast alloys are solute rich, as the molten metal cools down falling under its liquidus phase, small crystals of primary phase will start solidifying, growing alongside the most energetically favorable direction and taking tree-like shapes called dendrites. The size of these structures depends on the composition and the solidification rate [13],with finer structures resulting in castings with increased mechanical properties, while bigger, more developed dendritic structures will result in much weaker components [12]. The distance between dendrite's secondary arms, also called SDAS (secondary dendritic arm spacing), can be measured in order to have an understanding of the mechanical properties of the casting.

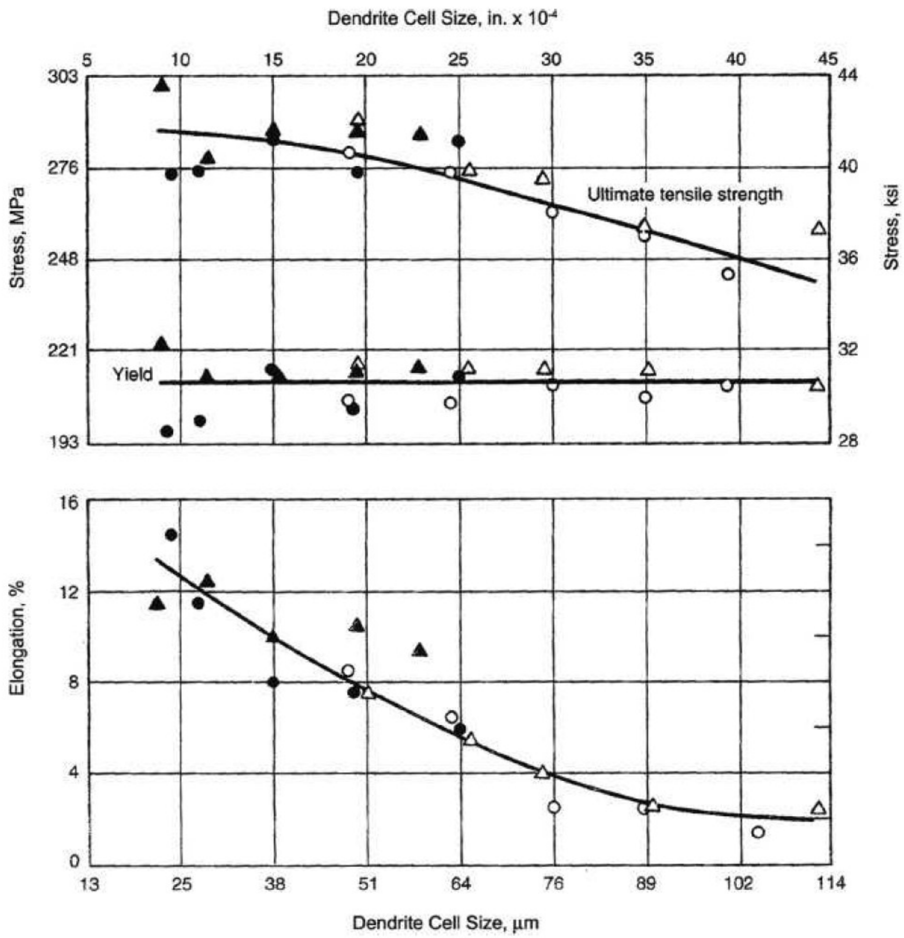


Figure 4: Tensile properties of an Al-Si casting alloy depending on dendrite cell size (image from [12]*)*

It's possible to restrict the growth of the dendritic structures with the use of grain refiners. Titanium (Ti) and Boron (B) in alloy act as solidification nucleation sites, turning the coarse dendrites into finer, equiaxed structures, with more finely distributed second phases at the grain boundary (see Fig.5).

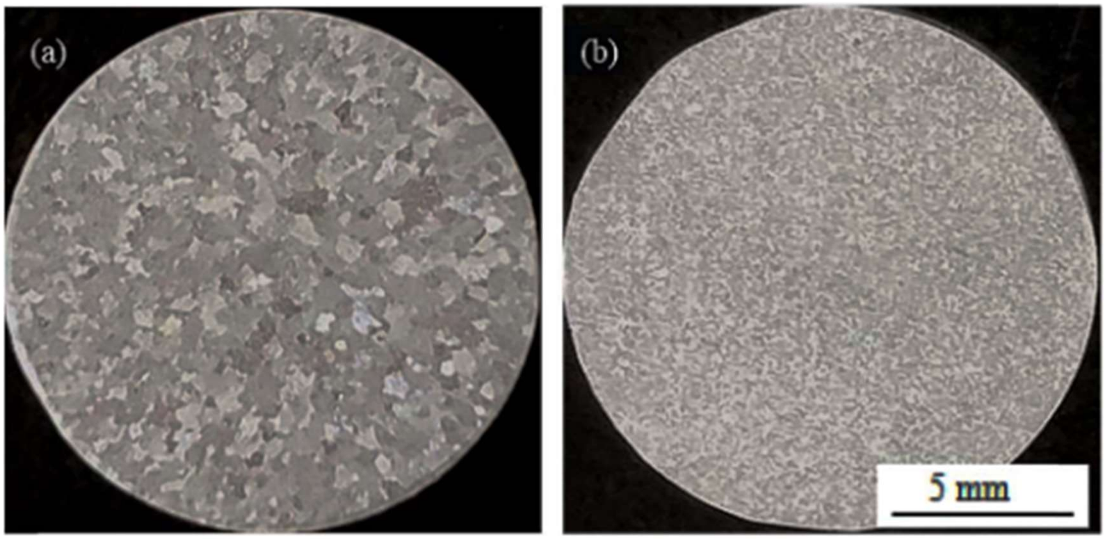


Figure 5: Anodized microstructures of an Al-Cu alloy with coarse grain structure as cast (a) and fine grain structure after grain refinement (b) (image from [14]*)*

The impact of titanium as a grain refiner depends on the silicon content. Grain-refined aluminum casting alloys can contain 0.1 to 0.2% Ti, possibly with some boron in a 5 to 1 titanium-to-boron ratio [13]. Compared to alloys without grain refiners, these alloys display increased mechanical properties, better response to thermal treatments, increased hot cracking resistance, and less porosity levels [12].

1.3.2 Eutectic modification (primary phase refinement)

The mechanical properties of Al-Si alloys, especially ductility and toughness, can be improved by modifying the distribution and shape of the silicon particles. Alloys in which the silicon particles (either eutectic or primary) are finer, rounded, and more evenly distributed have better properties and are much more ductile than alloys in which the silicon particles are faceted and acicular, which act as stress concentration points [10].

It's possible to obtain finer eutectic particles by either increasing the solidification rate, or through the addition of chemical modifiers. Some elements, when put in the alloy, are known to modify the growth process of the eutectic silicon crystals, such as Strontium (Sr), Sodium (Na), and Antimony(Sb). These elements are proven to modify the eutectic silicon very efficiently even in small quantities [15].
In Fig. 6 it's possible to see a comparison between the mechanical properties of normal Al-Si casting alloys compared with the properties of modified alloys.

In industrial applications, Strontium is preferred over the others. Antimony can be toxic, and it will modify the eutectic in a characteristic lamellar shape that can negatively impact the mechanical properties. Sodium's high reactivity make it difficult to handle and store, and when dissolved in the molten alloy, sodium tends to turn into gas much faster than strontium does.

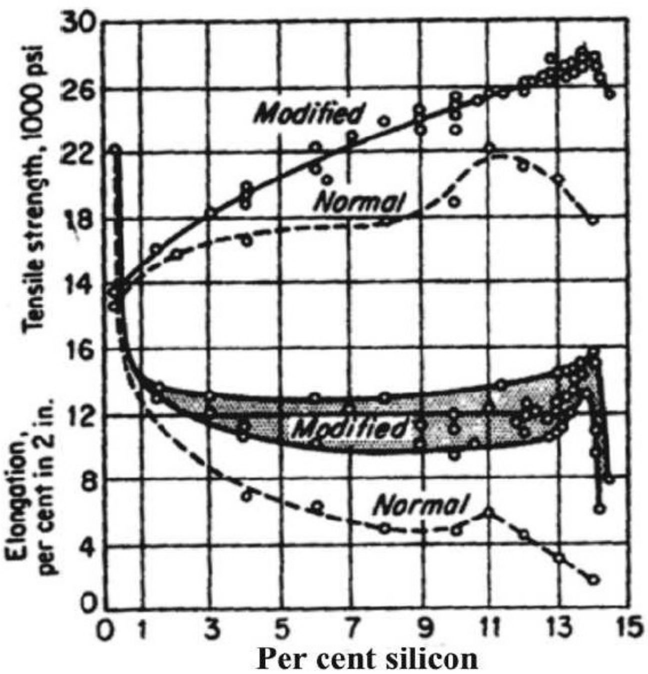


Figure 6: Comparison of mechanical properties, tensile strength on top and elongation % on the bottom depending on the % Si present in the alloy and whether it is modified or not (image from [22]*). It's possible to see the beneficial effects of the eutectic modification.*

A study by Chen [16] tested the effects that different quantities of Strontium had on the alloy, with incremental steps going from 0,0014% (14 ppm) up to 0,0120% (120 ppm). The study shows how the eutectic modification levels increased with the increase of Sr% in alloy, with the results shown in Fig 7. The figure represents the eutectic microstructure of an Al-Si7 alloy with the following Sr% presence in alloy:

- a) unmodified
- b) 0.0014 % Sr
- c) 0.0038 % Sr
- d) 0.0056 % Sr
- e) 0.007 % Sr
- f) 0.012 % Sr

It’s possible to see how the silicon particles get more and more rounded with the increase of Sr% present in alloy. As a reference point, for the Al-Si7 alloy shown in the figure, the structure can be considered fully modified when the Sr content in the alloy reaches 56 ppm (picture d).

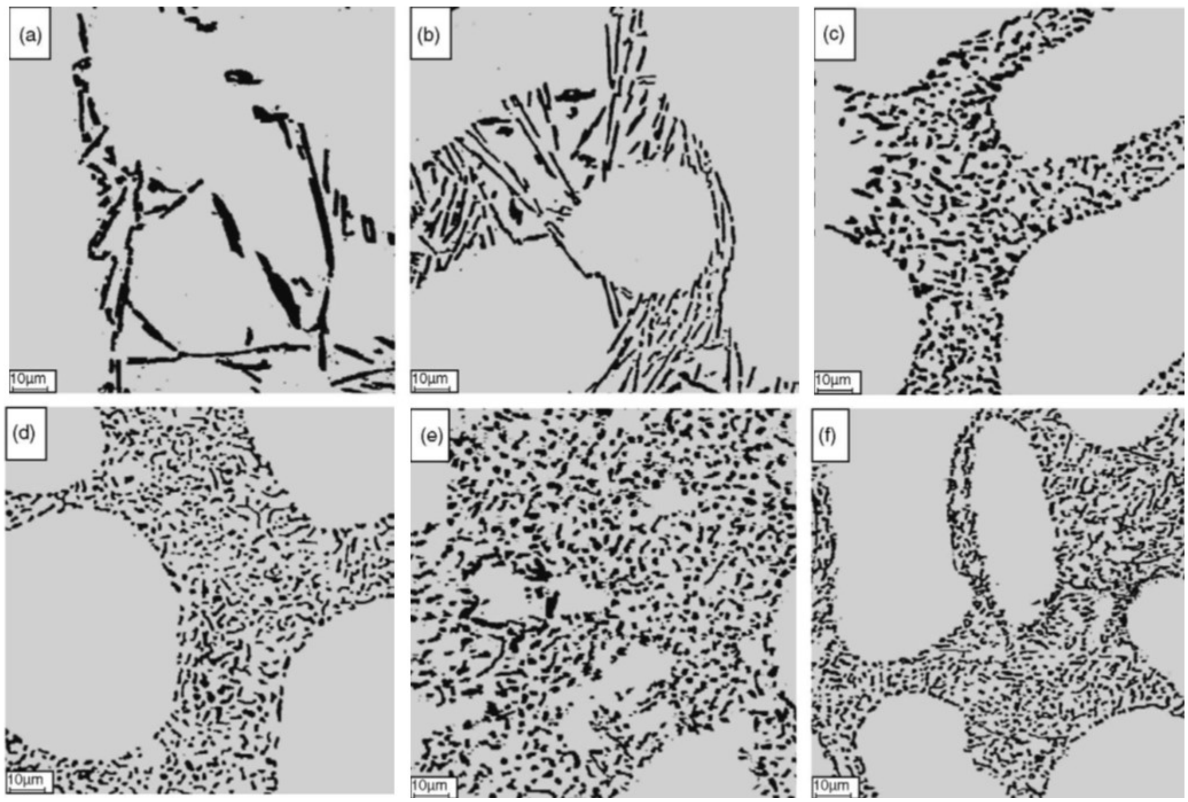


Figure 7: Eutectic microstructure of an Al-7Si alloy (image from [16]*).*
The different pictures show an increasing modification of the secondary phase depending on the strontium% present in alloy, going from condition “a” (unmodified), to “f”(with 0.012 Sr%).

1.3.3 Intermetallic phases

Intermetallic phases derive from the precipitation of phase particles as their solubility in primary phase diminishes throughout the alloy’s solidification. There are two main categories of intermetallic phases: those deriving from precipitation hardening and heat treatments, with largely beneficial properties, and those deriving from impurities’ presence in the alloy, such as Fe particles and oxide inclusions [17].

The inclusion of iron (Fe) particles presence in the alloy is due to the nature of the production process, and their presence can’t be avoided. In aluminum casting alloys, they react with the silicon to form β-Al5FeSi particles (β-particles) which are plate structures with acicular endings (see Fig.8). These growths can block the feeding to the interdendritic regions, acting as porosity nucleation sites, and the platelets offer a preferred pathway for crack nucleation and growth, greatly diminishing the alloys ductility, fatigue resistance and tensile strength [18].

It's possible to alter the shape of β-particles with the addition of manganese (Mn). Manganese is added with a 2 to 1 iron-to-manganese ratio, and it bonds with the alloy to form α-Al15(FeMn)3Si2 (α-particles), also referred to as "China script" due to their compact, ideogram-like shape that's less detrimental to the alloy's mechanical properties [19]. Also magnesium (Mg) can react to form something similar to china script in the form of π-Al8FeMg3Si6 (π-particles), which still have a negative impact on the strength and ductility of the alloy, but are less harmful than other Fe intermetallics [20].

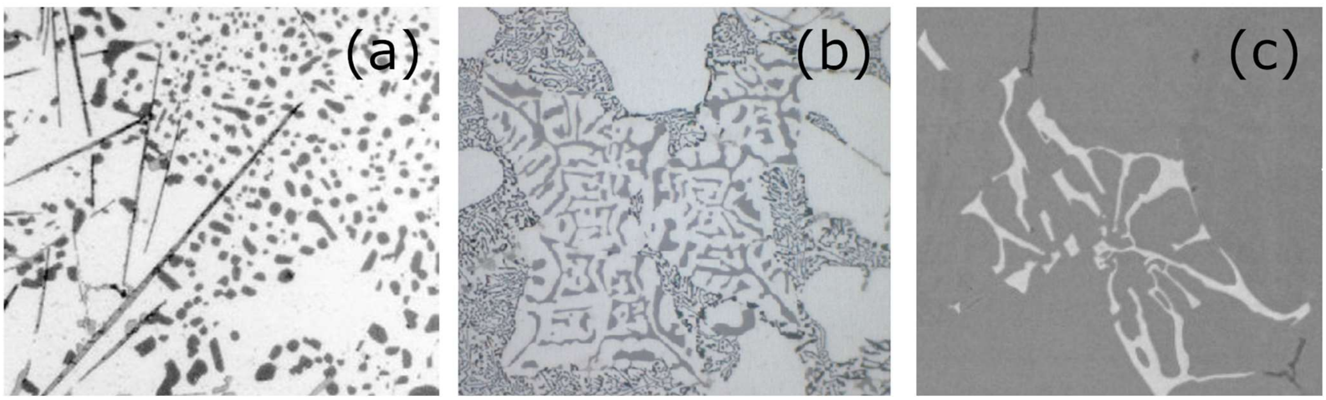


Figure 8: Example of different intermetallic phases, with β particles on the left (a) (β-Al5FeSi), α-particles in the center (b) (α-Al15(FeMn)3Si2), π-particles on the right (c) (π-Al8FeMg3Si6)

1.4 Heat treatments

After being cast, aluminum alloys can be subsequently strengthened by heat treatments to increase their physical and mechanical properties [13]. Wrought aluminum alloys are strengthened by strain hardening as well, but parts made with casting technologies are usually produced near net shape, so strain hardening is not intended for cast aluminum parts.
Also, not every aluminum alloy can be heat treated, for cast aluminum alloys it's possible to apply heat treatments to the 2xx.x, 3xx.x, and 7xx.x series.

The Aluminum Association (AA) has developed specific a nomenclature for standard heat treatment practices. Standard heat treatments are labelled with a T followed by a single digit, which identifies the specific treatment applied. There are variations from the standard treatments that are identified with a second and third digit (for example T61, T572, etc.) that can be used to reach different final properties.

Standardized temper designations are listed in Table 3 below:

Designation	Heat treatment
O (formerly T2, T2x)	Annealed
T4	Solution heat treated and quenched
T5	Artificially aged
T6	Solution heat treated, quenched, and aged
T7	Solution heat treated, quenched, and overaged
T8	Cold reduced before aging

Table 3: Aluminum alloys heat treatments designation system

The most common heat treatment is a solution heat treatment followed by quenching and precipitation hardening (T6 treatment). Cold reduction can be performed before aging in order to improve the compressive yield strength, it's performed usually only on bearings (T8 treatment).

1.4.1.1 Annealing

Annealing is a heat treatment performed to restore the crystalline structure of a strain-hardened material, in order to reduce its hardness and increase its ductility and machineability. Annealing in casted parts is performed to relieve residual internal stresses, that could warp or deform otherwise, and can even be done on alloys that are not considered heat treatable.
The process consists in bringing the part above its recrystallization temperatures for a set amount of time, then slowly cooling it in air. For aluminum, a typical annealing treatment consists in keeping the part between 300° to 410° C (see Fig.9), for 30 minutes up to 4 hours depending on the size and composition of the part.

1.4.1.2 Solution heat treating and quenching

Solution heat treating for aluminum is a process that temporarily increases the alloys workability and machineability, performed by forcing the alloy to have a structure with more alloying elements dissolved in solid solution than it would normally have at room temperature.

If the metal was simply allowed to cool in the following hours after being cast, the alloying elements would simply precipitate, straining the aluminum's part microstructure (impinging slip planes) while increasing its hardness and strength. But if the part needed to be machined and worked on, in some cases it's preferred to have these alloying elements in solid solution first, resulting in a much more ductile and workable matrix, and then allowing them to precipitate later (either naturally or artificially) after the machining operations are done.

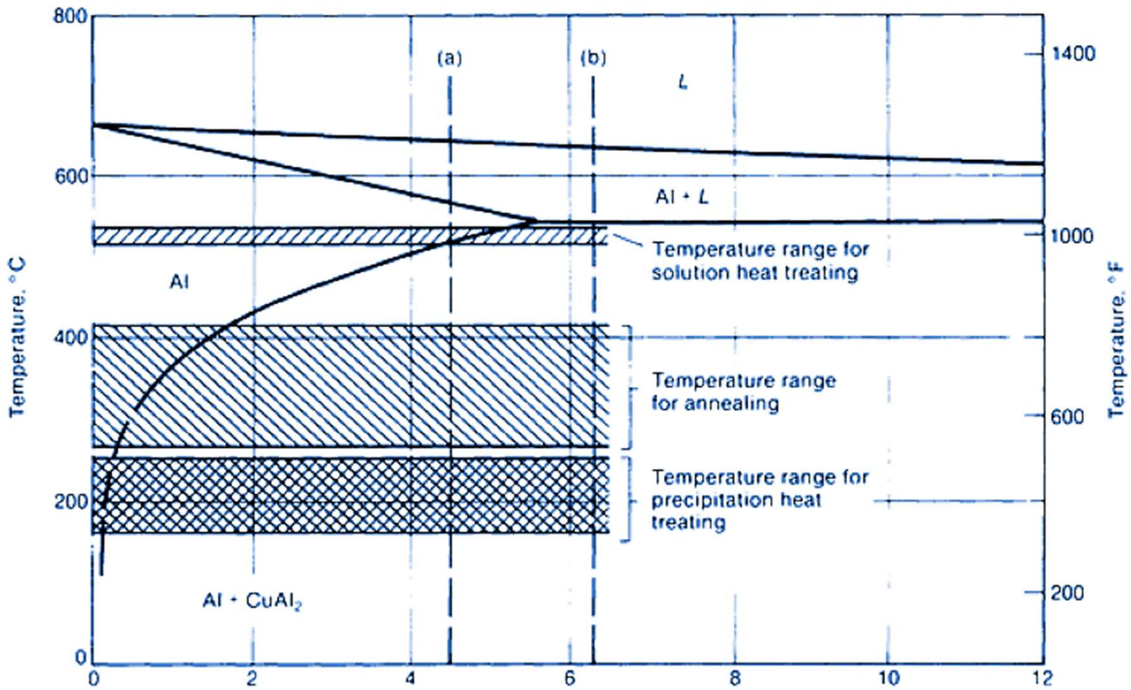


Figure 9: Al-Cu binary phase diagram displaying temperature ranges for typical heat treatments, such as solution heat treating, annealing, and precipitation heat treating (image from [13]*)*

Solution heat treating consists in bringing the alloy above its solvus temperature but right under its eutectic temperature for multiple hours, typically between 1 to 12 hours at 450° to 575°C depending on its size and composition, then quenching it to freeze the resulting structure.
At these temperatures where aluminum's structure can dissolve the most alloying elements in solid phase, which will take spheroidal shapes resulting in a very ductile, homogenized structure.

Quenching is done to freeze the crystalline structure that the metal assumes after reaching these high temperatures, and it's performed by immerging the part in a vat of quenchant as soon as it comes out of the heat-treating furnace. After quenching, the parts can be moderately formed and machined within a couple of hours before they naturally start to harden again.

If the quench is not executed properly, it can result in high internal stresses and it can warp or twist the part. Typical quenchants for aluminum are room temperature water or boiling water to reduce the distortion effect, but other quenchants can be quenching oils, organic solutions, forced air streams or salt baths.

In the equilibrium diagram for the Al-Cu system (shown in Fig.9), it's possible to see how the solubility of the eutectic increases with temperature. This is valid for all the other alloy systems such as Al-Si, Al-Mg, Al-Cu, etc.

Multicomponent alloy systems, such as Al-Si-Cu-Mg and Al-Zn-Cu-Mg systems, will have a multitude of different second phases with different melting temperatures. For these alloys, in order to avoid melting the phases with lower melting temperatures, it's suggested to perform stepped solution treatment.
For example, for an Al-Si-Cu alloy such as the alloy 319 (Al-Si6-Cu4) a stepped heat treatment would consist in a solution heat treating at 495°C for two hours (which allows the Cu rich phases to dissolve without melting) followed by a second heat treating at 515°C for four hours [21]. This kind of stepped heat-treatment will improve the mechanical properties, especially in parts with thicker sections.

1.4.1.3 Aging and precipitation hardening

After solution heat treatment, the elements in the metastable structure will begin to precipitate over time, impinging slip planes and increasing the part's strength and hardness, while lowering ductility. This hardening process can happen at room temperature and is called "natural aging", but it can even be artificially sped up at high temperatures to have all the elements dissolved in solid solution fully precipitate out faster. Artificial aging is performed between 100° to 260°C for multiple hours and it allows the alloy to reach peak hardness much faster than it normally would.
Usually the full aging procedure is not carried out, aging curves have been developed in order to understand how long the aging will take before the part can reach the required properties [13]. Longer times at lower aging temperatures will result in higher strengths, if the process is carried out for longer than required to reach the peak strength, it takes the name of "over-aging".

2 Casting processes

Casting is the process in which the molten metal is poured into a mold with a negative impression of the desired shape, which is then allowed to cool and solidify into the final part.
The final shape is achieved in a single stage, going from liquid metal to finished or near-finished part in a single process. This method is used to produce parts with complex geometries that wouldn't be possible to make through other methods.
The molds used for this method vary in shape and material depending on the technological properties we want to achieve. Depending on the kind of mold used, casting processes can be grouped into two main categories [22]:

- Expendable mold casting
- Non-expendable mold casting

2.1 Expendable mold casting

Expendable mold casting is the set of casting technologies that involve the use of temporary molds. After the casting, the mold is considered "lost" and it's not possible to use it again. This is a broad classification that includes:

- Sand casting
- Shell mold casting
- Investment casting
- Others

2.1.1 Sand casting

In sand casting the casting mold is made out of compacted sand. The molding process is described as follows:
A pattern part is used to give the negative shape to the mold, around which the sand is then compacted to form the two sides of the die. The sand is mixed with bonding agents (such as clay, chemical binders or polymerized oils), while the negative of the part is covered in separating agents (such as talk) to ease the removal of the sand from the finished part after the casting is done.
The sprue and the risers are carved out of the compacted sand, and for undercuts or internal cavities it's possible to use cores made out of sand.
The molten metal is poured into the mold trough the sprue, and once it cools down the mold is broken to remove the solidified part. The sand, once broken, can be recycled and used to make molds again.

In the industry, this process is employed for manufacturing either very large parts and/or small batches for very reasonable costs. Having to destroy and remake the die for each pouring makes this a very lengthy process that can be justified only if the part takes a relatively long time to solidify, or if the demand for the part in question is not very high [23].

For aluminum castings the cooling is very slow, wich allows the growth of dendrites size, and the silica secondary phase takes a very acicular shape which vastly diminishes the alloy's mechanical properties. The sand can also trap moisture, and the bonding agents evaporate trough the casting leading to plenty of gas ending up trapped in the cast itself [23]. For aluminum, this technology is used for parts with modest mechanical properties.

2.1.2 Shell mold casting

Similar to sand casting, the mold is made by pouring resin into the sand around the pattern part, which solidifies into two hardened shells that make the two halves of the die. The shells are only 10 to 20 mm thick, much thinner than the molds required for sand casting. Once the metal is poured in and solidifies, the shells are broken and the finished part is taken out. The sand can be used again after burning off the resin in high temperatures ovens.
This process can be used to make very large parts, it's faster and lower cost compared to sand casting, and since the sand used in the process is much finer it leads to better surface finish, but the equipment required and the production itself are slightly more expensive.

An alternative to shell molding is ceramic mold casting, where the shells are made out of ceramic rather than sand. A silicate slurry is poured around the pattern part, which is then baked to burn the volatiles from the slurry, leaving a ceramic shell into which the molten metal can be poured [23].

2.1.3 Investment casting

Investment casting processes are a class of casting processes that use a sacrificial pattern model of the required part, that can be made either out of wax or a low-density foamed polymer, which evaporates during the pour. The molds around the sacrificial model can be made out of plaster shells or sand.
When using wax models, before the molten metal is poured, the mold must be heated to evaporate or melt out the wax, leaving the cavity ready to pour the metal in.
When using expanded polymers, usually polystyrene foam, the sacrificial model can be simply left inside the mold, as the molten metal pour will burn it off by itself. Alternatively, when using other polymers like PET and PLA, it can be burned off beforehand to leave no residues for a better surface finish [23].

Investment casting is usually adopted to produce small and intricately shaped parts, for example jewelry, but it can also see industrial applications. The accurate control over the dimensions and the mechanical properties achievable make it a viable alternative for the making of precision instruments and in aerospace applications, even if the cost is higher than average.
For aluminum, it's possible to achieve castings with walls as thin as 0,40 -0,75 mm, but the cooling is very slow so this kind of casting technology can lead to high levels of porosity and low mechanical properties [24].

2.2 Non-Expendable mold casting

Non-expendable mold casting is the set of casting technologies that involves the use of permanent, reusable molds. The mold is solid and isn't disposed of after every use, compared to expendable mold casting technologies they can provide better repeatability in the parts produced.
This is a broad classification that includes:

- Die casting
- Permanent mold casting
- Semi-solid casting
- Centrifugal casting

2.2.1 Die casting

Die casting is the process in which molten metal is rapidly injected at high pressure into hardened steel molds. The molds are machined into dies which are designed to sustain the high pressures and to rapidly disperse the heat and solidify the material. They produce high quality parts with good surface finishes and close tolerances, and are designed to have between 100'000 to 150'000 cycles of life [23].

This technology is used for the mass production of small, thin parts and is best used to obtain uniform wall thickness. Die casting of bigger parts up to 50 kg is possible but not common. The rapid solidification under high pressure results in a very fine grain size, especially on the surface, which provides really good mechanical properties and fatigue resistance.

For aluminum cast alloys, the die casting technology is the most widely used for achieving great volumes of small components with thin walls. The most used aluminum alloy for die casting is the 380.0 series (aluminum, silicon, copper alloys) and its modifications, as it provides a really good combination of mechanical and thermal properties, with resistance to hot cracking and good fluidity.

Different alloys must be used when better corrosion resistance is required. Also, unless the alloy has been properly degassed, the entrapped gases can lead to gas porosities in the finished part. Aluminum die castings are not usually heat treated, in part due to the presence of these porosities, but it's possible to have dimensional or metallurgical stabilization treatments instead.

2.2.2 Permanent mold casting

In permanent mold casting the metal is poured, usually by gravity, into the metal molds, which remove the heat from the liquid metal to rapidly solidify it into a cast with relatively high mechanical properties, good dimensional tolerance and good surface finish. The molds are designed to withstand repeated heating and cooling cycles so they can be reused many times.

Typically, permanent mold castings are used for manufacturing aluminum, magnesium and copper alloy based products [25]. For industrial applications, depending on how the material is poured into the mold, it's possible to identify three main types of permanent mold casting technologies:

- Gravity casting
- Low-pressure mold casting
- Vacuum casting

2.2.2.1 Gravity casting

In gravity casting the casting mold is made out hot working steel, where the negative shape of the desired part is machined into the two halves of the mold to form the casting cavity, along with the sprue and the necessary risers. For any undercuts or internal cavities, it's possible to use cores made out of either metal or sand.
The molten metal is poured into the mold trough the sprue, and once it solidifies the mold opens to allow the removal of the finished part. This technology will be further explored in chapter 3.

2.2.2.2 Low pressure mold casting

This casting process uses a gas at low pressure, usually between 3 and 15 psi to push the molten metal into the mold. The pressure is applied on top of the liquid metal, forcing it up a refractory pouring tube which feeds the mold from the bottom. The seal between the two mold shells must be tight in order to avoid having molten metal spill out through the casting.
This method is able to achieve slightly better mechanical properties than gravity casting can, and the mold does not need risers as the constant metal feed compensates for any shrinkage that may occur during solidification.

2.2.2.3 Vacuum casting

In this casting process the molten metal is pulled by a vacuum imposed on the mold, while at the same time getting rid of any dissolved gases, resulting in a porosity free cast. The process can make very detailed parts, achieving a really good surface finish and slightly better mechanical properties than other permanent mold casting methods could, but it's limited for making small parts as it's not possible to pull much weight just trough the vacuum. The seal between the two shells also must be exceptionally tight in order to hold the vacuum.

2.2.3 Semi-solid Casting

Semi solid casting is a casting process where a highly viscous, semi liquid alloy is injected in the metal die. The molten alloy should be 35% to 70% liquid, resulting in a viscous pour which fills the cast slowly without turbulence, virtually eliminating the porosities caused by trapped gasses. This technology is able to produce complex shaped parts with tight tolerances and thin walls, without the residual porosities present in most other casting processes, resulting in better mechanical properties obtainable compared with other processes.

This technology is very commonly used for aluminum alloys (Thixocasting), where it's possible to use pre-cast billets with an extremely fine, non-dendritic structure to make the final part, resulting in much better mechanical properties. The billet is heated into a semi-solid temperature range, usually trough induction heating, then injected in the die into shape. By eliminating the residual porosities, it's also possible to heat treat the castings to T4, T5 or T6 tempers [26].

2.2.4 Centrifugal casting

Centrifugal casting is used for larger parts with rotational symmetry, in this process the molten metal is poured into a fast-spinning mold, where the centripetal forces push the metal outwards into the mold walls until it solidifies. The forces allow the viscous metal to reproduce very fine surface details, while virtually eliminating porosities.

Centrifugal casting of aluminum alloys produces very fine microstructure, porosity free and high dimensional accuracy, resulting in better mechanical properties compared with other processes [24].

3 Gravity mold casting of aluminum alloys

Aluminum alloys are ideal for casting technologies. They have all the properties good casting alloys should have, such as low melting point, which allows them to solidify relatively quickly, and good fluidity, ideal for thin-walled profiles and complex part designs. The castings are pressure tight, so they can be used for fluid retaining parts (valve bodies, pump housing, hydraulic fittings, etc)

Some typical cast aluminum products are presented below:

- Automotive parts: outboard motor parts like pistons, transmission housings, connecting rods, steering knuckles.
- Industrial applications: impellers, compressors, machine tool parts, valve bodies
- Aircraft and marine applications: aircraft wheels, marine hardware, missile components
- Medical devices: Surgical tools, dental equipment, monitor components.
- Home items: Hand tools, lawnmowers housings, skillets and cookware, corrosion resistant outdoor furniture
- Others: escalator parts, typewriter frames, instrument cases, etc.

3.1 Gravity mold casting

In gravity die casting the molten metal is gravity-fed into metal permanent molds (see Fig.10). While the pouring rate is relatively slow, the heat is rapidly dispersed trough the metal mold, hence the solidification process happens rather quickly.

This technology is better suited for the casting of bulkier parts, with walls no thinner than 5 mm. The high heat transfer rates of the metal mold allow for a sufficiently fast solidification rate, resulting into a cast with good dimensional tolerances (typically ±0.1~0.2 mm) and surface finish (typically 1.6~3.2 μm), and a fine microstructure meaning high and uniform mechanical properties [27].

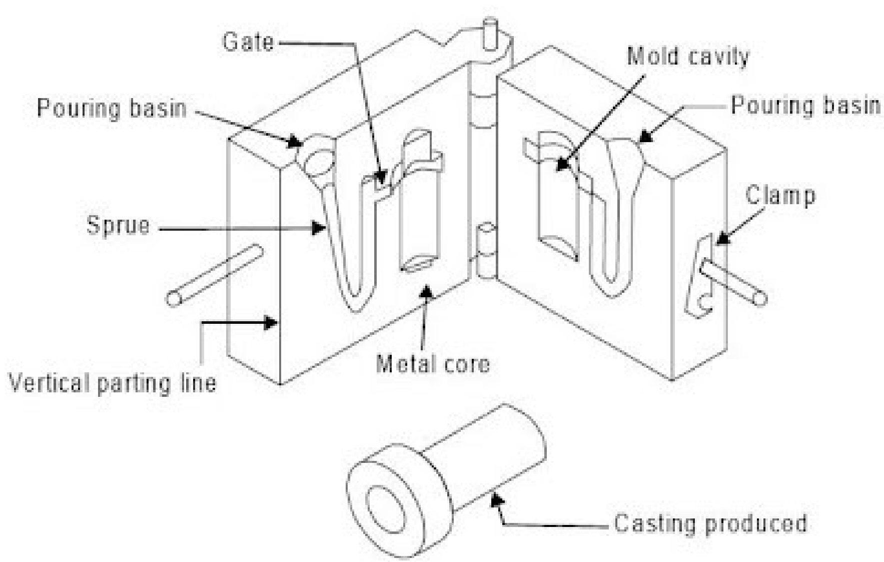


Figure 10: A typical permanent mold, for gravity mold casting, with hinged halves

Typical qualities of a gravity mold casts are listed below [28]:

- Fine grain size: The rapid solidification results in castings with fine grain size and high mechanical properties. The fast solidification also freezes the shape to avoid shrinkage.
- Excellent surface finish: Dense surfaces with extremely fine microstructure, with rugosity values typically between 4 to 5 μm, although values from 1.6 to 2 μm are attainable. If needed, they can be further machined, polished or plated.
- Excellent dimensional tolerances and uniformity: Can cast intricate profiles, with the castings come out near-net shape, requiring only a few finishing processes. It's possible to achieve tolerances of ±0.20 mm on the cast, with a ±0.25 mm tolerance in the parting line left between the mold sides.
- Excellent repeatability: with tolerance differences between parts casted by the same mold being typically ±0.5 mm.

Gravity casted Al-Si alloys typically display the following mechanical properties [12]:

- Ultimate tensile strength R = 150~190 MPa
- Yield strength Rp0.2 = 100~160 MPa
- Young modulus E = 70'000 MPa
- Elongation at break A% = 0.5~3%
- Brinell hardness = 50~90 HB

For smaller, thinner castings, the cooling rate achieved in the mold is usually sufficiently fast to achieve a fine grain size, but for bigger, thicker casting, subsequent heat treatments may be required to achieve optimal mechanical properties.

3.1.1 Comparison between die casting, gravity casting, and sand casting

Compared to die casting, gravity mold casting production rates are much lower, as the pouring rate and longer cooling times limit production, and the resulting grain size after solidification is coarser, meaning lower mechanical and technological properties.

However, not every part design can be made through die casting technologies. The expensive tooling required for die castings requires an extremely high demand for the product in order to justify the cost. Die castings are limited to the mass production of light parts with thin-walled profiles, as anything bulkier wouldn't be able to cool sufficiently fast to meet the production rate quota. For the batch production of thicker, bulkier parts with good mechanical properties, permanent mold die castings are the better alternative.

Compared to sand casting instead, gravity die castings show higher mechanical and technological properties, mainly due to the higher heat transfer rates of the metal molds and the faster solidification times, with better dimensional accuracy and surface finish.

Although the tooling cost for the gravity die process is much higher, the faster cooling rates and the partial (or full) automatization of the process allow for much higher production rates, which justify the higher tooling cost. When properly executed, sand castings are viable for small, customized production runs, but for longstanding batch productions, gravity die casting technologies are the better alternative.

In Fig. 11 below it's possible to see a comparison between the microstructure, of the same alloy, casted with the three different technologies aforementioned:

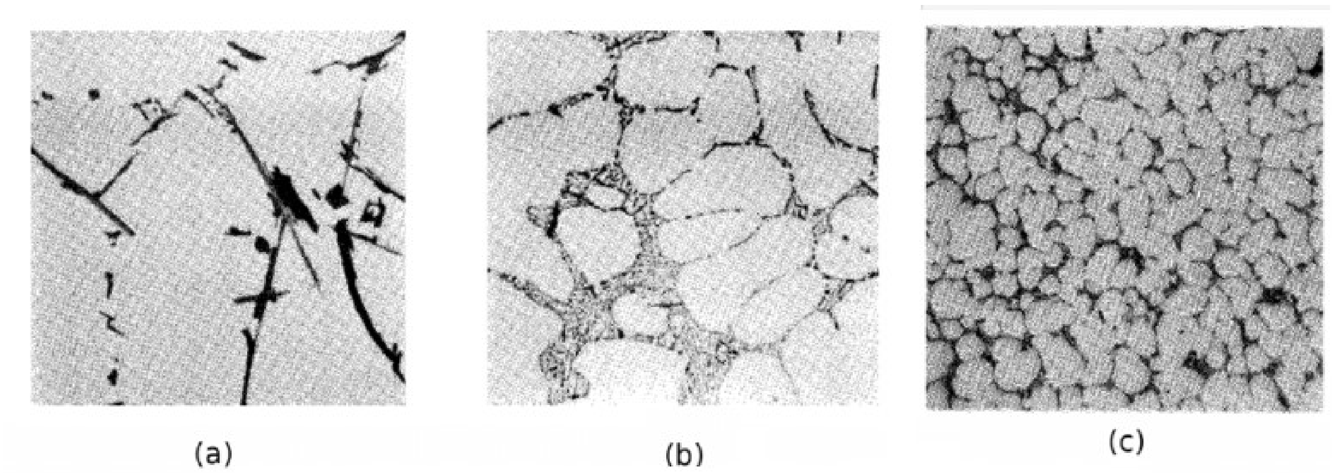


Figure 11: Microstructure of a 443 aluminum casting alloy (Al-Si5), (a) as sand cast, (b) as gravity mold cast, (c) as die cast (image from [29] *). It's possible to see how, for slower solidifications, the silicon phase deposits have a more acicular morphology,*

To sum up, the advantages of gravity die casting over sand casting are listed below:

- Finer grain size: due to the higher heat transfer rate and faster solidification
- Greater mechanical properties: increase in strength, hardness, and tenacity due to the smaller grain size.
- Better dimensional tolerance and surface finish: due to the enhanced stability and smoothness of the metal mold cavity
- Smaller stock allowance: due to the high dimensional tolerance achievable, less subsequent machining operations are necessary.
- Long production runs: the steel mold can last up to 150'000 cycles with proper maintenance.
- Higher productivity: due to not having to rebuild the mold at every casting cycle.
- Can be automated: the casting cycle consists in repetitive and standardized motions.

3.2 The machine

For gravity die casting processes the mold is divided in two halves, with a fixed part and a moving part (see Fig.12). Even though they could be operated manually, large dies can prove difficult to handle, so the operations are usually performed trough hydraulically or pneumatically operated casting machines.

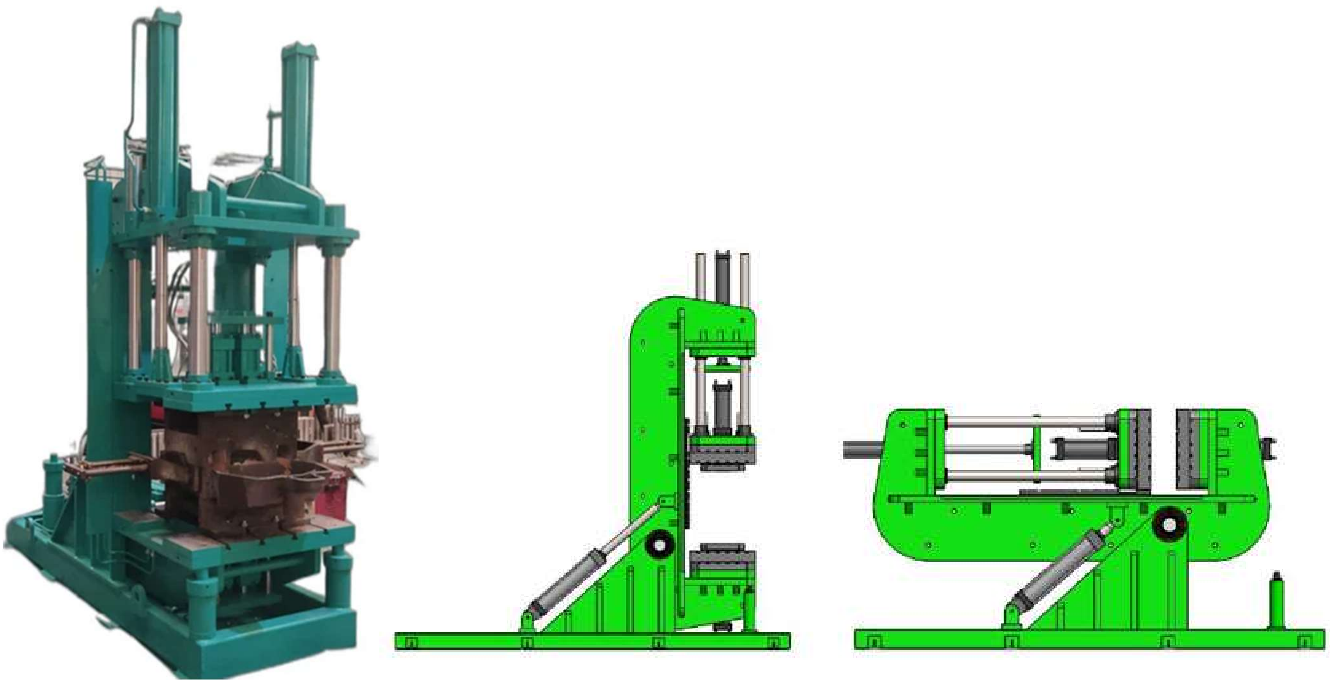


Figure 12: Typical gravity die casting machine (left), and two possible configurations, with vertical configuration (mid), and horizontal configuration (right)

These machines can safely manipulate the mold through a series of programmed actions.

1. The two mold sides are parted (either horizontally or vertically, depending on the configuration) and the die halves are presented to the operator to apply refractory coats and any metal inserts or cores.
2. Then the two halves are clamped shut by the pneumatic actuators and the molten metal can be poured (either by the operator or by a programmed robotic arm) down the sprue trough the gating system to fill the mold cavity.
3. After an appropriate amount of time has passed, usually around 1 to 2 minutes, the mold can be opened and the casting ejected.

The entire cycle can take between 3 to 6 minutes, depending on the cast size and the automation level.

3.3 The steel mold

As mentioned before, the mold is divided into a fixed part and a moving part.
On the two halves it's possible to distinguish the casting cavity, machined on the mold, along with the gating system and the necessary feeders (see Fig.13).
For the realization of any undercuts or internal cavities, it's possible to use cores made out of either metal or sand.

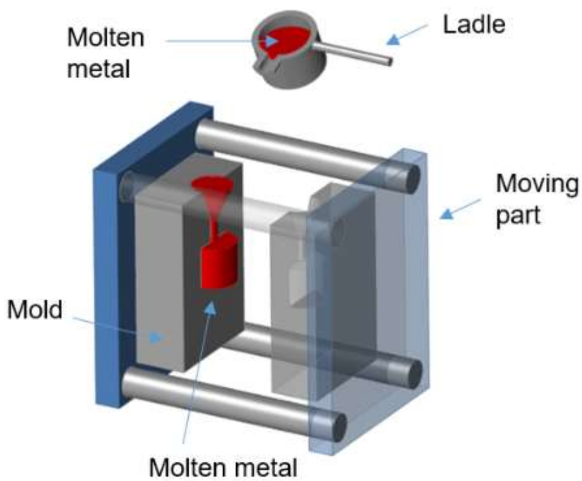


Figure 13: Gravity die casting schematic, displaying the casting cavity

3.3.1 Design Geometry

The limits of casting technologies must be taken into account when defining the geometry of a casted part. Some of the various geometric features to consider are listed below:

- Draft angle: It's the taper given to the surfaces parallel to the parting direction, in order for the part to better detach from the mold once the cast is finished (see Fig.14). Usually 1° to 2° degrees of taper are enough for a part's profile, while more taper is given to holes and windows achieved through cores as they tend to stick more due to the cast shrinking around them. Surfaces with no draft result much harder to eject off, leading to damages to both the casting's surface and the mold itself.

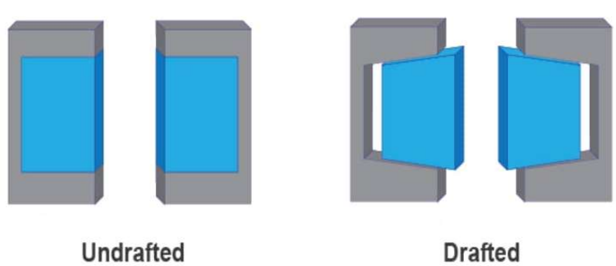


Figure 14: Schematization showing the difference between an undrafted mold and a drafted one

- Parting line placement: The parting line is where the two halves of the die will join together. The part cavity in the die should be oriented in a way that takes into account all the geometrical features of the casting part, such as holes, undercuts, slots and grooves. The parting line will intersect all these features while cutting the part in half through its maximum section, to allow proper separation of the mold halves. It's suggested to avoid parting lines parallel to the mold's opening direction [50] (see Fig.15).

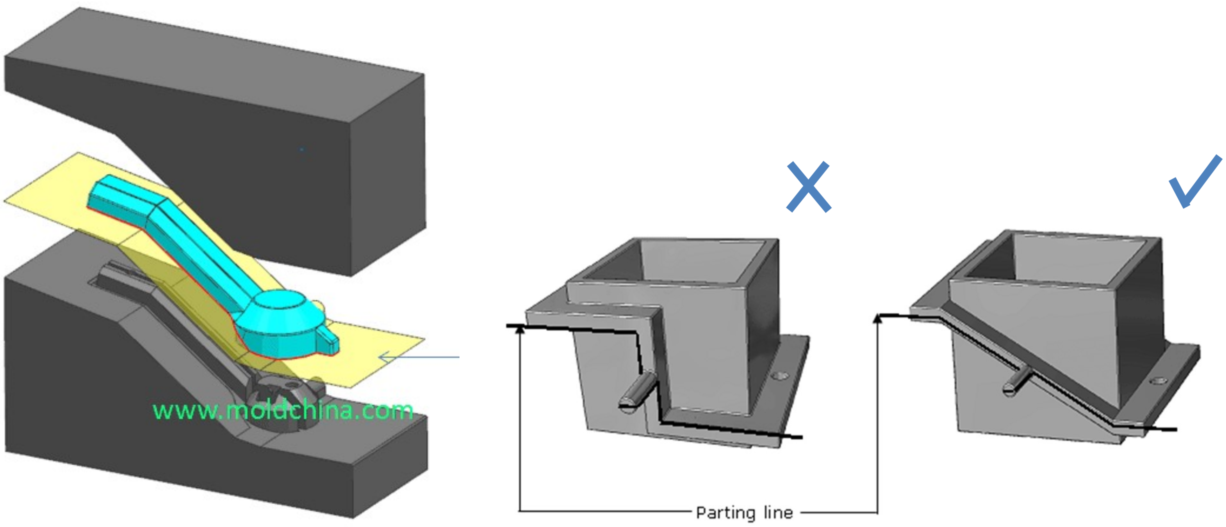


Figure 15: Mold 3D model displaying the separation plane, which identifies the parting line

- Fillets and radii: When filling the casting with metal, sharp corners and edges will cause turbulence, won't dissipate heat (hot spots), and will cause high concentration of stresses, both in the die itself and in the finished cast. The use of fillets and blends, usually with 0.8 to 1.6mm radii or higher, will considerably strengthen the cast. The term "fillet" refers to rounded inside corners, while "radii" refers to external ones (see Fig. 16).

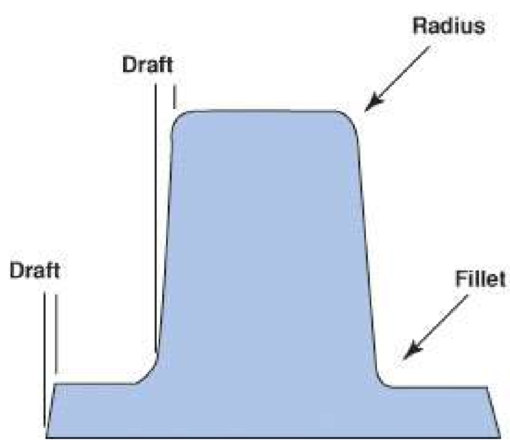


Figure 16: picture displaying the nomenclature for common casting features

- Ribs: structural supports, used on adjacent sections or flat surfaces, that increase the strength and dimensional stability of the cast without having to increase the wall thickness. Also called "metal savers", they should have rounded off, tapered edges, and be evenly distributed throughout the surface we want to strengthen (see Fig.17).

Figure 17: Casting 3D model displaying typical rib configurations, for increased structural stability

3.3.2 Gating system

The gating system consists in the set of channels trough which the molten metal is fed into the casting cavity (see Fig.18). When in contact with the cold mold, the molten metal can solidify rather quickly, and if its flow is not controlled properly it can turn turbulent and splash, leading to a series of surface and internal defects on the final cast (laps, cold shuts, wrinkles, etc).

The gating system is designed to take out the flow's inertia and turbulence, ensuring a smooth, controlled filling of the casting cavity. A traditional gating system will be composed by the a pouring basin, a sprue, runners, gates, risers, and vents. In gravity casting, all of these components are usually machined directly on the mold itself.

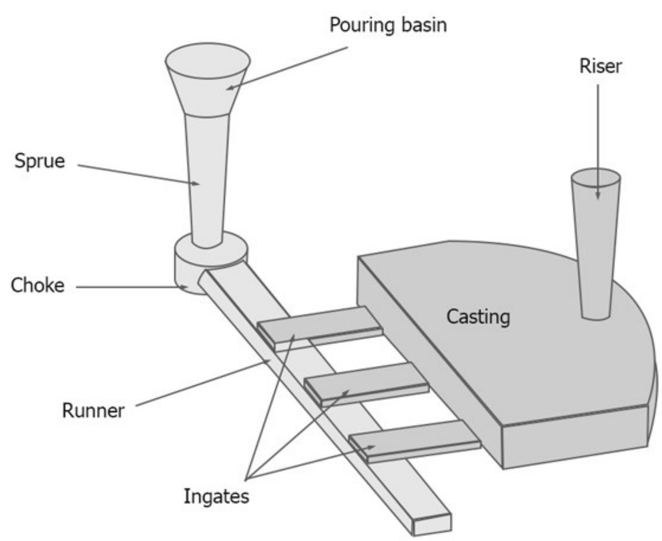


Figure 18: Schematic display of a typical runner system, meaning the set of features required to feed the molten metal into the casting cavity of the mold

3.3.2.1 Pouring basin

The pouring basin or pouring cup is where the metal is poured first. The molten metal is poured from the ladle into the cup, offset by the sprue, where it will form a puddle and slowly pour down the sprue when it fills up. Its main purpose is to take the inertia out of the molten stream, if the metal were to be poured directly down the sprue the flow would be too fast and turbulent to fill the mold properly.

3.3.2.2 Sprue

The sprue is a vertical channel, usually with circular cross section, that leads the molten stream from the pouring cup to the runners. As the stream accelerates down the sprue due to the effect of gravity, from Bernoulli's law we know that its pressure will decrease (see Fig.19). If this phenomenon is not accounted for, the fluid could reach pressure levels low enough to start pulling air from the top of the sprue, leading to gas porosities and cavities resulting in the final cast.

By describing the molten stream of metal as an incompressible, ideal fluid, it's possible to use Bernoulli's law to calculate the fluid's velocity and pressure depending on its elevation and cross section.

$$h_1 + \frac{p_1}{\rho \cdot g} + \frac{{v_1}^2}{2 \cdot g} = h_2 + \frac{p_2}{\rho \cdot g} + \frac{{v_2}^2}{2 \cdot g}$$

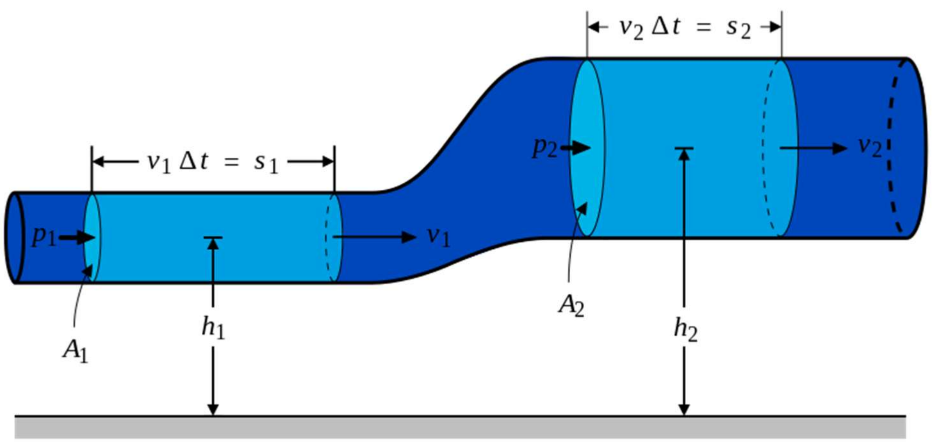


Figure 19: Bernoulli's law derivation diagram

Where:

- h: potential head $[m]$
- p: pressure $[Pa]$
- v: molten metal velocity $[m/s]$
- g: gravity acceleration 9.81 $[m/s^2]$
- ρ: molten metal density $[kg/m^3]$

For this reason, sprues are tapered to follow the contraction of the stream (see Fig.20), with the upper and lower cross-sections calculated with the following formula:

$$\frac{A_1}{A_2} = \frac{\sqrt{h_1}}{\sqrt{h_2}}$$

Where:

- h1: metal static pressure head on top of the sprue.
- h2: metal static pressure head at the bottom of the sprue.
- A1: cross-sectional area at the top of the sprue
- A2: cross-sectional area at the bottom of the sprue

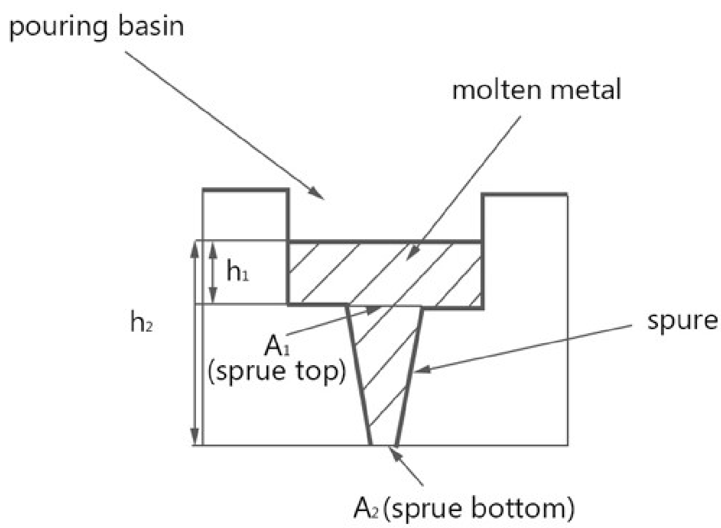


Figure 20: Schematic representation of the sprue of a gating system, displaying the typical taper of a sprue and highlighting the geometrical features required to apply the Bernoulli theorem

3.3.2.3 Runner

The runner (or cross gate) is a horizontal channel that connects the sprue to the casting cavity through the gates. Its purpose is to slow down the metal stream while ensuring that no air or debris make it to the final cast (see Fig.21).
The cross-section of the runner must be calculated properly, to ensure that the channel fills completely as to avoid any air entrapment. In order to provide an equal flow rate to each gate, the cross section of the runner must gradually decrease by an area equal to the gate’s area.

This calculation can be done with Bernoulli's law, but it doesn't take into account different phenomena such as friction, inertia, and surface tension. For example, due to the inertia of the heavy stream, the final gate will be provided with greater volumes than expected.
For a proper calculation the use of fluid flow simulation tools is preferred.

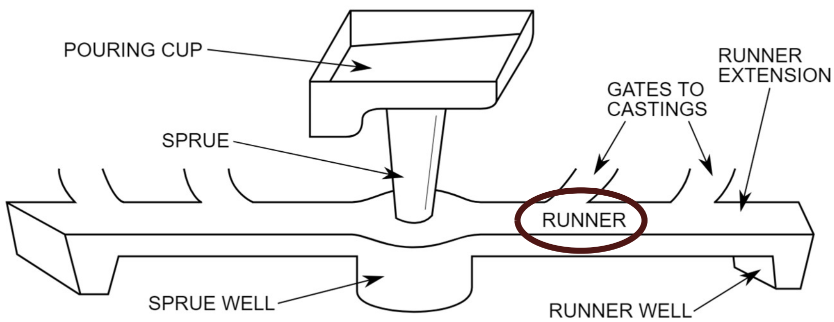


Figure 21: Schematic representation of a typical gating system for a horizontal parting plane mold

3.3.2.4 Sprue well and traps

The connection between the sprue and the runners is not direct, as there's a sprue well which fills up first whose purpose is to further reduce the turbulence and trap any inclusions which might have been included with the first pour (see Fig.22).

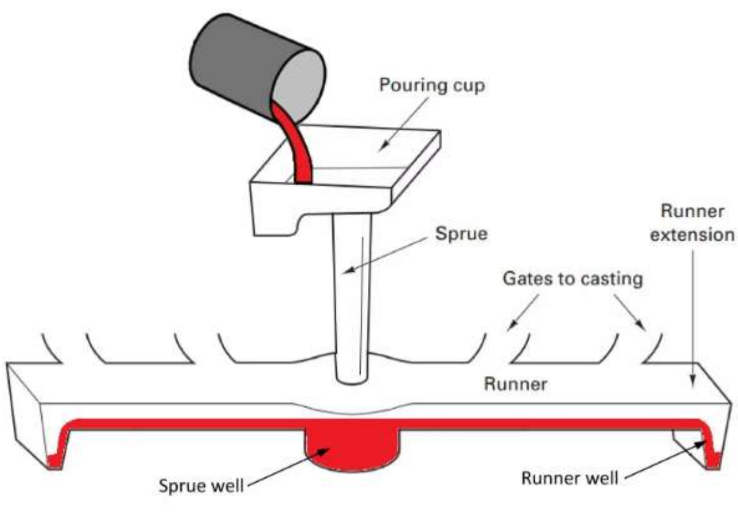


Figure 22: Scheme showing the debris-trapping function of a runner well

The sprue well should have a circular cross section twice the size of the sprue's bottom area, and a depth twice the size the depth of the runners [28]. To prevent erosion, it's possible to place an impact core here as well. At the end of the runners instead a runner well can be placed in order to exploit the stream's inertia in order to collect the slag and other impurities, to prevent their inclusion in the cast.

3.3.2.5 Ingates

Ingates are what connect the gating system to the casting cavity, bringing in the molten metal. Their main purpose is to slow down the velocity of the flow, while ensuring that the flowing rates are proportionally coherent with the size of the casting area.

Depending on how the metal is fed into the casting cavity, it's possible to distinguish three kinds of gating systems (see Fig. 23):

- Top gate system (a): The metal is fed directly from the top of the casting cavity. This method can give more control over the direction of the solidification, but it's suitable only for the casting of flatter parts.
- Bottom gate system (b): Used for bulkier parts, the metal is fed from the bottom of the casting cavity. The flow will be much less turbulent, but the cavity filling will be slower and if the casting hasn't been properly designed, it can solidify and clog before the mold cavity has been filled.
- Parting line gating system (c): A lateral feeding, it's a compromise between the two solutions, usually the preferred alternative.

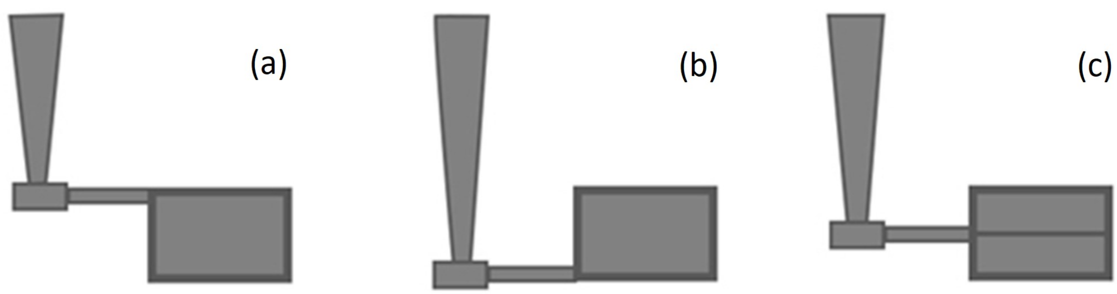


Figure 23: Schematic representation of the 3 possible gating configurations, with a top gate system (a), bottom gate system (b), or parting line system (c)

3.3.3 Risers

Risers (or feeders) are additional cavities included in the casting cavity which fill up with molten metal, that are designed to provide metal to the cast as it solidifies to compensates for the volume shrinkage. They're designed in such a way that the metal inside them stays liquid for longer than the metal in the casting area they feed.

Being the last area to solidify, they collect all the impurities and expelled gases that would otherwise stay trapped in the actual cast. They can either be open or blind, depending on if they're open to the atmosphere or not (see Fig.24).

3.3.3.1 Riser's design

Riser design is very complex as the material transport phenomenon that takes place in a riser depends on multiple different factors, such as the cast volume, shape, solidification direction, temperature differences due to the filling process, geometric features, presence of cores, etc. In order to find the ideal riser volume, they must be designed with the help of simulation programs and databases.

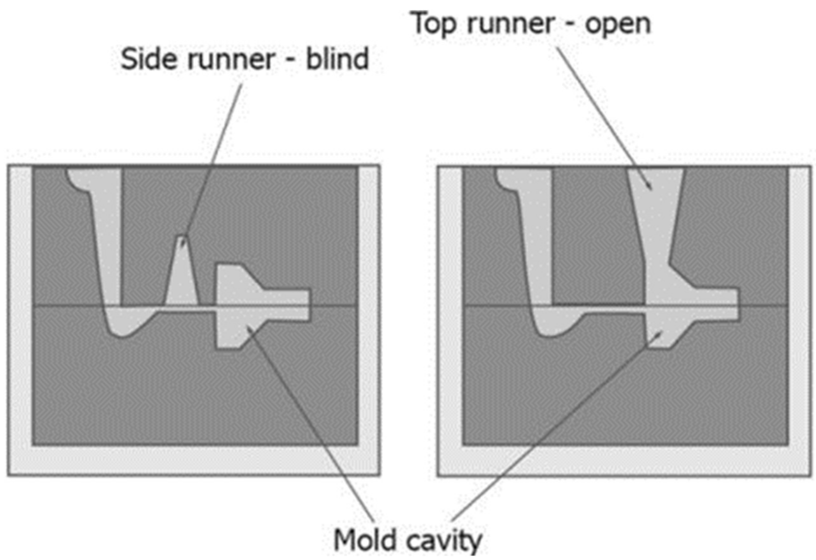


Figure 24: Schematic representation of the two typical riser configurations, with a blind runner on the left, and an open runner on the right

There are some basic approaches developed through the years in order to estimate the correct riser size. Two simple methods that can be used are either the modulus method or the Huever's circles method. The modulus method consists in imposing an increasingly growing volume-to-surface ratio on the cast in order to have the greatest ratio end up on the riser. The volume-to-surface ratio is called "modulus", a part with a bigger modulus will solidify later than a part with a smaller one. For a generic x part it can be calculated with the following formula:

$$M_x = \frac{volume\ of\ the\ x\ part}{heat\ exchanging\ surface\ of\ the\ x\ part}$$

$$M_{i+1} = 1.10 \sim 1.20\ M_i$$

A generic part can be broken down into smaller, basic shapes, for which the modulus can be easily calculated. In order to establish a proper directional solidification, the part should have a module at least 10% to 20% bigger than the previous one (see Fig.25). It's important to ensure that the connection between the riser and the cast does not solidify early as well, staying open long enough to ensure the necessary material transfer.

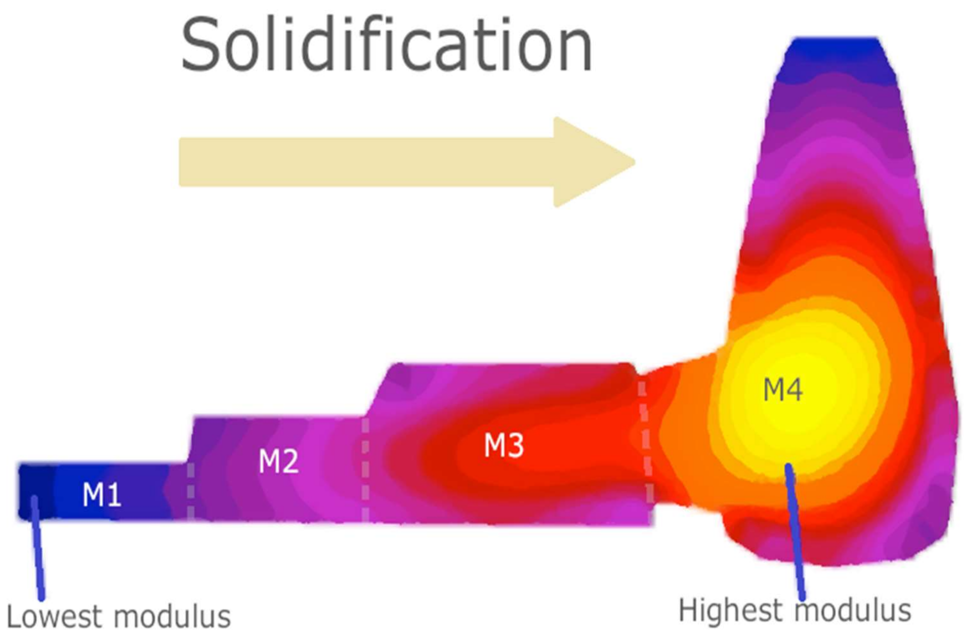


Figure 25: Simulated solidification of a casting broken down into simpler parts, highlighting how the directional solidification goes from the part with the lowest modulus to the one with the highest

3.3.3.2 Vents

Vents are small channels that allow the entrapped gases to escape from the mold. These gasses are allowed to escape through the top of open risers, but also through dedicated channels, usually located along the mold's parting line, designed to be small enough to let the gasses out but not the molten metal. The vent holes must be cleaned regularly as they can clog up and trap the gas in the cast.

3.3.4 Mold material

The life of a casting mold depends on multiple factors, such as the mold material, the pouring temperature, the size and complexity of the cast, the cycle times, and the temperature distribution throughout the cycle.

For aluminum castings, after reaching regime conditions the mold temperatures can reach around 330 °C. Before the first operative cycle the mold must be preheated to avoid thermal shocks, then continuously utilized in order to keep the temperature uniform throughout its section, as to avoid thermal fatigue as much as possible. The mold material adopted must be chosen depending on their resistance to erosion and thermal fatigue.

Due to the high temperatures, molds are subject to:

- Thermal fatigue: due to the cyclical thermal expansion and contraction, evident on the grain boundaries
- Distortions: especially problematic on the mold interface, can compromise the seal between the two halves of the die.
- high temperature creep

For aluminum alloys, commonly used materials for the molds are gray cast iron, tool steels, refractory metals, or superalloys. Gray cast iron has very good thermal fatigue resistance and can be easily machined, but they're susceptible to oxidation and its oxides crack easily under the cyclical expansions and contractions, affecting the surface finish of the cast.
For more expensive productions, AISI H13 tool steel can be used. H13 is a hot work tool steel characterized by very high strength and good resistance to thermal fatigue, erosion, and wear. Its superior properties, improved surface finish and longer operative life make it a better alternative to cast iron molds [28].

For the casting of aluminum, gray cast iron molds have a life of 75'000 to 150'000 casting shots before wearing out, while H13 molds can produce 250'000 castings, up to several millions with proper maintenance [12].

3.3.5 Cores and slides

Cores are devices used to obtain features in the cast that can't tolerate draft or that wouldn't be possible to obtain otherwise, such as internal cavities or reentrant angles. Cores can either be made out of sand or metal (see Fig.26).

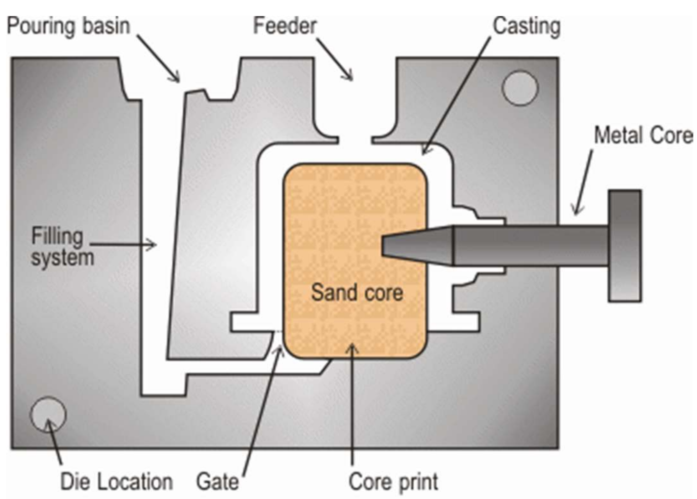


Figure 26: Schematic view of a typical permanent casting mold, displaying the gating system, the casting cavity, and the necessary cores required for achieving different internal features

Depending on their configuration they can be divided in 3 categories:

- Fixed cores: Made out of metal, they're machined directly into the die. Their axis must be parallel to the mold's opening direction and they must be tapered to allow the mold to open properly.
- Movable cores: Made out of metal, these cores can slide in and out of the mold to get in their position. They're inserted before the metal is poured in (after the mold closes), and removed right after the cast solidifies, before the mold can open.
  Slides work under the same principle, but are used for making undercuts (see Fig. 27)

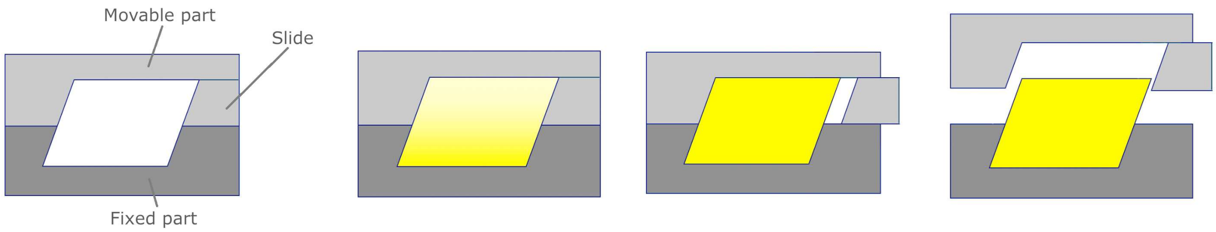


Figure 27: Steps displaying the functioning of a movable slide, used to make undercuts

- Floating cores: Used for the making of more intricate features. They're manually inserted before the mold can close, and can be made out of either metal, if their shape allows for simple extraction, or chemically bonded sand.
  If the cores are made out of sand the process takes the name of "semi-permanent" mold casting, as the sand cores are sacrificed each cycle (see Fig.28).

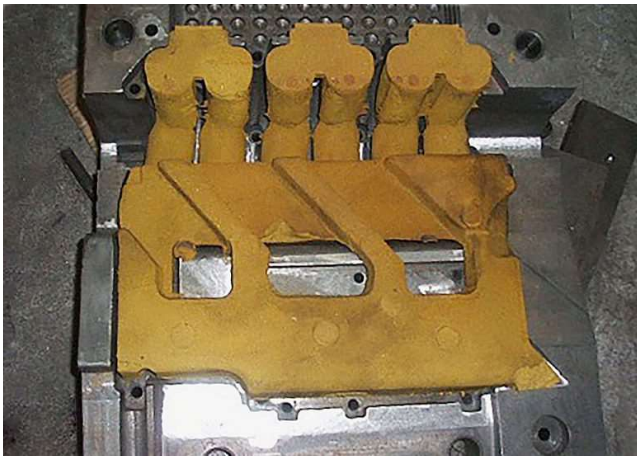


Figure 28: Example of a sand core placed into a mold. The resin binders give the core enough strength to be handled and resist the pouring forces, but after the casting is done the temperatures reached during the pour burn off the resin, leaving only a fragile sand shell which can be easily removed

The sand cores must be strong enough to keep their shape trough the pouring of the molten metal, but weak enough to collapse when the cast solidifies and shrinks around them, otherwise the core's presence could lead to high stresses and hot tearing. As the cast solidifies, the binders used on the sand burn off into gasses, which must be accounted for and properly vented out of the cast to prevent porosities.

3.3.6 Coatings and ejector pins

To protect the mold from the high temperatures reached through the cycle, steel molds must be coated with refractory washes (see Fig.29). These washes not only prolong the mold's life, but also improve surface finish, help detach the cast from the mold, and, when using washes with different thermal conductivity, can be used to establish the solidification's direction.
These washes are thermically applied before the production cycle can begin, and they can last for multiple production runs. They're usually sodium silicate based, and have different filler materials depending on their purpose:

- Refractory coatings (white): Alumina washes that thermally insulate the mold and facilitate the cast release from the mold. For the sprue and other areas that reach higher temperatures, thicker, more insulating coatings should be applied.
- Conductive coatings (black/blue): Graphite washes that increase the thermal conductivity with the mold, in order to freeze the structure in certain critical areas that might need to solidify first.
- Insulating coatings (red): HallCoat or other insulating washes with higher thermally insulating properties that help keep the temperature higher locally in certain areas that might need to solidify later (such as the connection between a riser and the cast).

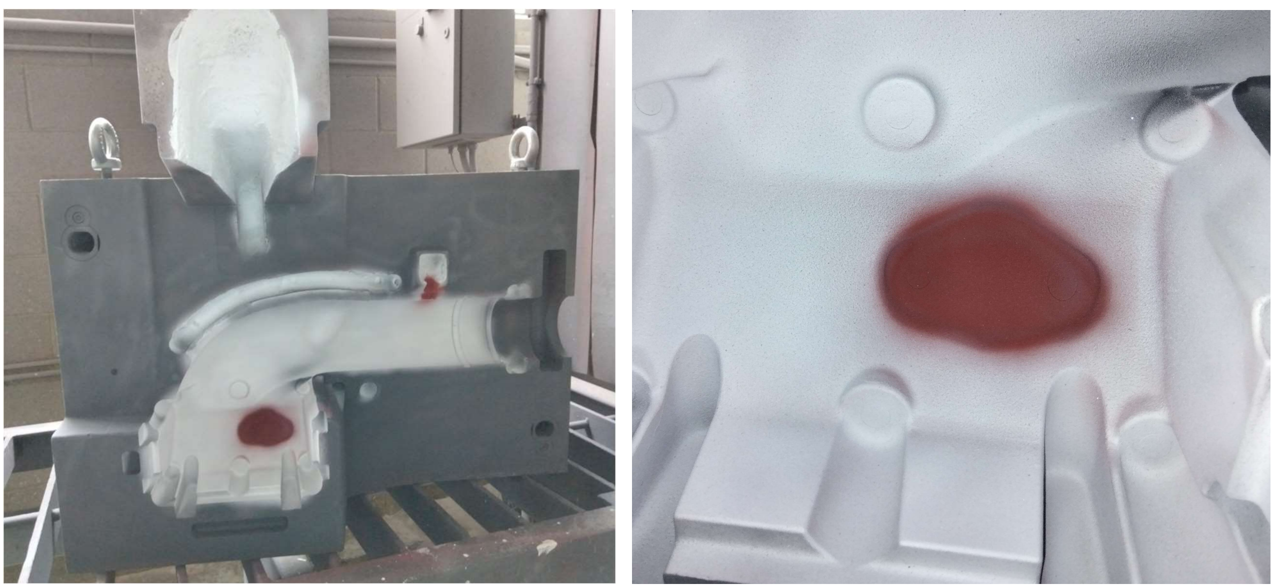


Figure 29: Example of different coatings applied on the same mold. In white, refractory alumina coatings; in red, insulating coating set to impose a solidification gradient towards the red area

3.3.6.1 Ejector pins

In order to further aid with the detachment of the cast from the mold, talc powders are spread on the die in between each cycle. When that isn't enough, it's possible to use ejector pins to push away the part when the cast cycle is complete. They are installed throughout the mold, when not zeroed properly their housings can leave small round impressions on the cast.

4 Defects

Casting defects can be expected to occur if the casting process is not properly controlled and performed. One of the most complete defect classifications comes from the StaCast program, a European project that in 2012 proposed a multi-level approach to the classification of cast defects, specific for aluminum casting [30].

There can be different kind of defects due to a multitude of different reasons, depending on their morphology they can be classified into three main categories:

- Category A: Internal defects and imperfections (porosities, inclusions, hot tears, etc.)
- Category B: Surface defects and imperfections (ejection marks, cracks, sinks, etc.)
- Category C: Geometrical defects and imperfections (incomplete cast, deformation, etc.)

The StaCast classification divides each of these macro-categories further into levels, with each level representing the level of detail at which the defect is described.

- Level I) morphology/location of the defect: a macro classification of the defects depending on whether they're internal, superficial, or geometrical.
- Level II) metallurgical origin of the defect: a more detailed classification of the defects depending on which source led to their formation.
- Level III) specific type of defect: different defects can have the same metallurgical source, this level identifies each defect by name and type

4.1 Internal and superficial defects and imperfections

1st Level	2nd Level		3rd Level	
A Internal Defects and Imperfections	A1	Shrinkage defects and imperfections	A1.1	Macro-shrinkage
			A1.2	Interdendritic shrinkage
			A1.3	Layer porosity
	A2	Gas-related defects and imperfections	A2.1	Air entrapment porosity
			A2.2	Hydrogen porosity
			A2.3	Vapor entrapment porosity
			A2.4	Lubricant and/or die release agent entrapment porosity
	A3	Filling-related defects and imperfections	A3.1	Cold joint
			A3.2	Lamination
			A3.3	Cold shot
	A4	Undesired phases	A4.1	Inclusion
			A4.2	Undesired structure
	A5	Thermal contraction defects and imperfections	A5.1	Cold crack
			A5.2	Hot tear, hot crack

B Surface Defects and Imperfections	B1	Shrinkage defects and imperfections	B1.1	Sink
	B2	Gas-related defects and imperfections	B2.1	Blister
			B2.2	Pinhole
	B3	Filling-related defects and imperfections	B3.1	Cold joint, vortex
			B3.2	Lamination
			B3.3	Cold shot
	B4	Undesired phases	B4.1	Surface deposit
			B4.2	Contamination, inclusion
	B5	Thermal contraction defects and imperfections	B5.1	Cold crack
			B5.2	Hot tear, hot crack
	B6	Metal-die interaction defects and imperfections	B6.1	Erosion
			B6.2	Soldering
			B6.3	Thermal fatigue mark
			B6.4	Ejection mark
			B6.5	Corrosion of the die

Table 4: Classifications for internal (A) and Surface (B) defects and imperfections (from [30])

4.1.1 Shrinkage defects and imperfections

4.1.1.1 A1) Internal shrinkage defects and imperfections

As the metal solidifies, if the cast isn't properly fed, the volume contraction it undergoes through its solidification can lead to a series of metal discontinuities scattered throughout its volume [31]. The areas in the cast that solidify last, due to improperly set directional solidification, are called "hot spots", and it's where most dissolved gases and imperfections end up getting pushed towards as the metal solidifies.

Shrinkage porosities form due to the surrounding metal solidifying first, leaving a hot spot that can't be properly fed by the liquid metal. They can also appear along the neutral thermal surface or axis of the casting, surfaces that solidify slowly due to the thermal gradient being lower than in the adjacent points.

They're characterized by a jagged, intergranular shape that follows the dendritic arm structure (see Fig.30). Their size can vary, going from extremely small inter-dendritic cavities, to bigger, macro cavities that significantly impact the structural integrity of the cast.

4.1.1.2 B1) Superficial shrinkage defects and imperfections

Surface imperfections caused by shrinkage consists mainly in sinks, which are surface depressions caused by hotspots located relatively close to the surface. As the hotspot solidifies, it shrinks, collapsing the surface layer in itself (see Fig.30).

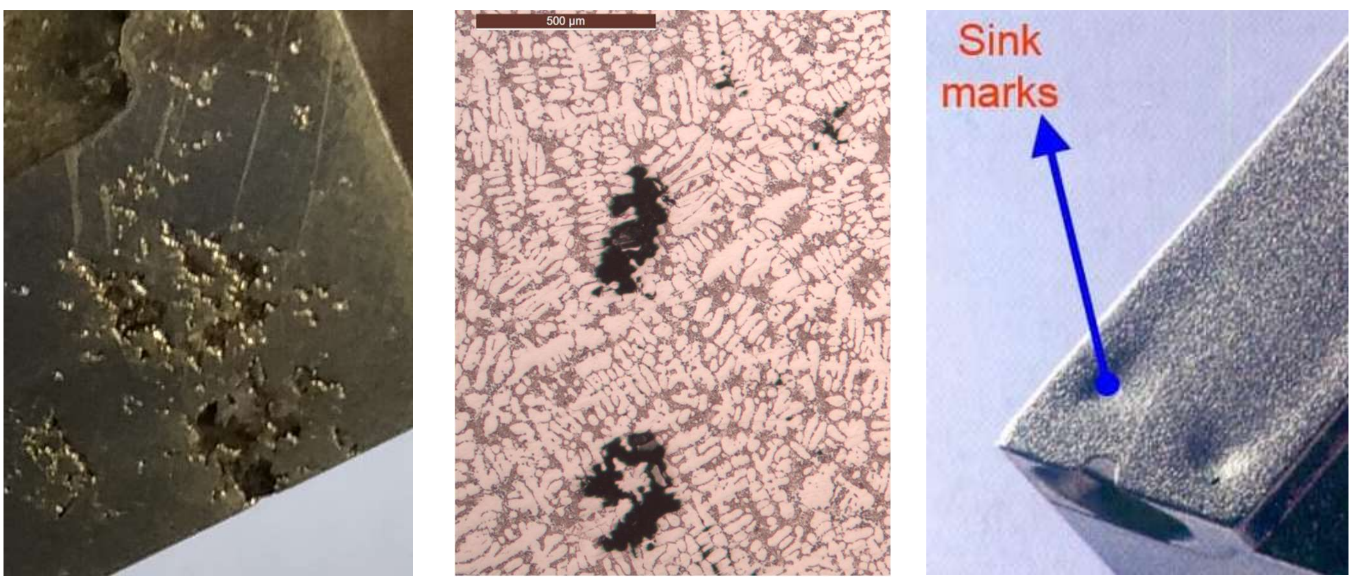


Figure 30: Example of internal shrinkage porosities on a macro level (left), on a micro level (center), and the macro level effect of shrinkage on the surface of a casting product (right)

4.1.2 Gas related defects and imperfections

4.1.2.1 A2) Internal gas related defects and imperfections

Gas related defects consists small cavities left by the entrapment of gasses in the liquid, usually caused by turbulence in the flow and improper venting system design. Their size can vary, going from small, microscopic round cavities, to bigger, elliptical macroscopic bubbles (see Fig. 31). The gases that can be trapped can be simple air, water vapor, lubricant, or hydrogen. When air gets trapped, inside the bubbles it's possible for a thin oxide layer to form, while for cavities cause by hydrogen entrapment that's not the case.

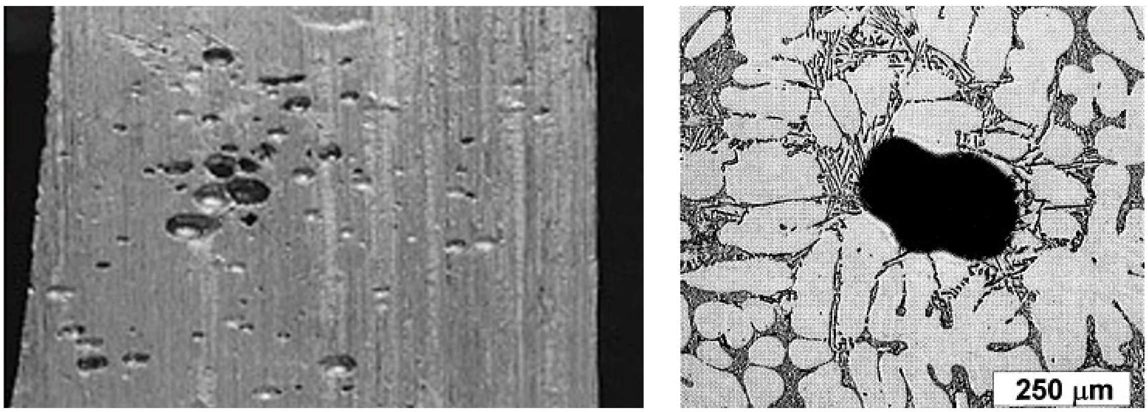


Figure 31: Example of internal gas porosities, on a macro level (left), and on a micro level (right)

4.1.2.2 B2) Superficial gas related defects and imperfections

Superficial defects caused by gas porosities, divided in blisters and pinholes. Pinholes are small, spherical bubbles, caused by the entrapped gasses, which show up on the surface and subsurface regions (see Fig. 32).

Blisters happen at high temperatures, either when the cast is being ejected from the mold or when the cast is going through subsequent heat treatments. They're small protrusions formed by the collection of underlying gasses below the surface, which push the solidified skin surface away while plastically deforming it.

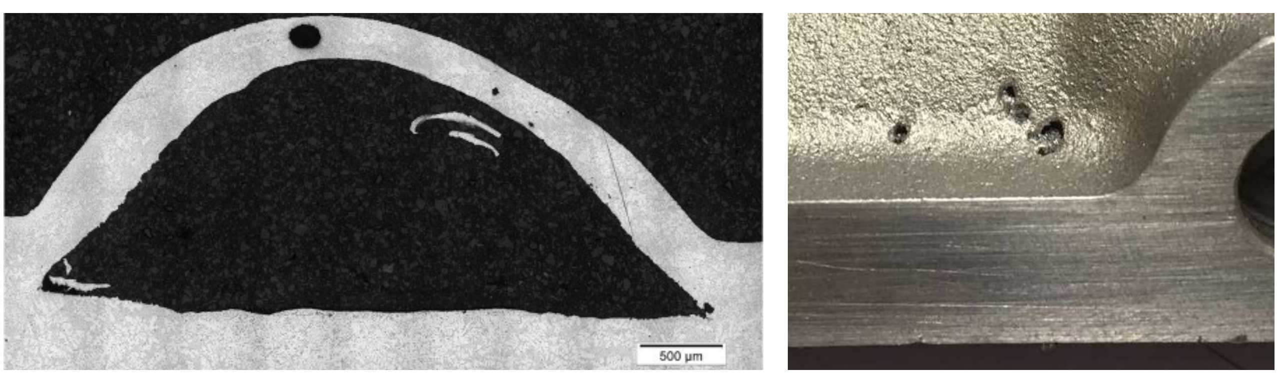


Figure 32: Example of B2 kind of superficial defects, with a superficial blister (left), and pinholes (right)

4.1.3 Filling related defects and imperfections

4.1.3.1 A3) Internal filling related defects and imperfections

Filling related defects consists in the family of defect caused by improper flow of the liqid metal in the casting cavity. If the distribution of the molten flow is not evenly distributed, it’s possible for the flow to separate in different streams and splash, solidifying at different rates and oxidizing before joining back to fill the cast (see Fig.33).

As the metal folds into itself, the different microstructures, along with the mixed oxide layers, cause discontinuities that impact the structural integrity of the cast, both inside the cast and on its surface [59].

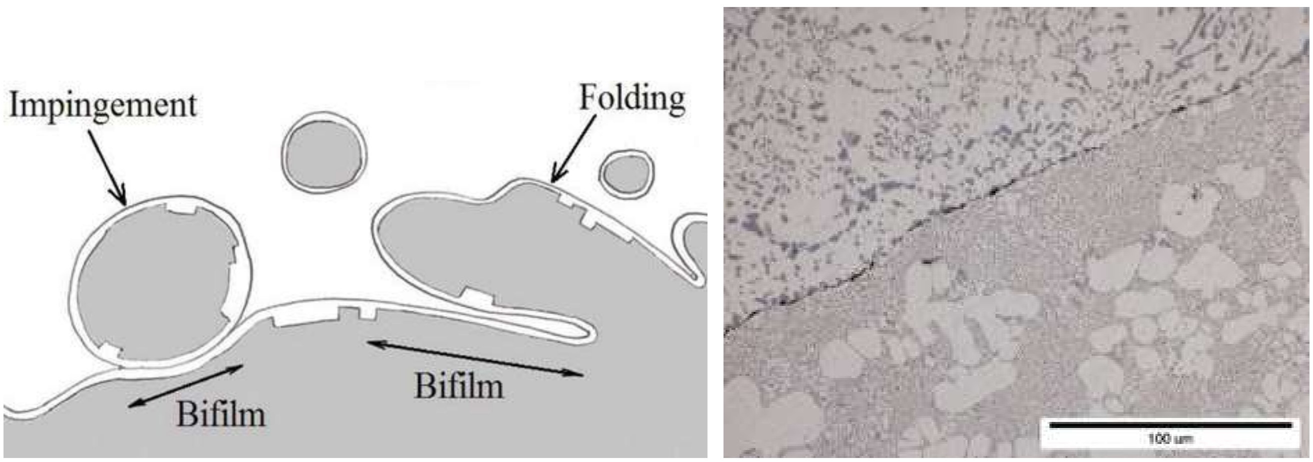


Figure 33: Example of the effect of an internal oxide layer discontinuing the crystalline structure

4.1.3.2 B3) Superficial filling related defects and imperfections

Similar to the phenomena described for internal defects, cold shuts and cold joints can be considered superficial defects if they display on the surface. Another filling related imperfection that’s predominantly a superficial defect consists in laminations, thin superficial layers similar to superficial cold shuts with an oxide layer separating them from the cast (see Fig.34). They’re caused by the fast solidification of the metal when it comes in contact with the mold surface.

Figure 34: Examples of cold joints (left, center) and surface laminations (right)

4.1.4 Undesired phases

4.1.4.1 A4 Internal and superficial undesired phases

This family of defects consists in all possible unwanted phases that end up in the structure or the surface, such as external particles and undesired microstructures of the material itself.

Inclusions of external particles have undesired qualities, such as high hardness and brittleness, that can impact the part's machineability and act as crack nucleation sites. These can consist in silicon carbide particles (refractory material that may have detached from the furnace) (see Fig.35), alumina particles (from the mold's coating), sludge, and aluminum oxide conglomerates.

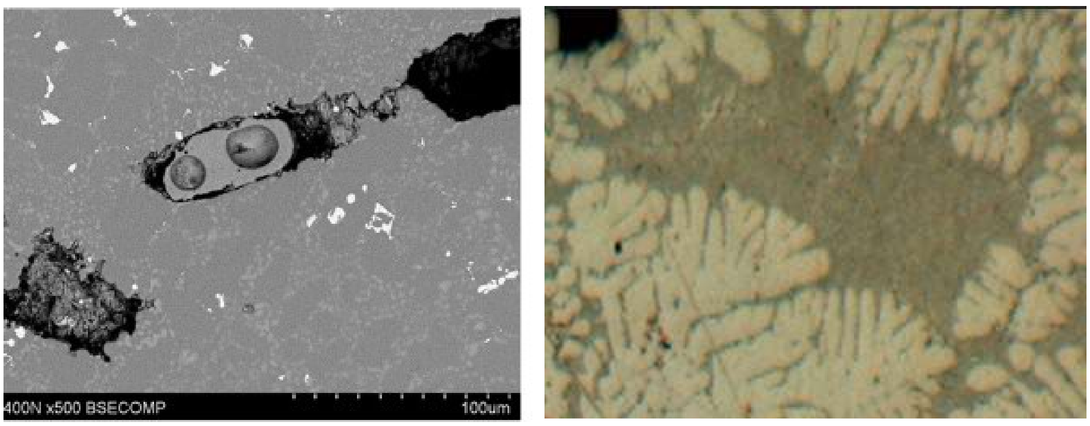


Figure 35: Examples of an inclusion (left), and a large second phase deposit (right)

4.1.4.2 B4) Superficial undesired phases

After the cast, it's possible for superficial deposits of other materials to adhere on the cast's surface, such as lubricants and die releasing agents like alumina, with different chemical composition and properties from the cast. It's possible also for the metal to react to the environment it's in, which may alter the cast's mechanical properties. These are called contamination defects and are identifiable from the different coloration the material assumes where the contamination has taken place (see Fig.36).

Figure 36: Example of a surface level contamination

4.1.5 Thermal contraction defects and imperfections

4.1.5.1 A5 & B5) internal and superficial thermal contraction defects and imperfections

Thermal contraction defects are defects caused by the volumetric contraction during the solidification of the cast. If the cast cavity does not allow for a free contraction of the cast and acts as a constraint (see Fig.37), or if there's inclusions and imperfections to act as nucleation points, it's possible for high stresses to locally develop and cause the cast to crack.

Figure 37: Hot tear displayed on a macroscopic level, caused by a geometrical constraint of the mold

If the material solidifies fast, the stresses need to surpass the aluminum ultimate tensile strength for it to crack. The crack will be intragranular and called "cold crack"
If the material solidifies more slowly, even light stresses can cause the material to crack. At high temperatures the tear will be intergranular and follow the dendritic arm structure (see Fig.38) and will take the name of "hot tear" [30].

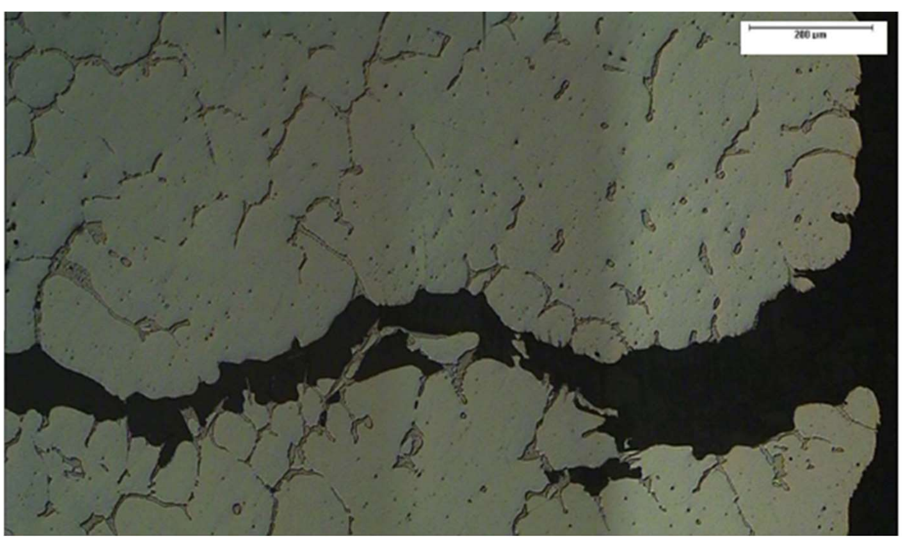


Figure 38: Hot tear analyzed on a microscopic level (image courtesy of STCast)

4.1.6 B6) metal die interaction defects and imperfections

The interactions between the cast and the die result in defects of different nature [30].

Erosion

Caused by erosion wear on the mold cavity after an high amount of cycles due to the high volumes of molten metal wearing down the die. Geometrical features of the cast cavity get eroded away, resulting in loss of dimensional shape, and higher volumes of liquid metal are required to fill up the mold.

Soldering

Caused by the adhesion of the alloy to intermetallic phases formed on the mold's surface . The cast ends up missing some of its volume, displaying a localized roughness in the areas where soldering has taken place.

Thermal fatigue marks

Due to the cyclical expansions and contractions of the mold, small thermal fatigue cracks end up forming on the surface of the mold. These cracks imprint on the cast, resulting in a series of thin reliefs sometimes called turtle marks (see Fig.39).

Ejection marks

As the mold cavity wears down, its geometry might get altered and the draft necessary for proper ejections might disappear, resulting in undercuts and plastic deformations on the cast as it gets ejected from the mold.

Die corrosion

Superficial roughness on the casting imprinted by a corroded surface on the mold.

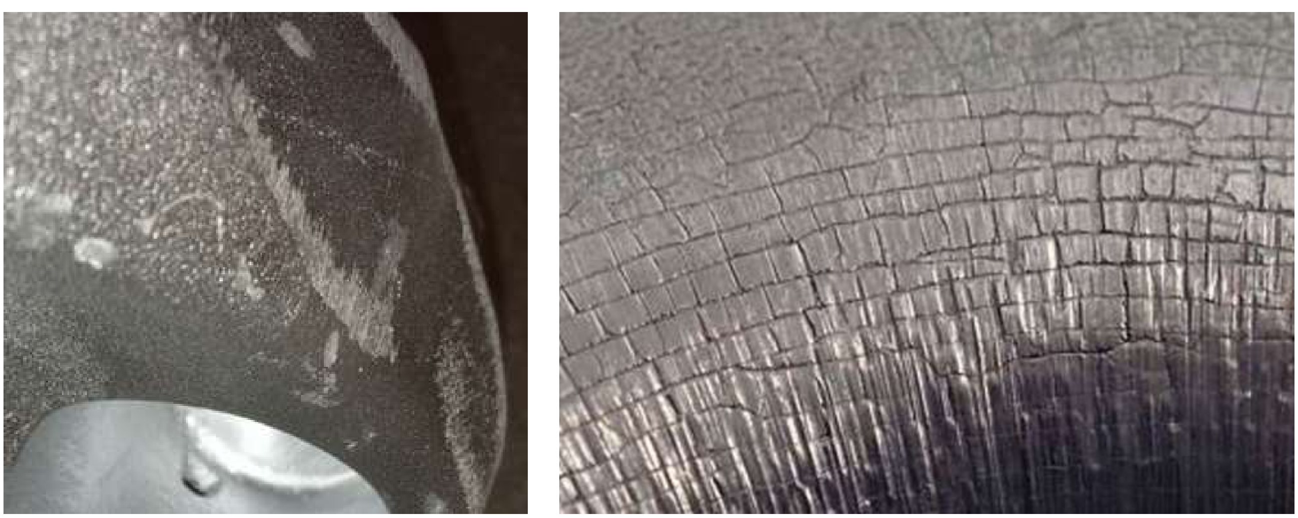


Figure 39: examples of ejection marks (left) and thermal fatigue cracks (right)

4.2 Geometrical defects and imperfections

1st Level	2nd Level		3rd Level	
C **Geometrical Defects and Imperfections**	C1	Lack of material	C1.1	Incompleteness
	C2	Excess material	C2.1	Flash
	C3	Out of tolerance	C3.1	Deformation

Table 5: Classifications for geometrical (C) defects and imperfections (from [30])

4.2.1 C1) Lack of material - Incompleteness

The final cast results incomplete, with missing material from its complete geometry. The incomplete filling of the cavity can be due to the lack of sufficient material being poured in the mold, or caused by an excessive viscosity of the liquid metal. Usually happens in the first few production cycles as the operator sets up the casting machine parameters.

4.2.2 C2) Excess material – flash

Some of the molten metal can spill out of the cavity between the die halves, requiring more volumes of molten metal to fill in the cast cavity (see Fig.40). This can be due to the mold wearing down, resulting in the two mold halves not sealing properly, or due to insufficient clamping forces.

4.2.3 C3) Out of tolerance – deformation

Caused by deformations from the thermal contraction, especially evident parts with complex geometries having thin surfaces adjacent to bulkier geometries.

Figure 40: Example of incompleteness defect (left), and flash defect (right) (image courtesy of STCast)

Experimental research

5 Part in analysis, process, and production problems identified

The company where the work of thesis took place was STCast SPA, an Italian company specialized in the gravity die castings of aluminum alloys for the automotive industry sector. The company is located in Rivoli, Torino (see Fig.41), and boasts a global market selling products in USA, Brazil, Spain, France, UK and Italy. In terms of quality, the company is IATF and ISO-9001 certified.

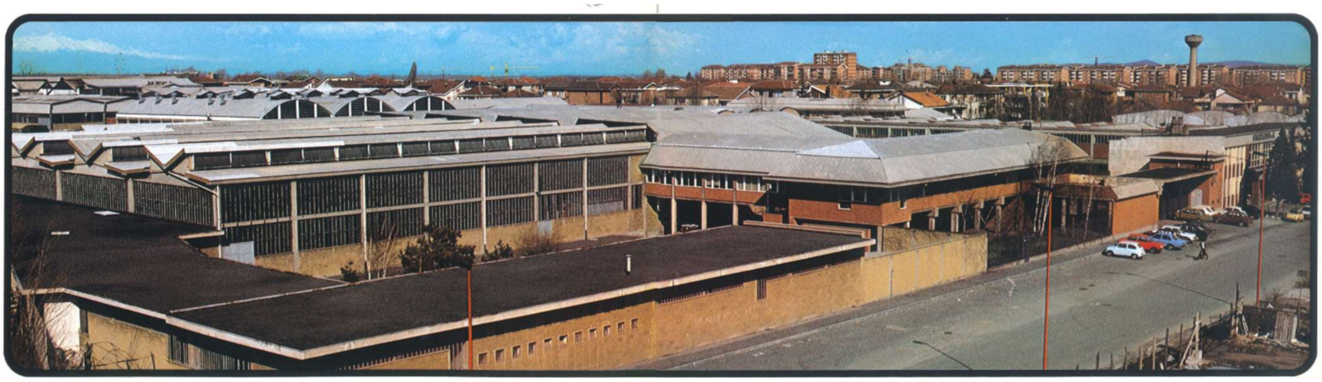


Figure 41: Picture of the premises where the work of thesis took place

In this work of thesis, the main focus is put on one of their manufactured product with a problematic production process (see Fig. 42). The goal is to identify the nature of the defects that arise throughout its production and to find a solution for them through an experimental analysis performed on the production run.

Figure 42: Manufactured part in analysis, the oil cup of an industrial engine

5.1 Manufacturing process

To be able to identify the nature of the defects and how they originate, it’s important to fully understand all the different operations the alloy goes throughout the production run. This chapter will illustrate the manufacturing process for a typical casting produced in STCast in its entirety, from the ingot’s smelting to the shipment of the finished parts.

5.1.1 Alloy composition controls

The aluminum alloy starts in the form of an ingot, bought in pallets from qualified external suppliers. After being labelled and classified, these are stored on company grounds and covered in tarp to protect them from the external elements.
Before being sent to the furnaces, several samples per shipment are controlled and their composition analyzed in the company’s laboratory to fully map their composition (see Fig.43).

The spectral analysis, performed trough a spectrometer, allows to determine the proportions of all the elements present in the sample.

The machine works by applying an elevated tension between an electrode and the metal sample, which will cause a continuous spark emission that will locally vaporize the metal. The different vaporized atoms will emit photons depending on their characteristic wavelengths, due to the quantum leaps between the electron’s energy levels of the different elements. The emitted photons are then collected and classified by a spectrophotometer, which allows to identify the elements present in the alloy and their percentages.

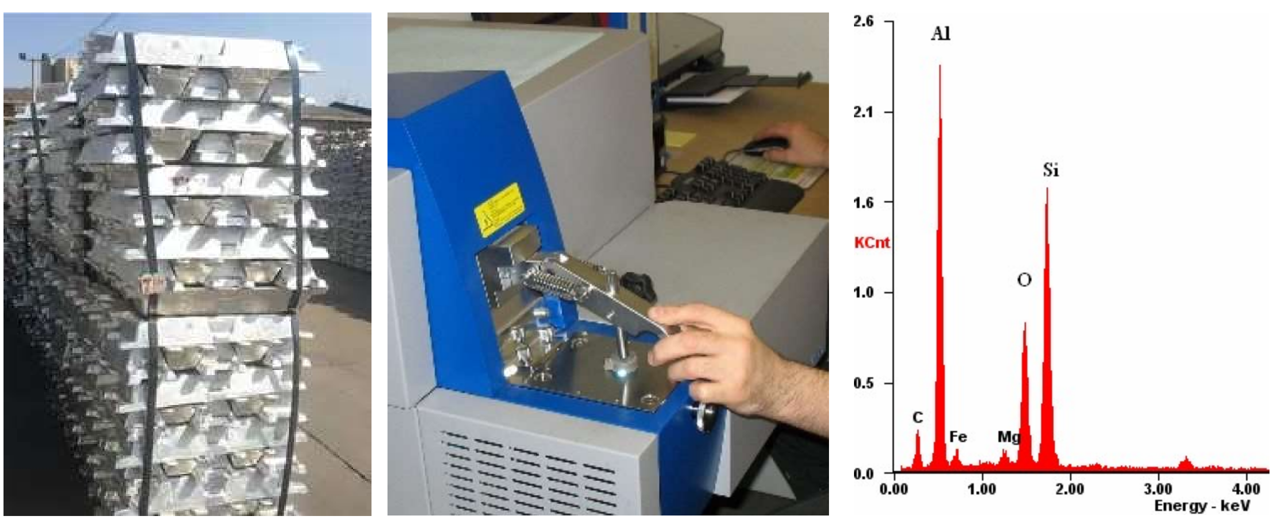


Figure 43: How the aluminum ingots arrive at the company (left), a spectrogram analysis machine (center), and the result chart of a typical spectrogram (right)

5.1.2 Melting operation

The melting of the aluminum ingots is performed through an induction furnace. The ingots are melted along with other aluminum scraps coming from post-machining operations (burrs, risers, runners, defective parts, etc) in quantities that are decided based on the daily production demand. The ratio of scrap-to-ingot fed into the furnace is usually around 50 to 50%, but the scrap percent can vary from 0% (meaning that only ingots are molten) up to 70% of the total furnace's intake. This process needs to be carefully tracked, as the alloying elements present in the scraps may slightly differ (either in quantity or composition) from the elements present in the ingots, thus altering the final alloy's composition. STCast operates mainly with two different alloys, A356 (Al Si 7 Mg) and A328 (Al Si 9 Cu 1 Mg), each of which will have their own dedicated furnace, to avoid mixing the compositions.

An induction furnace is an electrical furnace where the material is molten trough an induction heating process. The furnace consists in a crucible lined with refractory material, surrounded by a water-cooled copper solenoid, that will act as the primary circuit, while the metal inside the crucible will act as the secondary instead (see Fig.44).
Compared to fuel-fired furnaces, induction furnaces are more efficient and offer a more controlled, pollution free melting process with minimal drossing.

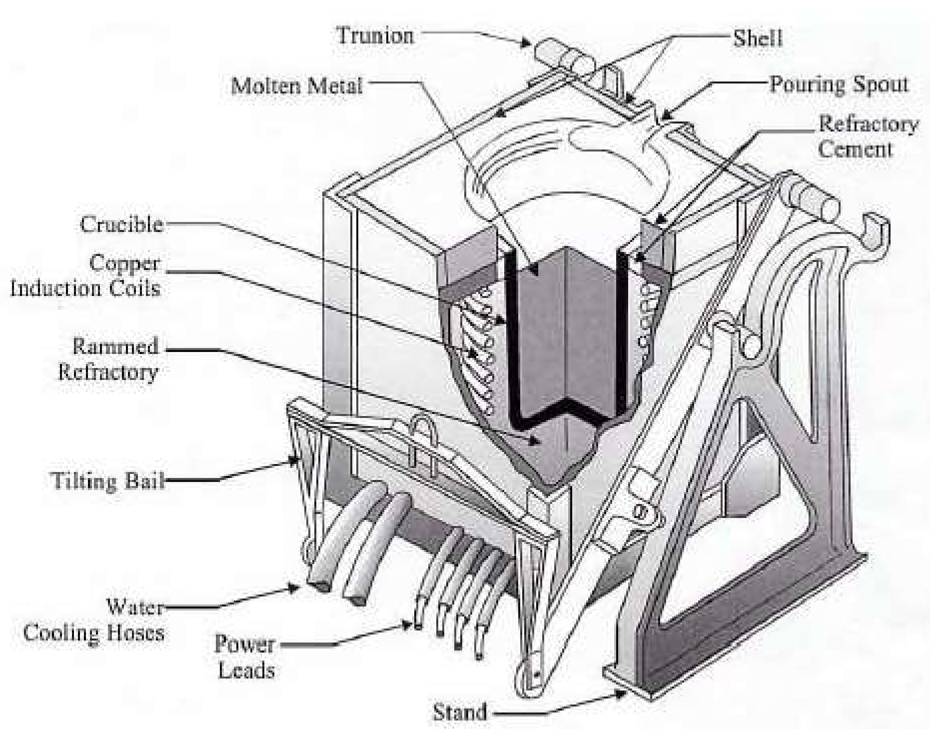


Figure 44: Schematic of a typical induction furnace, like the ones used by the company

5.1.3 Degassing and drossing

After being melt, the molten alloy is taken from the furnace into a steel crucible where it will be degassed. Degassing is the process through which it's possible to reduce the amount of dissolved gasses in the melt.

STCast adopts a rotary impeller degasser, that consists in a steel lance connected to a mechanical drive, which creates a shaft/rotor assembly that will rotate while injecting nitrogen bubbles at the bottom of the crucible (see Fig. 45). As the nitrogen bubbles get dispersed through the liquid, the gas dissolved in the alloy will be attracted towards them since their partial pressure in the bubbles will be null. The undesired gasses dissolved in the melt, mainly hydrogen, will then be driven from the liquid into the nitrogen bubbles by diffusion forces. As these bubbles rise, they'll pick up more and more undesired gasses until they reach the surface and escape.

The gas injection system consists in a disk divided in a series of vanes that will spin very fast while dispersing the nitrogen gas stream into fine gas bubbles. It's important for the bubbles to be extremely fine and well distributed in order to have an efficient degassing process.

One of the downsides of degassing is that it can cause elevated levels of drossing. Drossing consists in the accumulation of oxides, such as (aluminum oxides, MgO, SiO2, CuO, etc.) on the molten metal's surface. As the nitrogen bubbles reach the surface, they'll expose more and more of the molten alloy to the atmosphere, resulting in a continuous formation of different oxides.

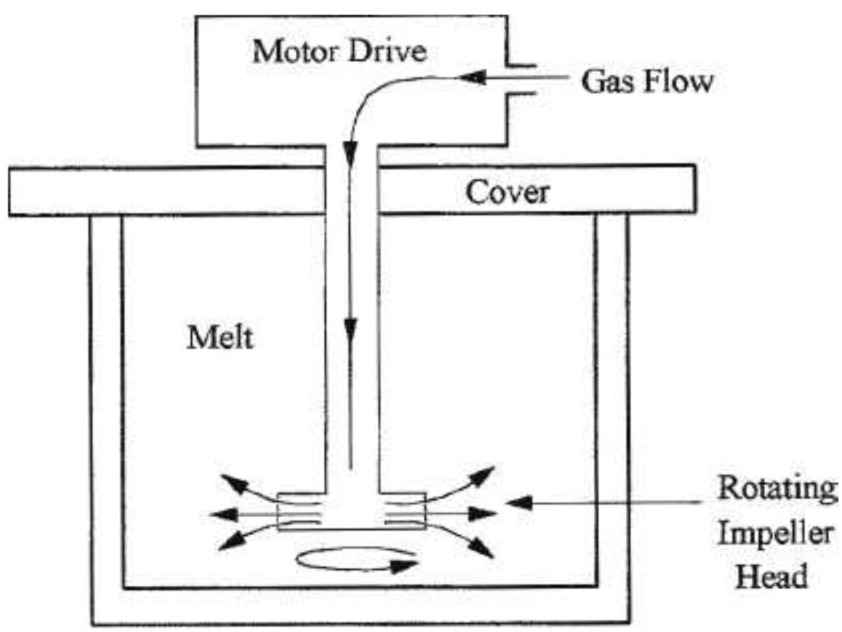


Figure 45: Schematic representation of a rotary impeller degasser. The inert gas bubbles are injected at the bottom of the melt, and as they rise through the molten metal they collect the other gasses dissolved in solid solution cause of diffusion phenomena.

5.1.4 Operative cycle

After degassing, the molten alloy is taken to the automatic gravity casting island (see Fig.46). Here it will be poured in the holding furnaces, which are refractory-laden crucibles that keep the temperature of the molten alloy at the optimal casting temperature (~ 720° C).

When casting a part, as the solidification in the mold can take different minutes to finalize, in order to increase the efficiency of operations the station can work on different castings at the same time. It's possible to install different holding furnaces side by side in order to cast parts made out of different alloys on the same island.

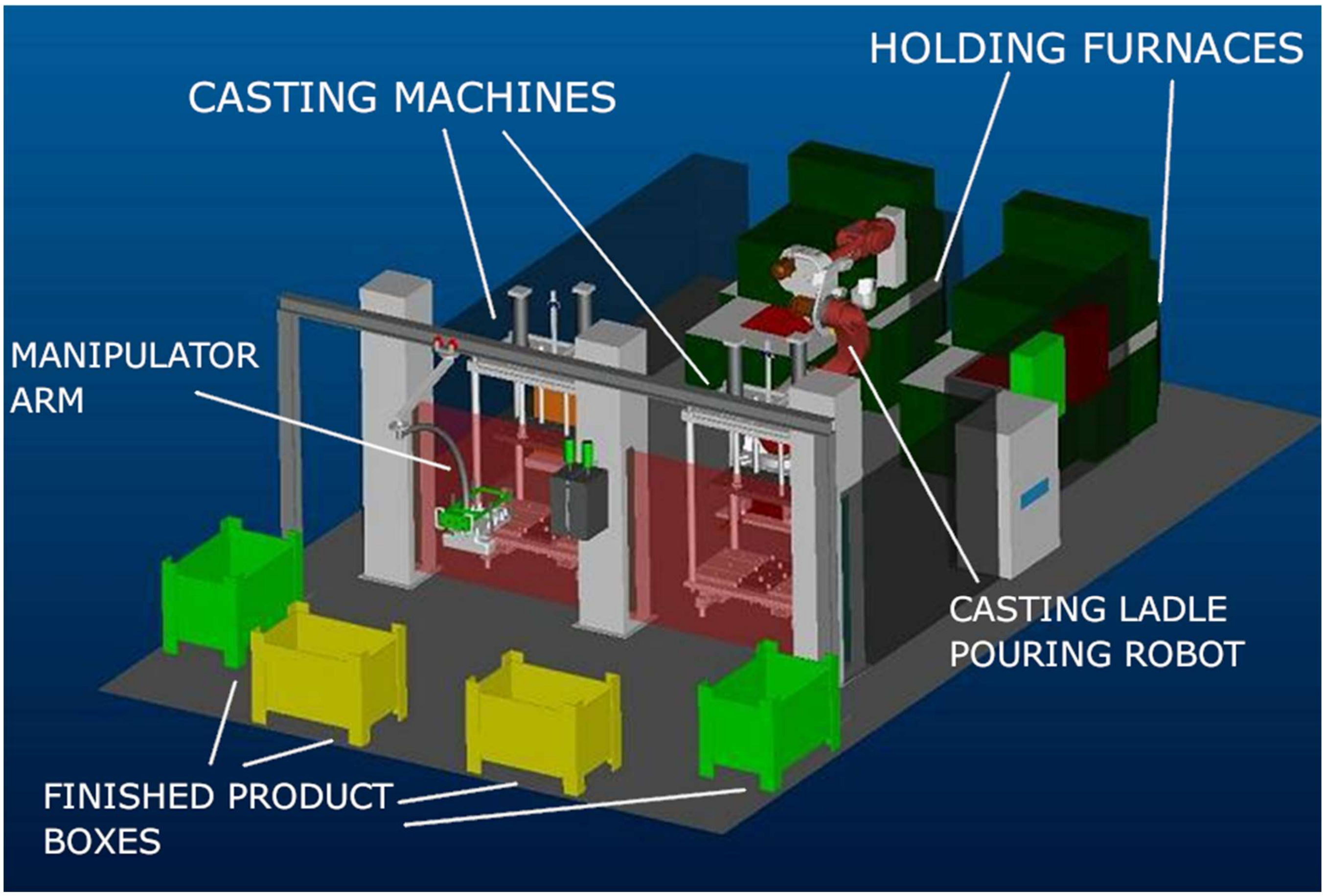


Figure 46: 3D model of a production island, with each of its components (image courtesy of STCast)
The robot arm designated to pour the molten metal will take the molten metal from the holding furnace to the casting machine according to its pre-programmed cycle

A typical operative cycle will take 4 to 7 minutes, depending on the casting's size and complexity of operations, and it will look like the following:

1. On the first pouring, the mold must be preheated to at least 150° ~ 200° C first in order to reduce thermal damage and ease the melt flow. In regime, with each subsequent casting, the mold's temperature should stabilize at ~ 330° C (although it can go up to ~ 450° C around the sprue).

2. The mold halves start open and an operator applies a detaching agent, which will help with the extraction of the part extraction. If needed, it's possible to stop production to refreshen the mold's refractory wash.

3. After applying the detaching talc, the operator manually installs the necessary cores and inserts in their respective positions, along with any filters in the gating system. The pneumatic system then pushes the sliding cores into position then clamps the mold halves shut.

4. From here, a robotic arm is programmed to pick up a pre-determined amount of molten metal with a pouring ladle, and pour it in the mold down the sprue. The solidification can take 60 to 180 seconds to occur, depending on the casting's size and alloy composition.

5. After the part has solidified, the mold halves can open and the ejector pins push out the part away from the mold. It's important for the halves to open as soon as the solidification is strong enough to be safely ejected to prevent hot tears due to volumetric shrinkage from happening.

6. The operator takes the part away from the open mold into the finished-product area with the help of a manipulator arm. The operator then can clean the mold halves from any debris, clean the venting system and the risers from being obstructed with a pressurized air jet, and the cycle can begin again.

To optimize the production, a single operator can work on multiple castings on the same island. The cycle is repeated until enough quantities are casted to meet the short-term production demand. Once the production run is over, the mold can be taken off of the machine and a different one can be installed to start the production of a different batch of castings. Maintenance is performed on the mold while it's off of the machine, such as the application of the refractory wash along with any necessary repairs or modifications.

5.1.5 Post-casting operations

Parts produced trough gravity mold casting technology more often than not come out of the mold near net shape, requiring only some trimming operations to remove the gating system and possible flashes in order to be considered finished. Nonetheless, more complicated productions may need a series of different post casting operations in order to obtain the finished part. Some of the most common practices employed in STCast are listed below

5.1.5.1 Shakeout

Semi-permanent mold casting makes use of expendable sand cores to make internal cavities that wouldn't have been possible to obtain otherwise. Shakeout operation consist in a percussive hammering of the casting which will break the sand cores into lumps, separating them from the casting walls. The cast is then collected and recycled in order to make more cores for successive production runs.

5.1.5.2 Trimming operations

Trimming operations consist in the removal of the gating system and any possible flashes with the use of mechanical tools. Gates and risers can be removed either manually, with hammers and wedges, or through the use of power tools like band saws and grinders (see Fig. 47).

5.1.5.3 Shot blasting

In order to improve the surface finish, conceal the marks left by the trimming operations, and remove any remaining casting sand, the castings will be cleaned in batch-type blast machines. Batches of different components will be inserted into a chamber where they'll be blasted with sand streams until the entire surface of the casting reaches homogenous levels of rugosity. This operation is performed before any finishing machining operations in order to comply with the rugosity levels established by the design.

5.1.5.4 Property enhancing treatments

Although the properties of the casted parts are already very good as-cast, it's possible to further enhance their properties trough post casting heat treatments. Depending on the goal set by the design, heat treatments can be used to increase machineability, improve mechanical and technological properties while homogenizing them throughout the casting's volume. Most common heat treatment for aluminum casting alloys have been illustrated in detail in the 1.4 chapter.

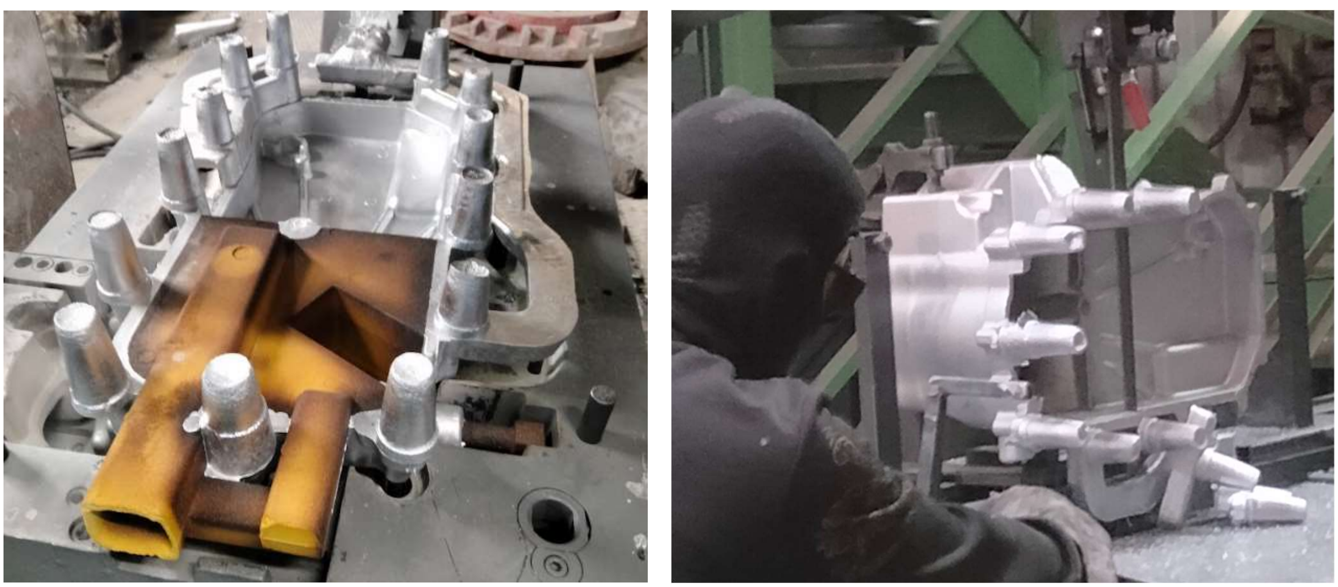


Figure 47: Image of a casting as it exits the mold, with the gating system still attached (left), and picture of an operator removing risers with a band saw in the post-casting operations department (right)

5.1.6 Inspections and testing

Castings can have visible or hidden defects, illustrated in chapter 4, which can be more or less impactful depending on the casting's application. Some small internal imperfections can be accepted with the client's approval if they don't interfere with the casting's functionality, but for critical components with important safety factors it's essential for the casting to be imperfection free.

Different inspection practices have been devised in order to identify the presence of defects in the casting, whether they're visually detectable or not. If the imperfection is caught internally the part can be simply repaired or recycled and the company will just put up with the production cost, but if the imperfection is caught by the client it can end up hurting the client-supplier relationship and cause damage. For example, STCast sells both finished and semi-finished castings, where the client will perform the final machining operation on the semi-finished product themselves. If there's hidden imperfections in critical areas, after the machining operations the client can end up exposing these defects themselves, thus having to reject the part. Therefore, it's important that each casting is thoroughly inspected to assure the quality of the finished product beforehand.

Out of the different inspection and testing practices, the most commonly performed at STCast are the following:

- Visual and dimensional inspections
- Leakage tests
- Radiographic examination
- Penetrant dye inspection

5.1.6.1 Visual and dimensional inspections

Depending on the morphology, some defects are immediately detectable just trough visual inspection, such as cracks, blisters, sinks, laminations, runouts, cracked sand cores and others. With it being the simplest inspection method, it can be performed in every stage of the manufacturing process, from the foundry to the post casting machining, to the quality control. Each operator is trained to identify the most common defect pertaining to their operations, and will reject the part if any visible defect is detected before further operations can be done on the part.

While visual inspections can be performed in every stage of the manufacturing process, dimensional inspections are performed mainly in the quality control department. Here, amongst other controls, it's possible to perform quick dimensional controls through the use of gauges. Different gauges allow to check for different shape dimensions, such as height gauges, depth gauges, go/no-go gauges, contour gauges etc. On a representative sample, it's possible to section a part to see whether the section thickness dimensions are respected or not. Although these controls can't fully confirm that the part is up to standard, they can quickly give an answer on whether the most critical dimensional tolerances are respected or not.

5.1.6.2 Leakage tests

Some castings are made for fluid retaining parts (oil cups, air pipes, etc.) therefore the castings need to be pressure tight and display no leakage. Pressure tests, or leakage tests, are inspection tests that allow to locate the presence of passing porosities in the casting. This test can be performed in different ways (air-to air configurations, fluid injection configuration, water immersion configuration, etc.) which can be either manually or automatically performed.

This test will be performed on both finished and semi-finished castings. For fluid retaining parts, STCast employs a water immersion configuration described below.

1. Every opening of the part except for one will be bolted shut and the part will then be secured to a backing plate.

2. On the one opening left, a nozzle connected to the pneumatic circuit will inject compressed air into the casting to bring the internal pressure to levels that far exceed the operating conditions. The pressures reached are usually either 3 or 5 bars, depending on the normative followed and the client's requirements.

3. The part is then submerged in a water tank for a period of 3 to 5 minutes. An operator is tasked to check for any bubbles escaping from the casting's surfaces. If a stream of bubbles is detected, the test is over and the part is rejected (see Fig. 48).

4. If the part stays in the water tank for the full duration of the test without showing any leakage, it's considered compliant. The backing plate is lifted from the water tank, the openings are freed and the pressurized air is allowed to escape.

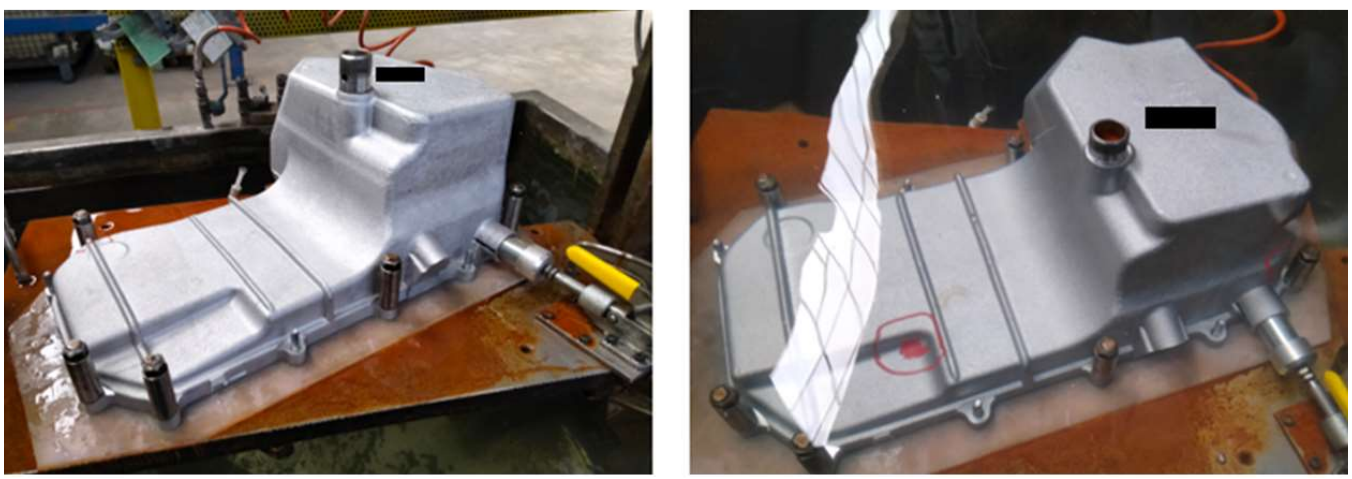


Figure 48: Picture of a part undergoing a leakage test, showing it getting sealed first (left), then submerged in water (right). Compressed air will be injected inside at a pre-determined pressure and if any bubbles are detected rising through the part's surface the cast is considered defective

5.1.6.3 Radiographic examination

A radiographic examination is a non-destructive test which allows to detect the presence of many hidden, internal defects, such as shrinkage porosities, entrapped gasses, internal hot tears and cracks, cold-shut surfaces, etc. The test can have different configurations (x-ray or gamma ray, analog or digital, etc), STCast employs a real time X-ray machine (see Fig. 49).

The test consists in converging X ray beams towards the casting (placed in a secure chamber), which will dissipate in proportion to the amount of material the beam goes through. The beams will then imprint a shadowgraph of the internal structure of the casting on an imaging device placed behind the part, which will send the received image directly on a screen for analyzing.

Figure 49: Picture of a real time X-ray machine as it's being used to analyze a part for internal defects

The energy of the beams will attenuate in proportion to the quantity of material they go through. Lighter areas represent higher levels of transmitted energy, meaning that any shrinkage or porosity will show up as light spots on the screen, contrasting with the darker areas representing thicker, denser sections.

5.1.6.4 Penetrant dye inspection

Penetrant dyes are an alternative, low-cost inspection method used for the detection of small surface defects that wouldn't be possible to detect with a simple visual inspection, such as hairline cracks and thin lapping defects. The test consists in the application of two different dyes, one with a low surface tension, and one that acts as a developer (see Fig. 50).

1. The penetrant fluid (red) is applied on the tested area, which will infiltrate into any possible fissure by capillary action.
2. After a certain amount of time has passed, the excess fluid is washed off.
3. A chalk-based developer (white) is applied on the tested area.
4. If any defects are present on the tested surface, the developer will draw out the penetrating fluid from the fissure, highlighting the defect.

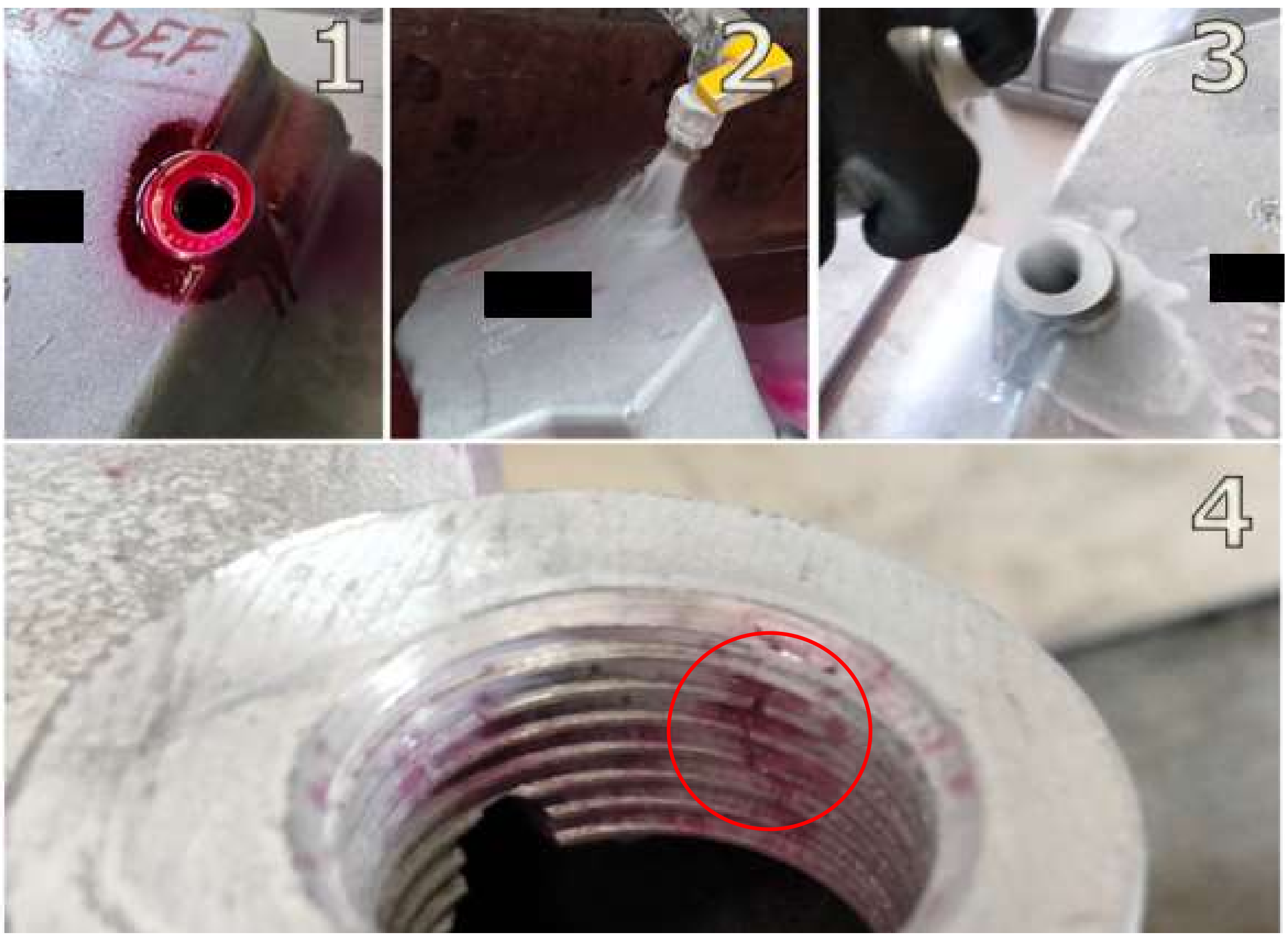


Figure 50: Pictures displaying the steps to perform a penetrant dye inspection. In this example, after the developing dye is applied, it's possible to see a thin superficial crack on the threading of the cap area, that would have went unnoticed without the dye test.

6 The oil pan

In this work of thesis, the main focus is put on the part with the most problematic production. Out of all the different parts produced by the company, this one results to be the one with the highest amount of rejected parts, both internally and by the client. In the last year around 43% of internally produced parts have been rejected due to misruns and other internally identifiable defects and, out of all the units sold, around 13% have been rejected and sent back to the company by the external client requesting the part. These numbers are far higher than what's acceptable by company standards, especially the number of parts rejected by the client, which ends up severely hurting the client-supplier relationships.

The part in analysis is an aluminum casting identified with the internal code CH 417, destinated for use in internal combustion industrial vehicles as an engine oil pan. The part is obtained through gravity mold casting, and it's characterized by a medium size and a semi-complex geometry (see Fig. 51).

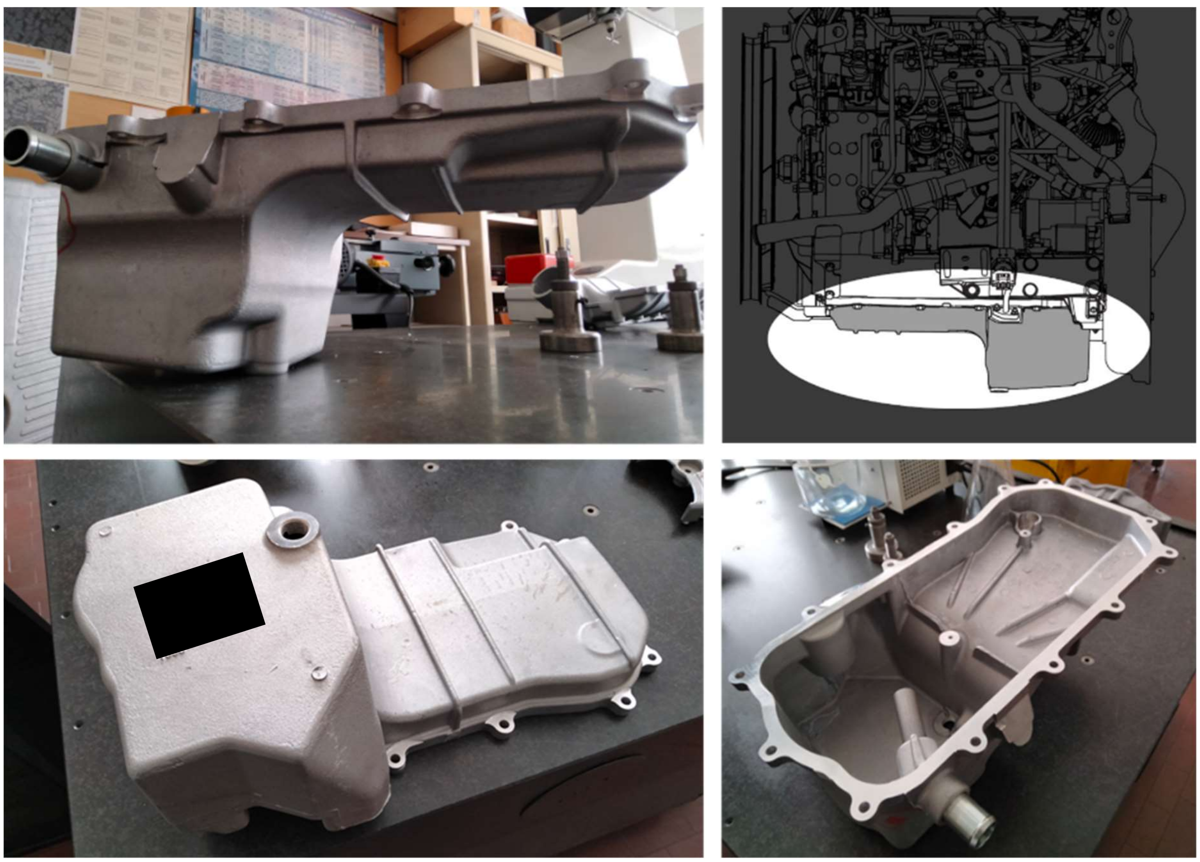


Figure 51: The oil cup, the component in analysis in this work of thesis.

With it being a fluid retaining part, the company must be able to guarantee not only the mechanical properties and dimensional tolerances of the castings, but also their pressure tightness. Water immersion leakage tests are carried out on each produced piece to guarantee the absence of passing porosities in the finished part before being able to sell it to the client.

6.1 Quality problems

After being cast, the part is rigorously checked and tested in the quality department to look for the presence of any possible defects. The part undergoes visual inspections, each part is tested for leakage, and sample X-ray inspections are performed on batch productions to look for any internal defects.

After the casting, trimming, and sandblasting operations, along with all the inspection procedures, the part is ready to be sold as a semi-finished casting. The final machining operations required to bring the part to its finished condition (milling, threading, etc.) are performed by the client. The 3D model in Fig.52 highlights in yellow the surfaces which will be subsequently machined by the client.

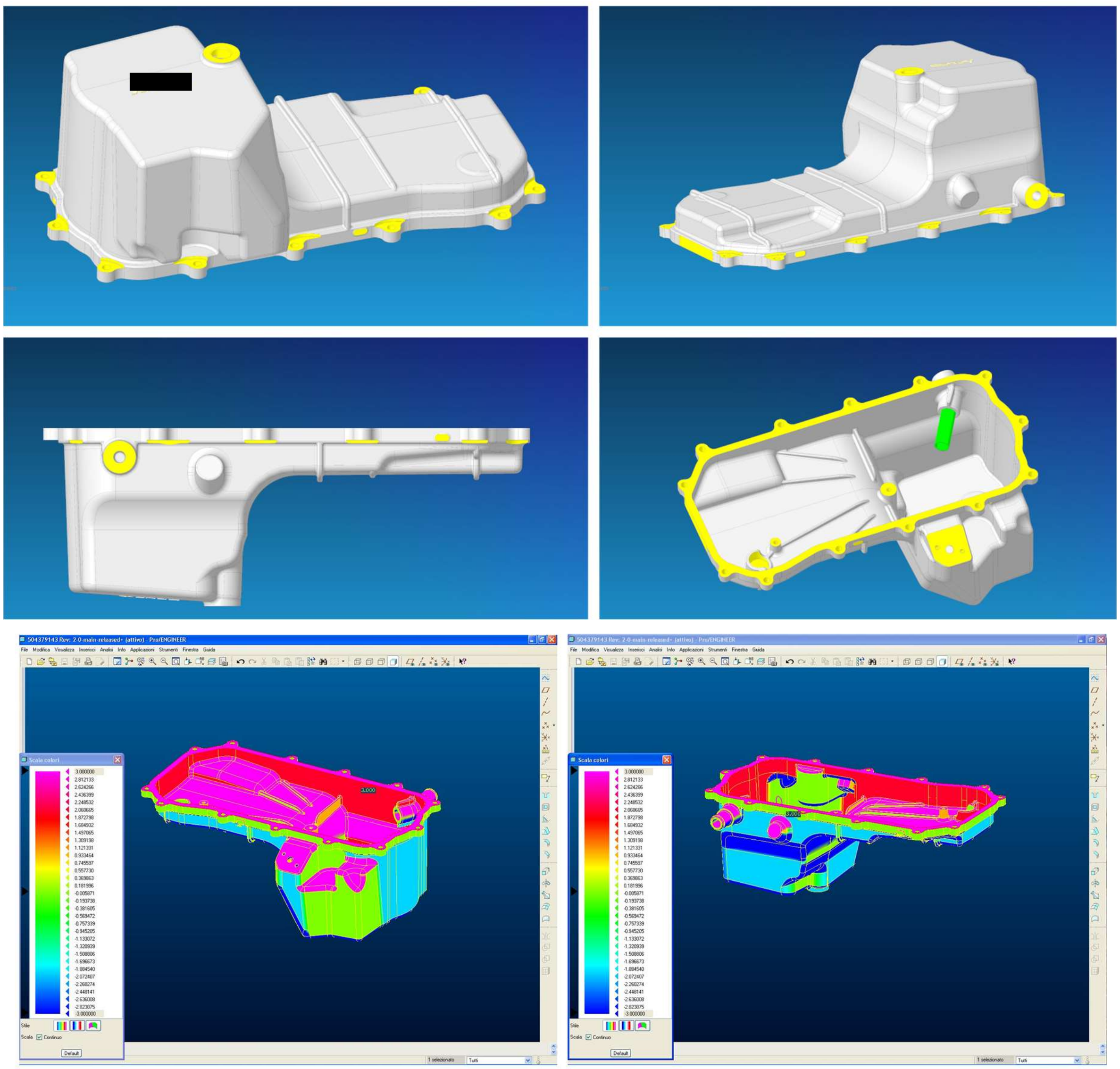


Figure 52: 3D model of the casting, highlighting the subsequently machined surfaces in yellow (top) and the drafting angles (bottom) with red highlighting positive angles, and blue for negative ones

Out of all the units sold, 13% of them get rejected by the client, of which 8% (variable) get rejected due to the presence of a crack propagating from the threading into the oil cap area, while 4% fail the leakage test, and 1% displays other problems (deformations, machining mistakes, sinks, etc.). Out of these, the defect which requires the most immediate attention is the crack's presence in the oil cap area, which compromises the pressure tightness of the casting. It's very important to find the source of this defect and devise a solution.

Figure 53: How the critical area will look post-machining. On the left is how the part looks as it is sold to the client, on the right how it looks after the client performs the machining operations

The presence of this crack is hidden by the bulk material surrounding the compromised area (see Fig.53). After passing the visual inspections and leakage test, the part is sold in semi-finished conditions to the client, which will bring these defects to the surface through their own machining operations (see Fig.54). Since X-ray inspection is only performed in sample tests for every batch, it's difficult to reliably catch these internal defects when only 8% of the units sold display them. In order to suggest a solution for this problem, the true source of this crack needs to be identified, further analysis is necessary in order to fully understand the nature of the defect, and why it happens only in 8% of the casted parts.

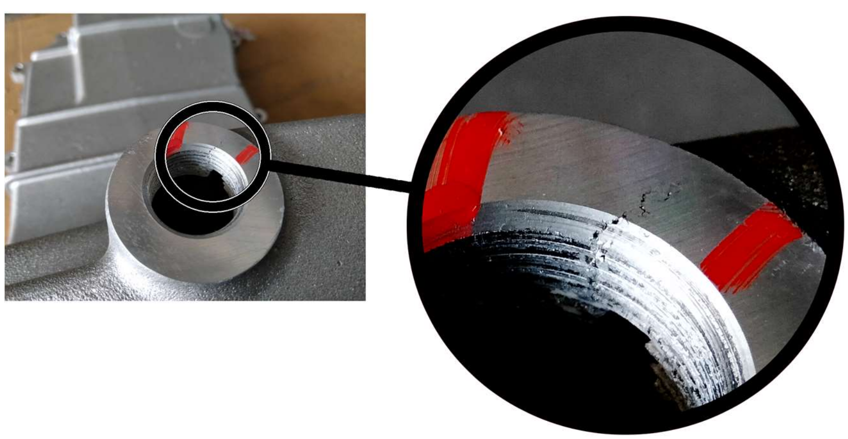


Figure 54: Detail showing how a typical internal crack defect appears after the machining operations

6.2 The mold

The mold in which the part is cast is installed on vertically parting machine, and it features a parting line gating system, with a splitting runner distributing the metal throughout the perimeter of the casting (see Fig.55). On the top half of the die, 12 open runners are distributed alongside the perimeter of the casting cavity in order to counteract the casting's volumetric shrinkage, while also acting as the venting system at the same time.

The mold that produces the part is made out of Superplast material, a proprietary steel alloy by Usinor Industrial specific for molds due to its thermal stability, with its main alloying elements being (in weight percent) [32]: 0.25% C , 0.20% Si, 1.30% Mn, 0.02% P , 0.06% S, 1.30% Cr, 0.40% Mo, +B.

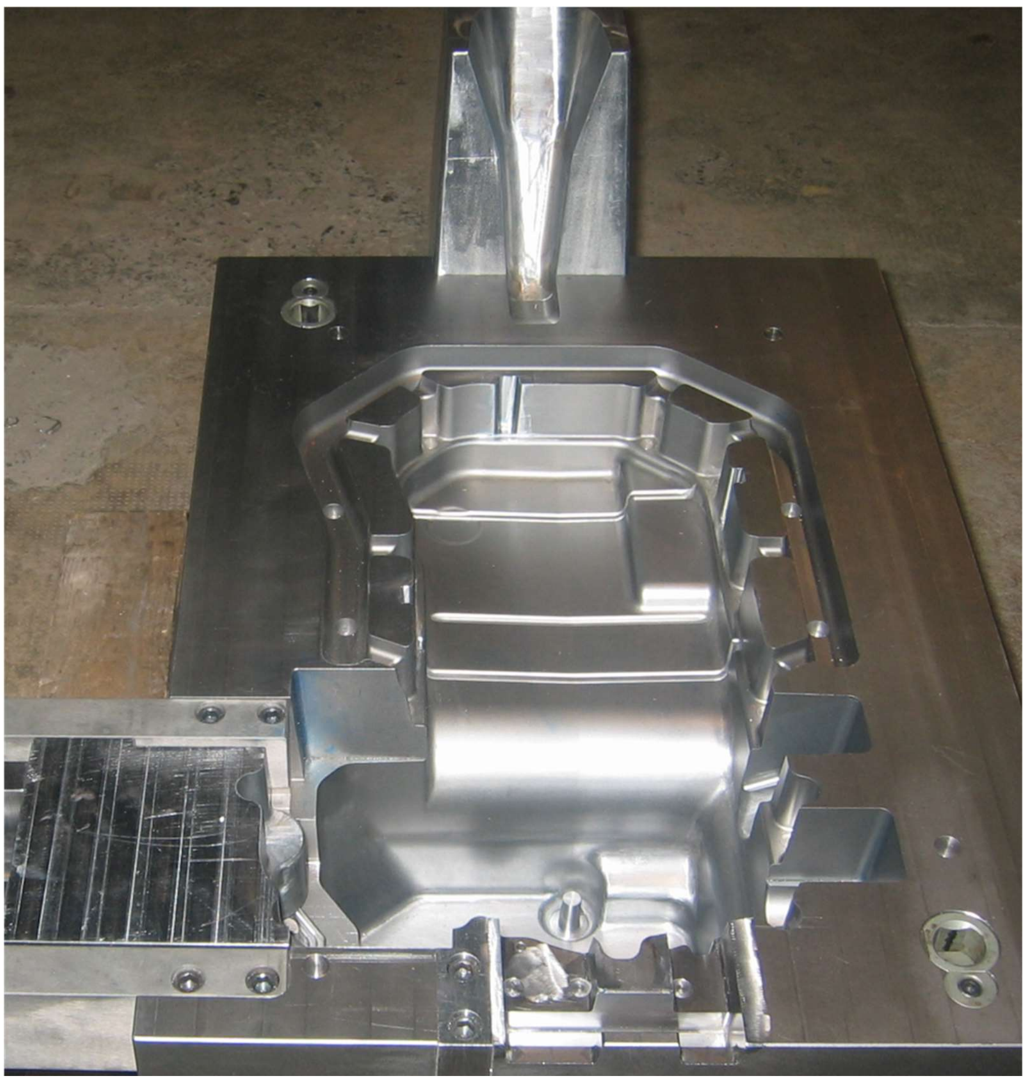


Figure 55: The bottom side of the mold. It's possible to distinguish a parting-line gating system, with the runners feeding the material from the sides. On the side (left), a pneumatically activated slide is used to achieve a particular undercut

The part requires a metal insert (bent pipe) by design at the bottom of the internal casting cavity, making it necessary to use a sacrificial sand core. The sand core is produced in-house by STCast, must be inserted along with the metal pipe before the mold closes (see Fig. 56), and will be removed through shakeout operations in the post-casting phases. The part also presents an undercut, which is obtained through a pneumatically activated sliding vane that will be activated before the mold closes and disengaged before the cast can be ejected.

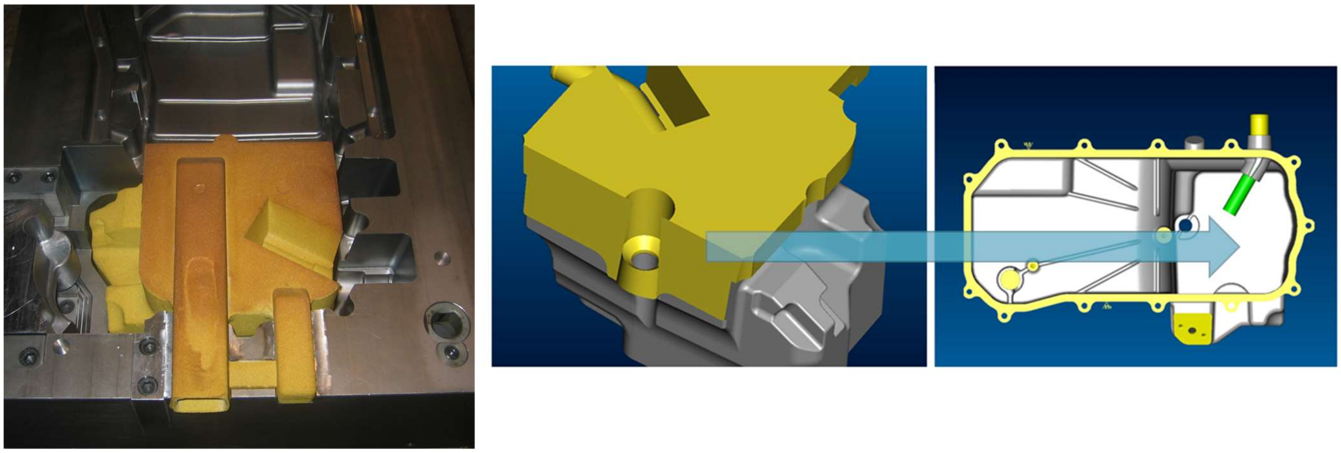


Figure 56: Picture of the sand core positioned in the mold, and its 3D model in the simulation. The rectangular shape at the top of the core is housed on the mold and its purpose is to set the core in the correct position, fixing it in place once the mold closes

The defect originates at the bottom of the casting cavity, far from the sprue, where a stud-shaped metal core (pin core), integrated with the die half, has been placed to help center in place and support the sand core (see Fig. 57). The circular cavity left by this core is where the client will machine the threading for the oil cap in later operations.

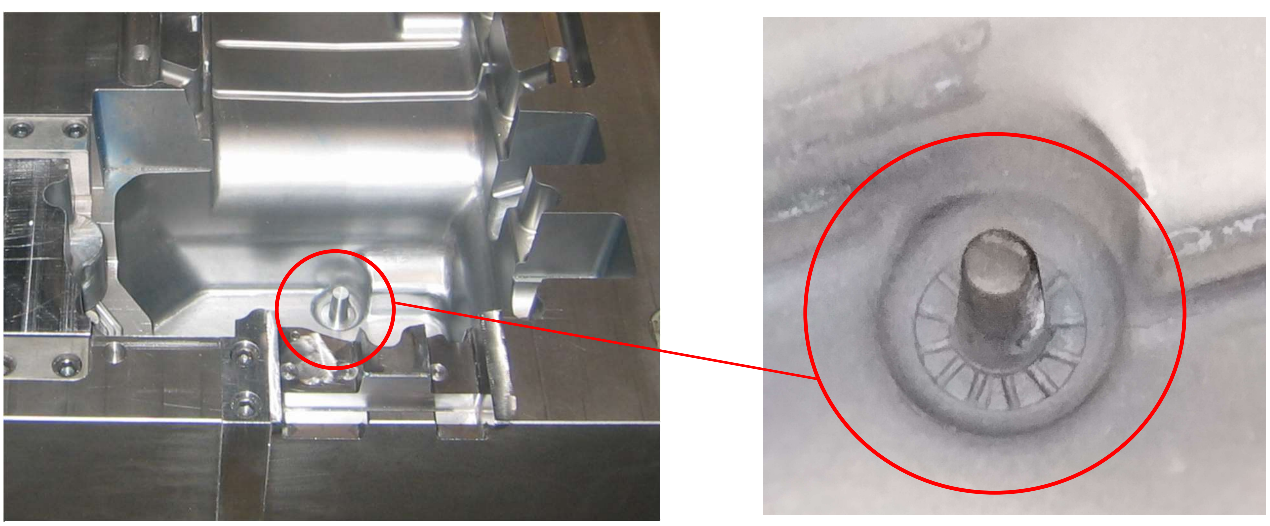


Figure 57: Picture of the pin core as it appears on the mold (left) and a close up detail (right). This is the corresponding area where the casted part will display the internal crack

The casting in this particular area will have a bulkier shape, which will solidify slower compared to the nearby thinner walls (see Fig.58), meaning that a riser must be set in this area to establish the proper directional solidification. However, due to the particular shape of the internal cavity, it would be impossible to set a blind riser in this position, as it wouldn't be in the company's ability with their currently available equipment to machine it away while keeping the shape and size set by the part's design.

Before the mold had been designed to begin with, computer-run finite element simulations of the gravity casting led the company to believe that the part was safe to cast even without the presence of a riser in this position, resulting in a very limited amount of shrinkage porosities.

From this first analysis on the mold, the crack's can be hypothesized to be caused by the shrinkage porosities caused by the latent solidification happening in the thicker section. Different solutions can be devised for this problem, the die halves could be re-designed considering a different orientation of the part in order to allow for a different orientation of the risers, or a different casting technology could be employed for the part's production, such as low-pressure casting, which would ensure every feature of the cavity to be homogeneously fed.

Before engaging in the more expensive and time-consuming solutions, it would be good practice to fully identify the source of the problem first, to see if different, more viable, and faster acting corrective actions can be taken instead.

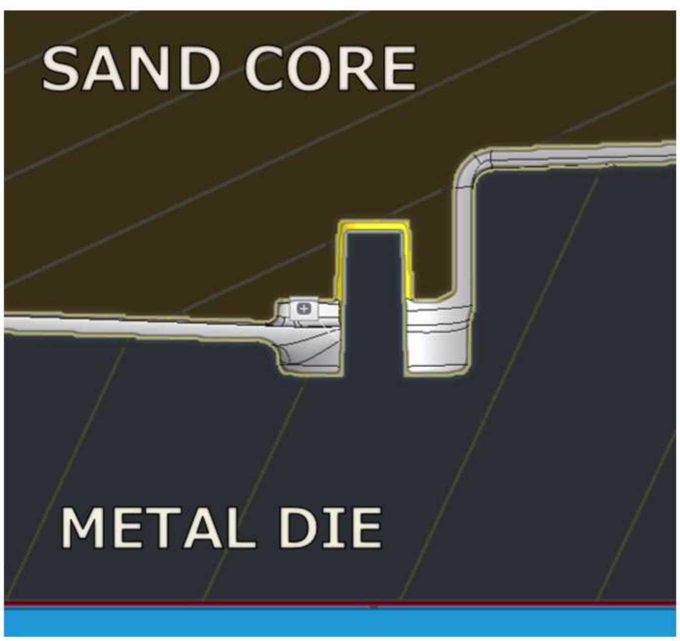


Figure 58: 3D model of the Cast-Die-Core ensemble as it looks like during the pouring operations (left), and the critical area of the casting on the 3D model (right)

7 Analysis on Normal production

A sample analysis is performed on a standard production run to see how the part is normally produced and if any anomalies are detectable. Twelve sample parts are taken from a new production run, with the first 3 samples taken from the first batch of products, casted right after a fresh coating has been applied on the mold's surface (see Fig.59), while the remaining 9 were sampled throughout the production run.

This-first analysis also allows to quantify the effectiveness of the mold coating washes. The entire casting surface is covered in a protective alumina wash (white), except the most critical areas, which are covered with a conductive graphite wash (black). The conductive coating in these areas increases the thermal conductivity with the mold, allowing for the faster solidification of critical features.

Figure 59: Freshly coated mold. In black the areas where a graphite coating has been applied in order to increase the solidification rate, including the pin core area

These coating are very effective at first, but with each subsequent casting they wear down relatively fast, especially the graphite coatings, exposing the bare metal of the die with the castings surface and losing the directional solidification gradients that were imposed with the wash's application. A picture of a freshly coated mold half is presented in Fig.59. A significative amount of conductive coating has been applied on the patch around the pin core, to promote a faster solidification of the casting's thicker section.

The analysis consists in the sampling of twelve pieces at different times throughout the production run, which started on Thursday 06/04/2023, at 17:00 PM,

- 3 samples taken on Thursday 06/04/2023, at 17:00 PM
- 3 samples taken on Friday 07/04/2023, at 08:00 AM
- 3 samples taken on Friday 07/04/2023, at 14:00 PM
- 3 samples taken on Friday 07/04/2023, at 17:00 PM

The main casting conditions parameters of each sample have been recorded as well, such as the mold temperature near the pin core, the molten alloy's temperature while in the holding furnace, the required time for the casting, the time it takes on average for the operator to remove the casting from the mold, etc. (see Fig.60). Each sample has been imprinted with a number, from 1 to 12, in order to identify which casting condition led to which result.

Figure 60: Some of the steps taken during the normal-production analysis, consisting in the measurement of the critical area's temperature with a radiation thermometer (left), and the marking of the sampled parts performed by engraving a number on their side (right)

7.1.1 Alloy composition and density of the parts in exam

The alloy's composition and its density have been measured as well in order to find any possible correlation with the defect's occurrence. Since the sampling took place over the span of two different days, the alloy has been sampled twice. The part is casted with A328 aluminum alloy (Al Si 9 Cu 1 Mg), an age-hardenable casting alloy for applications which require pressure tightness, its composition and impurity tolerances illustrated in Table 6.

The chemical composition of the alloy has been controlled with an arc spark spectrometer, with each step illustrated in Fig. 61. Some of the alloy has been ladled from the holding furnace before the part's production to cast some test ingots (1, 2), which were subsequently milled (3) and sparked (4, 5) in order to determine their composition. In Table 7 are reported the test results for the first, second, and third turn samples, nothing anomalous can be detected other than some slightly elevated iron levels, and strontium levels slightly above 150 PPM on the first turn's analysis.

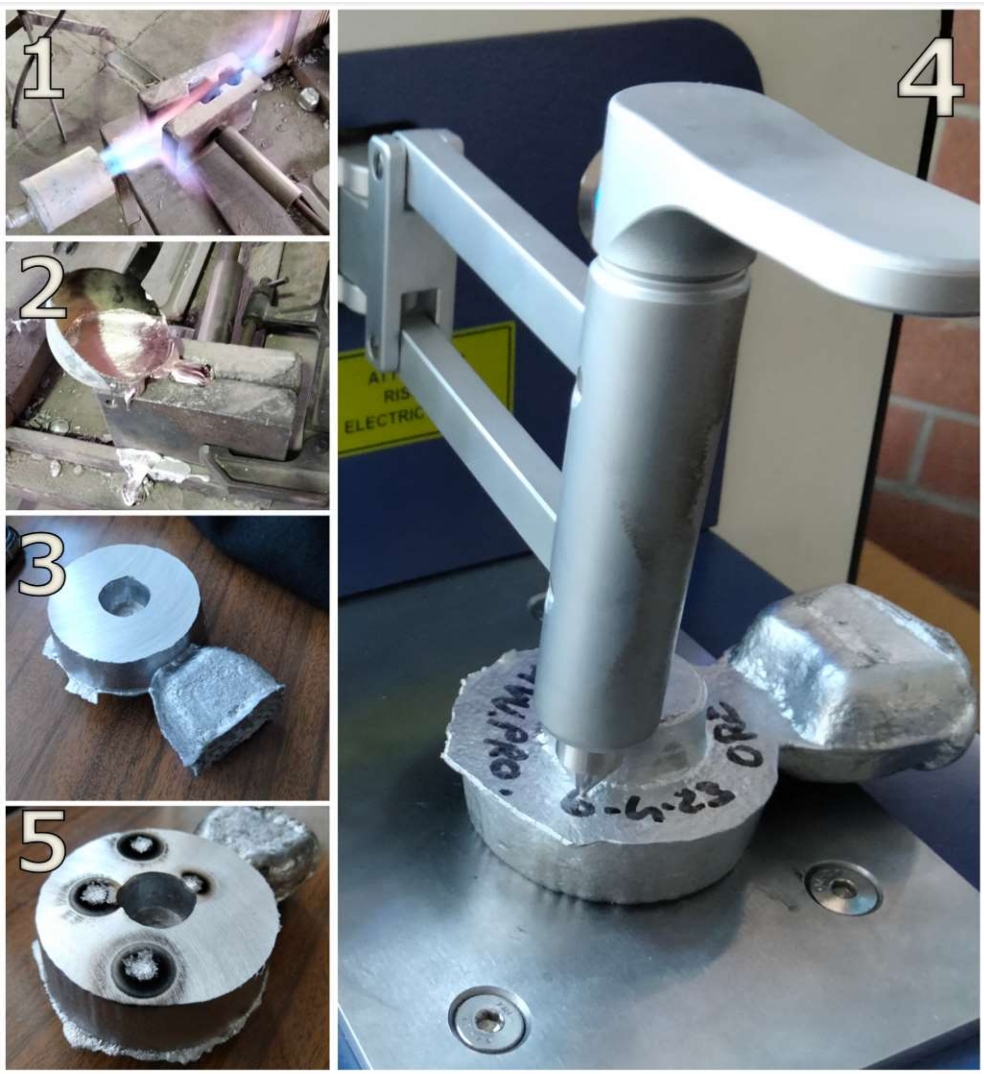


Figure 61:Steps to perform a spectrtogram, in order to determine the part's metallographic composition

5.1 **Composizione chimica % della lega SG - Al Si 9 Cu 1.**

Lega	Si	Cu	Mg	Mn	Ti	IMPURITÀ							Al
						Fe max.	Zn max.	Ni max.	Sn max.	Pb max.	Altre max.	Globali (escluso Fe) max.	
In pani	8,30 - 9,70	0,80 - 1,30	0,30 - 0,60	0,20 - 0,50	0,10 - 0,20	0,70	0,70	0,20	0,10	0,10	0,10	0,80	resto
In getti	8,30 - 9,70	0,80 - 1,30	0,30 - 0,60	0,20 - 0,50	0,10 - 0,20	0,80	0,80	0,20	0,10	0,10	0,10	0,90	

Table 6: Composition that an Al-Si9-Cu1 alloy should have by Normative UNI EN1706

Element	Min [%]	Average [%]	Max [%]
Al		87.747	
Si	8.30	8.872	9.70
Fe		0.822	0.80
Cu	0.80	0.998	1.30
Mn	0.150	0.233	0.550
Mg	0.250	0.372	0.650
Cr		0.0438	
Zn		0.584	0.80
Ti	0.10	0.111	0.20
Sn		0.0168	0.10
Pb		0.055	0.10
Ca		0.0013	0.002
Others		3.381	

Table 7 : Normal production run alloy composition

7.1.1.1 Alloy's density calculation

A small test ingot has been cast as well to measure the density of the alloy, which allows to check for anomalous levels of dissolved hydrogen in solution. After keeping the test casting under 0.5 bars of pressure for 3 minutes to remove any other extraneous entrapped gasses (see Fig.62), the sample has been measured with a density balance digital scale. The resulting density was 2.6 $[g/cm^3]$, a value within acceptable levels for this alloy.

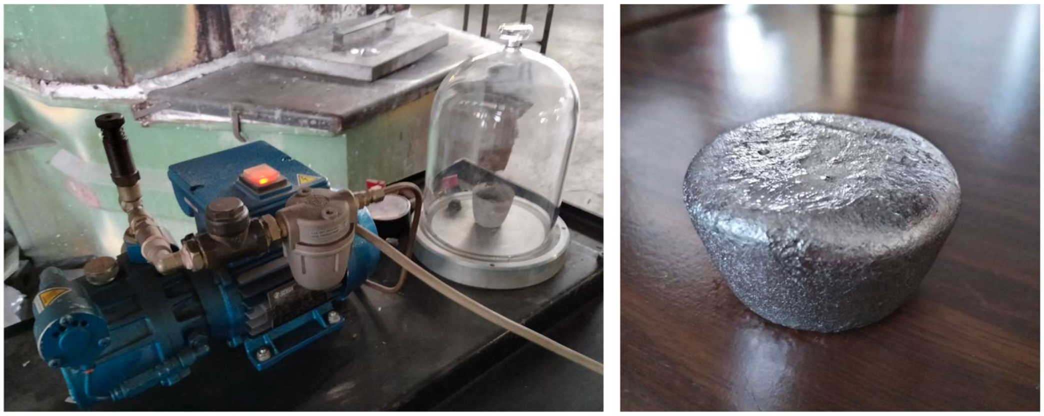


Figure 62: The vacuum machine used to prepare the ingot, with the holding furnace in the background (left), and the resulting ingot for the density analysis (right)

7.2 Results

To summarize in steps the sequence of operations for the production of the 12 sampling analysis units (see Fig.63):

1. After a casting is removed from the mold, the temperature of the mold is measured on the patch near the pin core with a radiation thermometer (pyrometer) calibrated for steel temperature measurements.

2. While the casting cycle is taking place, the temperature of the molten alloy as it comes from the holding furnace is recorded as well, along with any detected anomalies.

3. The casting can't be detached from the mold until the sliding vane is disengaged, the time it takes for the average operator to disengage the vane has been recorded to check for a possible correlation with the crack's presence.

4. After the casting is removed, the part is labelled with a number imprinted on an insignificant feature of the casting, which will help identify the part after the post-casting operations have occurred.

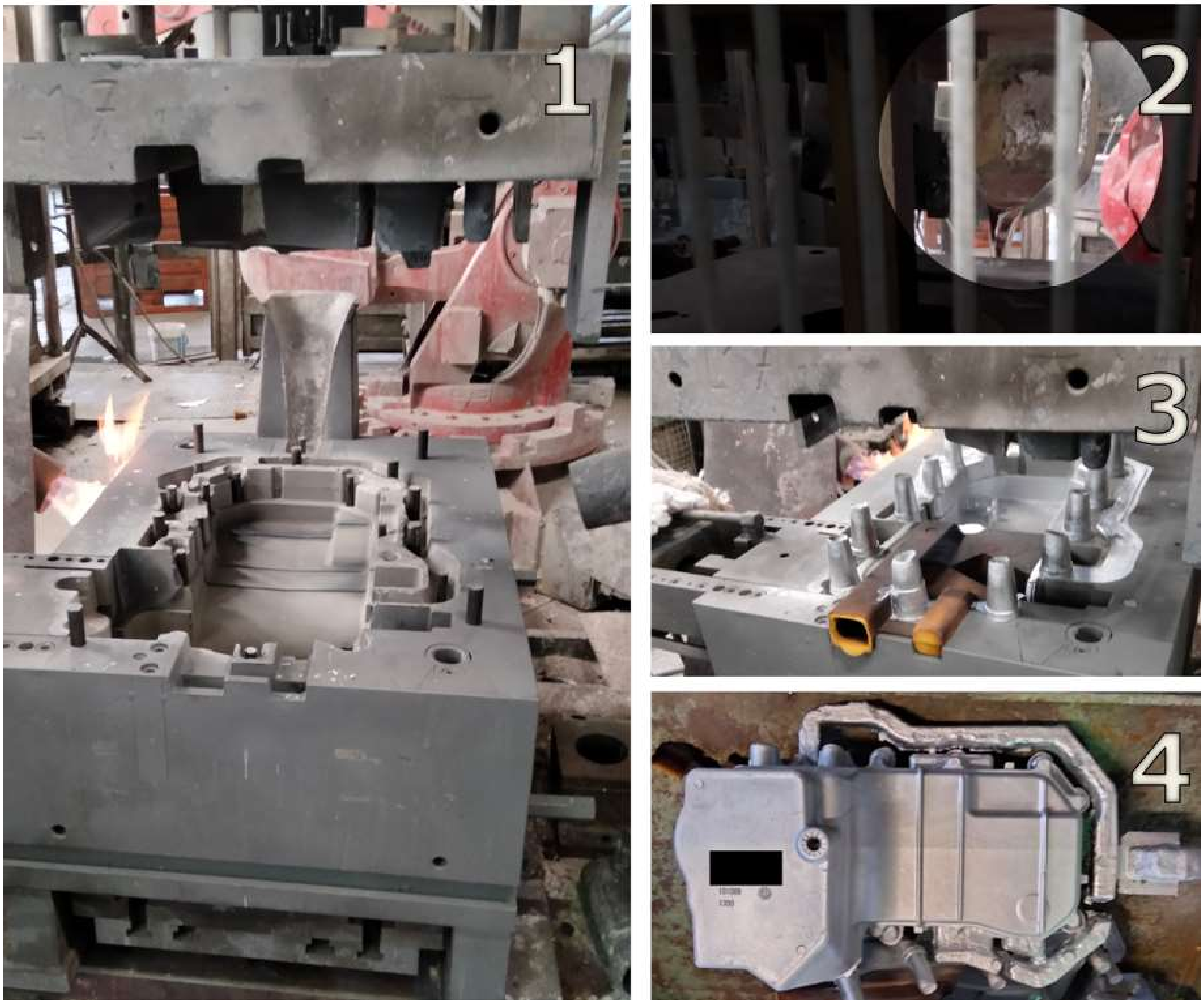


Figure 63: Picture displaying the steps for the production of the 12 samples rapresentative of a normal-production run, with the measurement of the mold's temperature performed in step 1, while the engraving of the identification number is performed in step 4

After the post-casting operations take place (trimming, sand blasting, etc.) the parts undergo an X-ray inspection to check for the presence of any internal cracking and other defects, with the results of the inspection shown in the Table 8 below. Even though the parts presented no external damage, 3 of the 12 units sampled (25%) displayed diffused porosity and a crack around the oil cap area.

Sample number	**T° mold [°C] (core area)**	**T° melt [°C]**	**Crack presence**
1st turn, at 17:00 PM (fresh coating on the mold)			
1	370	730	no
2	367	730	no
3	369	727	no
2nd turn, at 8:00 AM			
4	365	732	no
5	365	732	no
6	363	730	no
3rd turn, at 14:00 PM			
7	360	727	yes
8	360	730	no
9	359	730	yes
3rd turn, at 17:00 PM			
10	377	724	no
11	380	722	no
12	377	720	yes

Table 8 : Results of the normal production run, with 3 parts out of 12 displaying the internal crack

Despite the casting conditions and alloy compositions staying pretty much constant throughout the process, the number of defective parts seems to increase towards the end of the production run. The only other factor that may have influenced the crack's nucleation could be hypothesized to be the mold coating's condition, especially the conductive graphite wash's condition.

The effectiveness of the coating in the first few castings can lead to believe that a faster solidification in the affected area may be enough to stop the crack from happening, and it's only when the conductive coatings erode that the defect starts showing.

Further macro and microscopic analysis has been performed on STCast's laboratory on the 3 parts displaying an internal crack. The oil cup area has been cut from the defective units, sectioned, and polished through sanding discs and abrasive diamond pastes for a first metallographic analysis, performed through the company's optical microscope.

7.2.1 Unit n.7

Of the three units displaying the internal defect, the first one taken into consideration was unit n.7, for which a professional micrographic analysis was performed. The pictures in Fig.64 were the result, the sample displays a good microstructure and proper dendritic distribution, but also an unusually high amount of shrinkage porosities.

Sample number	**T° mold [°C]**	**T° melt [°C]**	**Crack presence**
7	360	727	yes

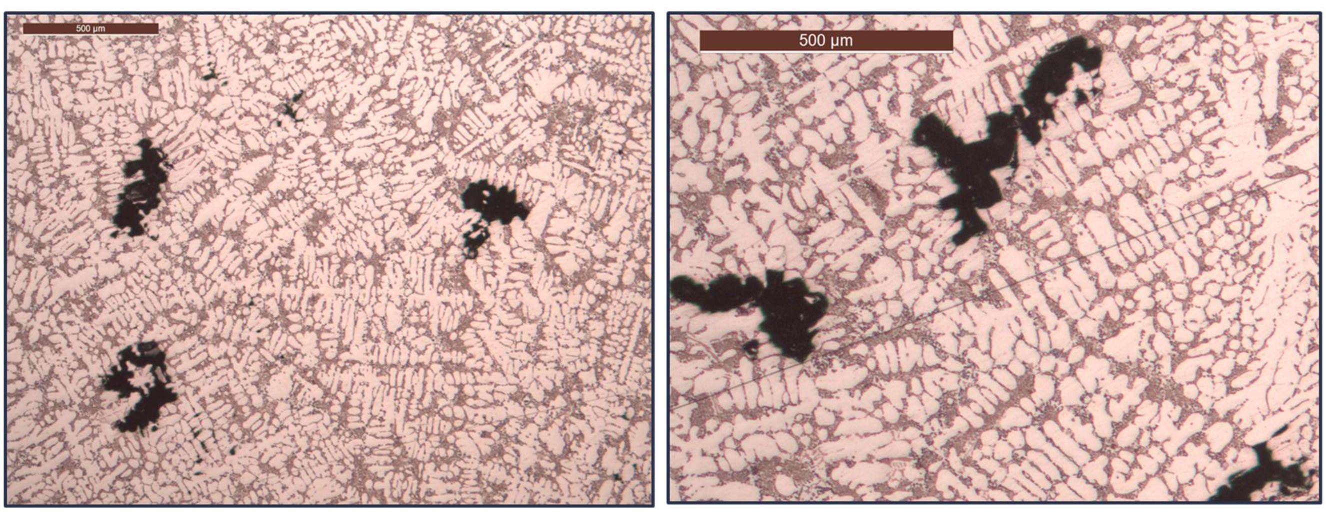
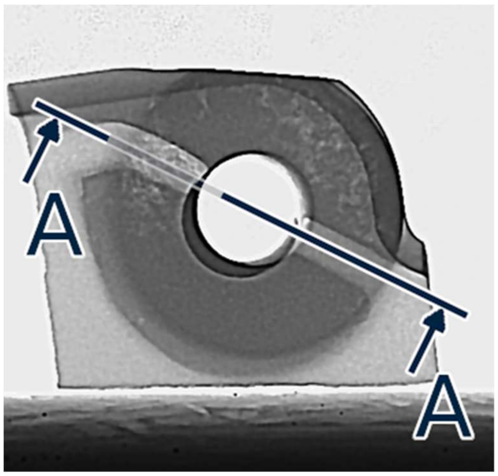


Figure 64: Some of the many shrinkage porosities displayed by sample n. 7

At the microscopic level it's already possible to identify a vast amount of shrinkage porosities, aswell as some unusual second phase deposits in the upper area of the section, confirming how the upper area of the bulky section is the last to solidify.

7.2.2 Unit n. 12

The second sample taken into consideration was unit n° 12. After sectioning and polishing the cross-section displaying the highest amount of internal defects, it was already possible to see at the macro level an unacceptable amount of shrinkage voids and cracks that would have no doubt showed up during the threading machining operations performed by the client. An assembly of micrographs for a particularly significant microporosity is represented in Fig.65 below.



Sample number	T° mold [°C]	T° melt [°C]	Crack presence
12	377	720	yes

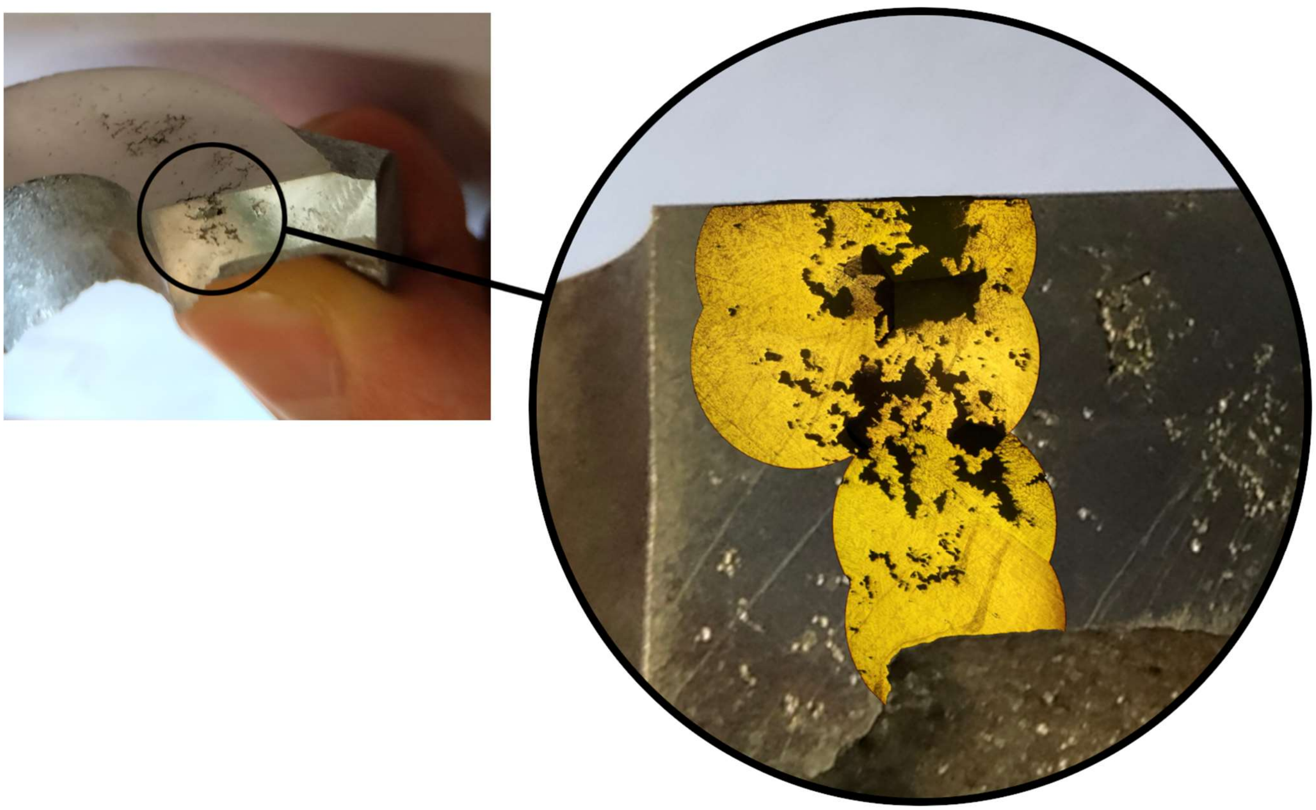
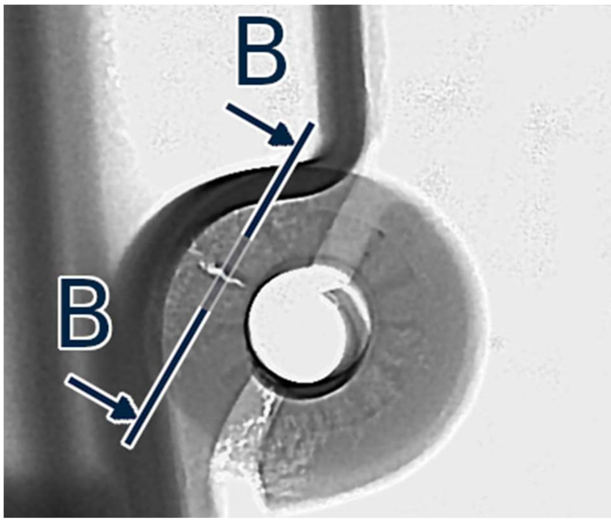


Figure 65: Macro picture of the sample 12 section displaying internal porosity after the X-ray analysis

7.2.3 Unit n. 9

The third sample taken into consideration is unit n° 9, which displayed a particularly evident crack during the X-ray examination. This time the part has been sectioned to better display the crack rather than the diffused porosities instead. An assembly of micrographs of the crack is represented in Fig. 66 below.



Sample number	T° mold [°C]	T° melt [°C]	Crack presence
9	359	730	yes

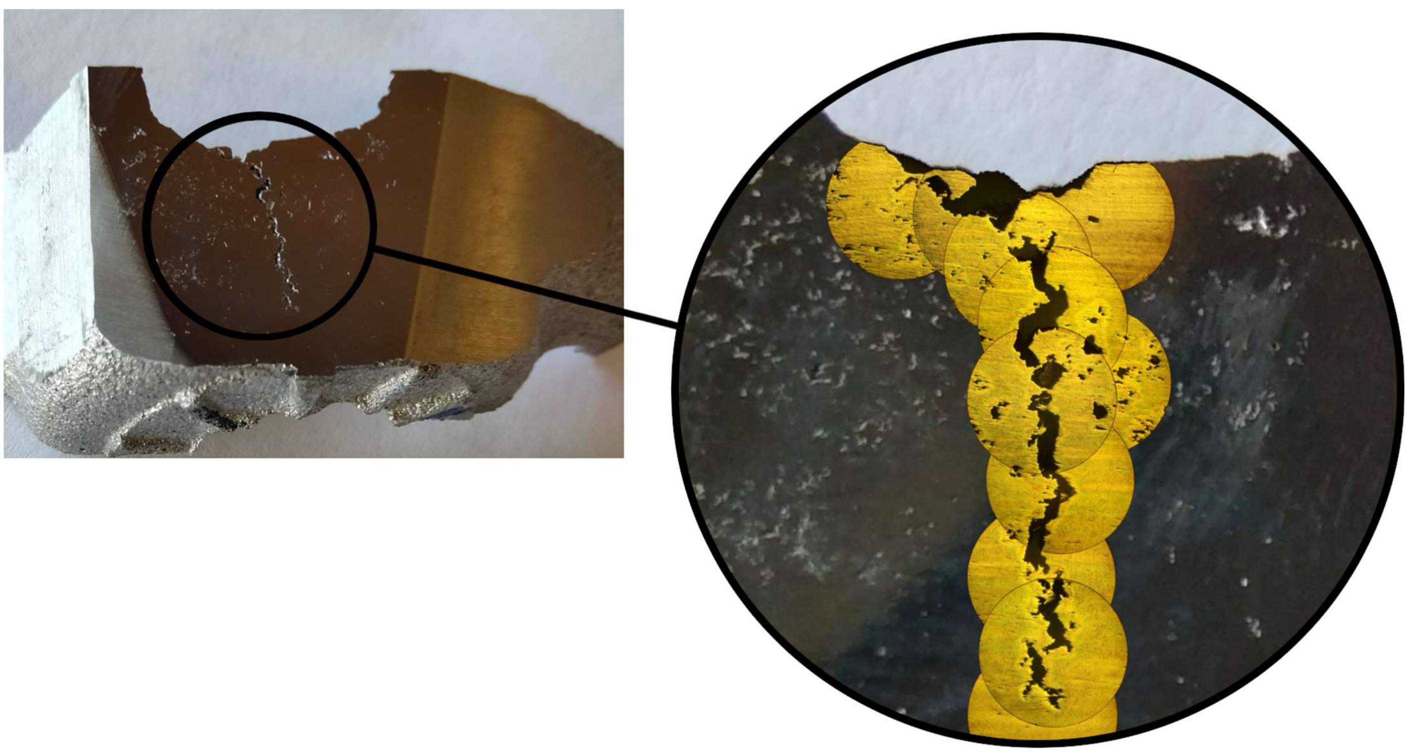


Figure 66: Macro picture of the sample 9 section displaying an internal crack after the X-ray analysis

8 Experimental corrective actions

After asserting the source of the defect to be caused by the loss of the thermal gradient set by the conductive coatings, it's possible to assess different countermeasures to prevent the shrinkage porosities from occurring. For shrinkage porosities to nucleate it's required for the metal to solidify around a molten area of metal (hot spot), which can't be fed with material anymore and will slowly contract due to the volumetric shrinkage associated with the solidification process, leaving empty voids diffused around the dendritic structures. If the base of the affected area is cold enough to impose a vertical solidification gradient from the bottom up, it would be possible to prevent the shrinkage porosities from occurring.

Given this assessment, two possible immediate corrective actions have been devised to solve the problem:

- 8.1) cooling directly with water-spray bursts between casting cycles
- 8.2) cooling indirectly with a continuous compressed air stream

The results of these two experimental corrective actions will be explored in this chapter.

8.1 Localized cooling trough nebulized water spray

An experimental production run is planned where the pin core is sprayed with an high pressure 50-50 air-water mixture in order to locally cool down the area (see Fig. 67). This time, 15 units will be sampled to see if the corrective action has any positive effect. The sequence of operations is listed below, unless stated otherwise, consider the main casting parameters (such as alloy composition, density, melt temperature) to be the same as the ones exposed in the normal-production analysis.

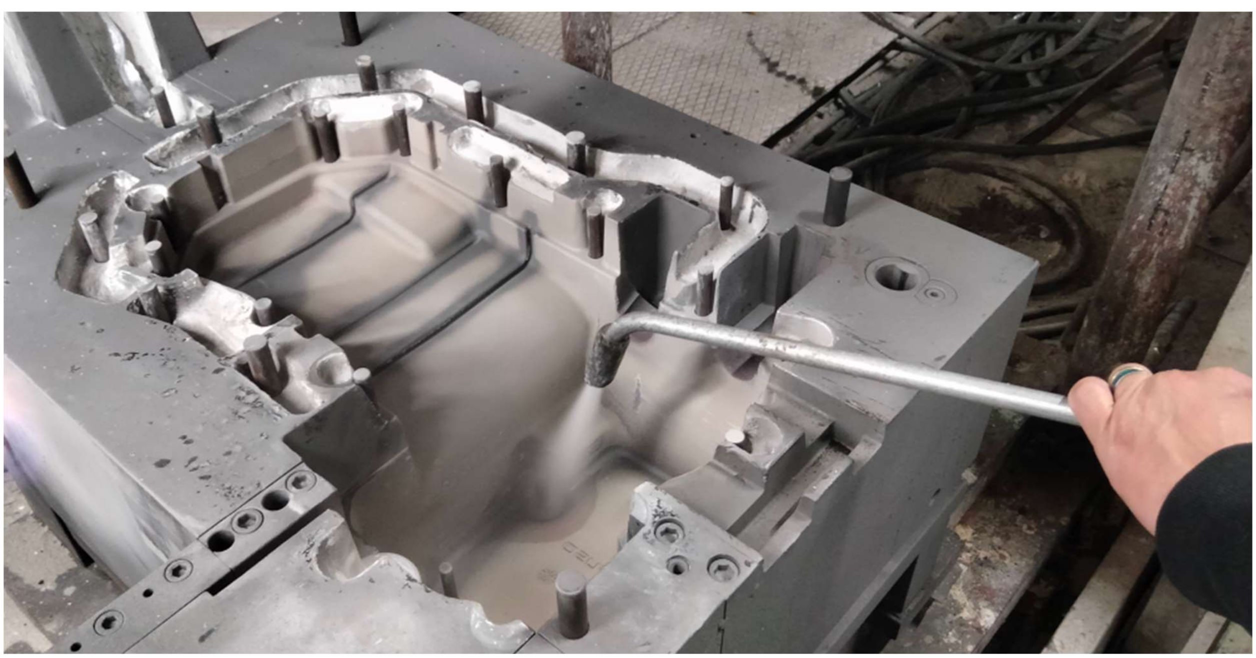


Figure 67: Manual localized cooling of the critical area, through the nebulized water/air spray system

The sequence of operations for the sampling of the 14 units is the following:

1. After the previous casting is removed from the mold, the temperature is measured on the oil cap area with the pyrometer (identified in the table below as pre-cooling T°).
2. As the operator is placing the part in the finished-part crate, a spray of nebulized 50-50 air-water mixture is sprayed directly on the pin core for around 5 seconds. The temperature of the oil cap area is measured again (post-cooling T°).
3. The casting cycle continues the same as in normal-production. All the other significant casting parameters, such as casting times and melt temperature, are monitored to detect any anomalous event.
4. After the casting is done, the part is removed and labelled to help identify it after the post-casting operations have occurred.

After the post-casting operations are enacted, the batch of units from the experimental run goes through X-ray inspection to check for the presence of any internal defects. Results are reported in the Table 9.

Unit number	T° mold [°C] (pre-cooling)	T° mold [°C] (post-cooling)	Crack presence
1	385	280	no
2	380	300	no
3	380	250	no
4	377	310	no
5	377	260	no
6	380	260	no
7	380	240	no
8	380	200	no
9	380	220	no
10	380	250	no
11	375	190	no
12	375	180	no
13	375	190	no
14	370	200	no

Table 9: Results of the experimental water cooled run

8.1.1 Comparison with normal-production sample

One of these units has been taken at random to perform further macro and microscopic analysis on STCast's laboratory (see Fig.68) . The oil cup area has been cut away from the unit and polished through sanding discs and abrasive diamond pastes for a first metallographic analysis.

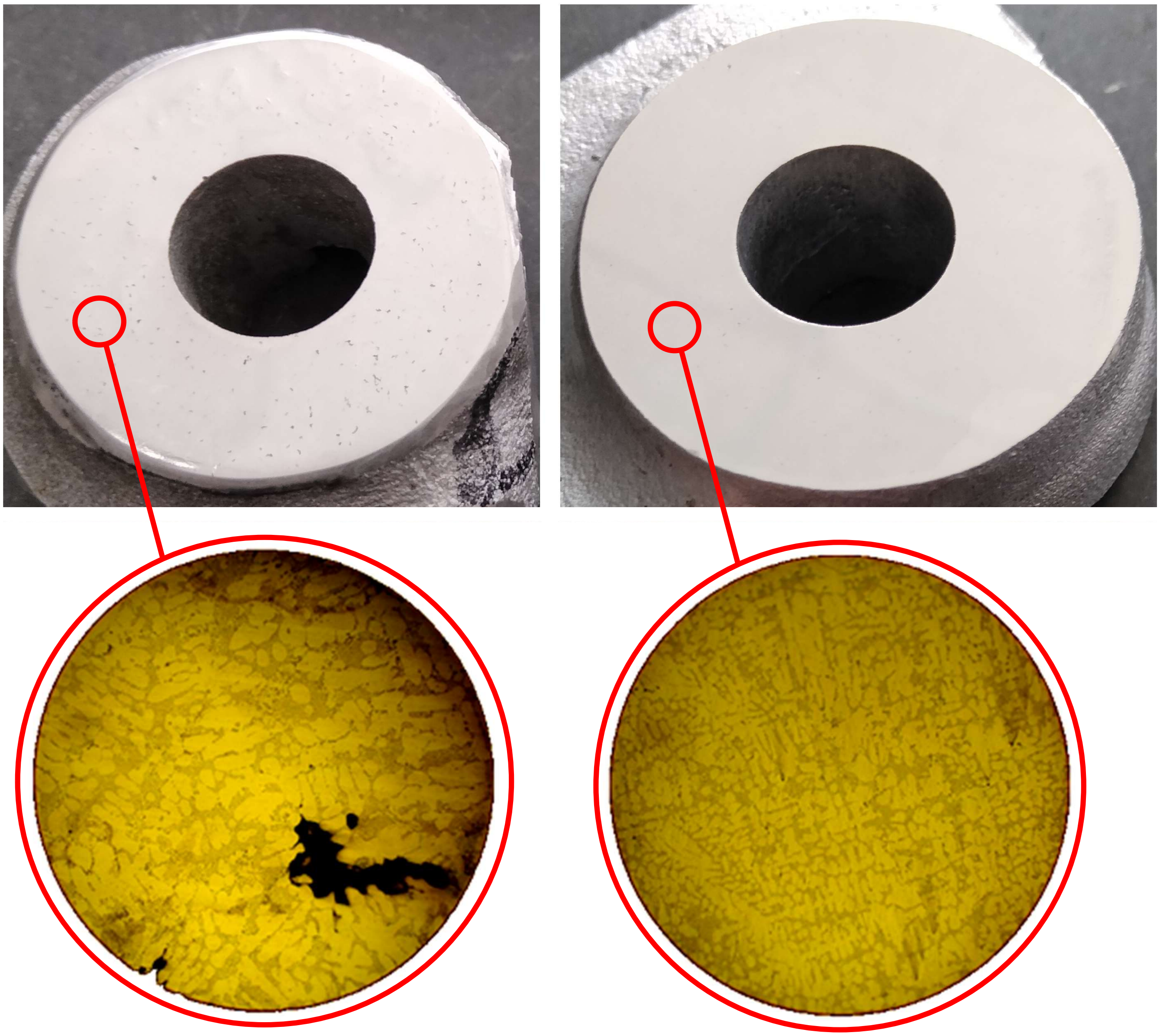


Figure 68: Microstructure comparison between a normal-production sample and a water-cooled sample, taken at the same magnification level. It's already possible to see a much finer and evenly distributed dendritic structure and, although hardly noticeable, even on the macro level it's possible to see a stark reduction of shrinkage porosities on the polished surface.

Micrographs taken at the same level of magnification for both samples. Although not conclusive (for further analysis on the microstructure see chapter 9) the finer structure on the water cooled sample, along with the lack of shrinkage porosities, is indicative of better properties.

Compared to a sample taken from the normal production, not only it's possible to distinguish a much finer, more evenly distributed dendritic structure, but even on a macro level it's possible to see a vast decrease in shrinkage porosities as well. The finer microstructure obtained trough the faster solidification will confer higher mechanical properties and better dimensional stability, which will greatly improve the thread's properties after the threading machining operations.

8.1.2 Problems with the method

As effective as the corrective action turned out to be, there's different problems with its implementation that can't go ignored.

- Although effective at bringing the temperature down, the thermal shock from the room-temperature water bursts can cause substantial thermal stresses on the die. Cyclically bringing the temperature down by 100° ~150° C degrees can significantly reduce the mold's life, hastening thermal fatigue damage.
- The coarse action of the nebulized water stream can easily strip the protective coating wash off the mold, especially the graphite-based conductive coating will come off very easily. Although these coatings are also used to establish a solidification gradient, their main function is to protect the mold and help the casting come off the cavity, without them the mold's life would be further reduced.
- After spraying the area, the average operator takes about 60 seconds to perform all the pre-casting operations (metal inserts and core placement, tracking, etc.). In this time, the heat dispersing from the rest of the mold has time to bring back the temperature of the oil cap area to 300° ~ 350° C, reducing the effectiveness of the corrective action.
- The spray has to be manually applied by the operator. The time of application for the nebulized spray was suggested to be around 5 seconds, but different operators have been recorded spraying the area for different time intervals, some for ten seconds, some only for one, compromising both the casting result and the mold's life. The manual nature of the operation achieves unreliable and inconsistent results.
- An unexpected effect from this treatment consisted in the increased effort required for the machining and working of this area of the part, due to the finer microstructure and the resulting strengthened mechanical properties.

For these reasons, a different, more consistent solution must be devised in order to bring down the temperature of this area.

8.2 Localized external cooling trough compressed air

Given the results obtained from the local cooling with water-spray bursts, it was decided to look for a more consistent and less damaging way bring the temperature down in the oil cap area. In the past, for different castings, STCast had tried to cool down the mold from the outside with a stream of compressed air aimed towards critical aeras, but the thickness of the mold prevented the cooling from having any significant action. For the product's casting, the critical area distances 5,14 centimeters from the surface of the mold, too much for an external stream of air to have any effect (see Fig.69).

It was decided to modify the mold by introducing a cooling channel through the pin core. By reducing the thickness between the critical area and the external air stream it would be possible significantly reduce the porosity levels, while shifting them away from the surface.

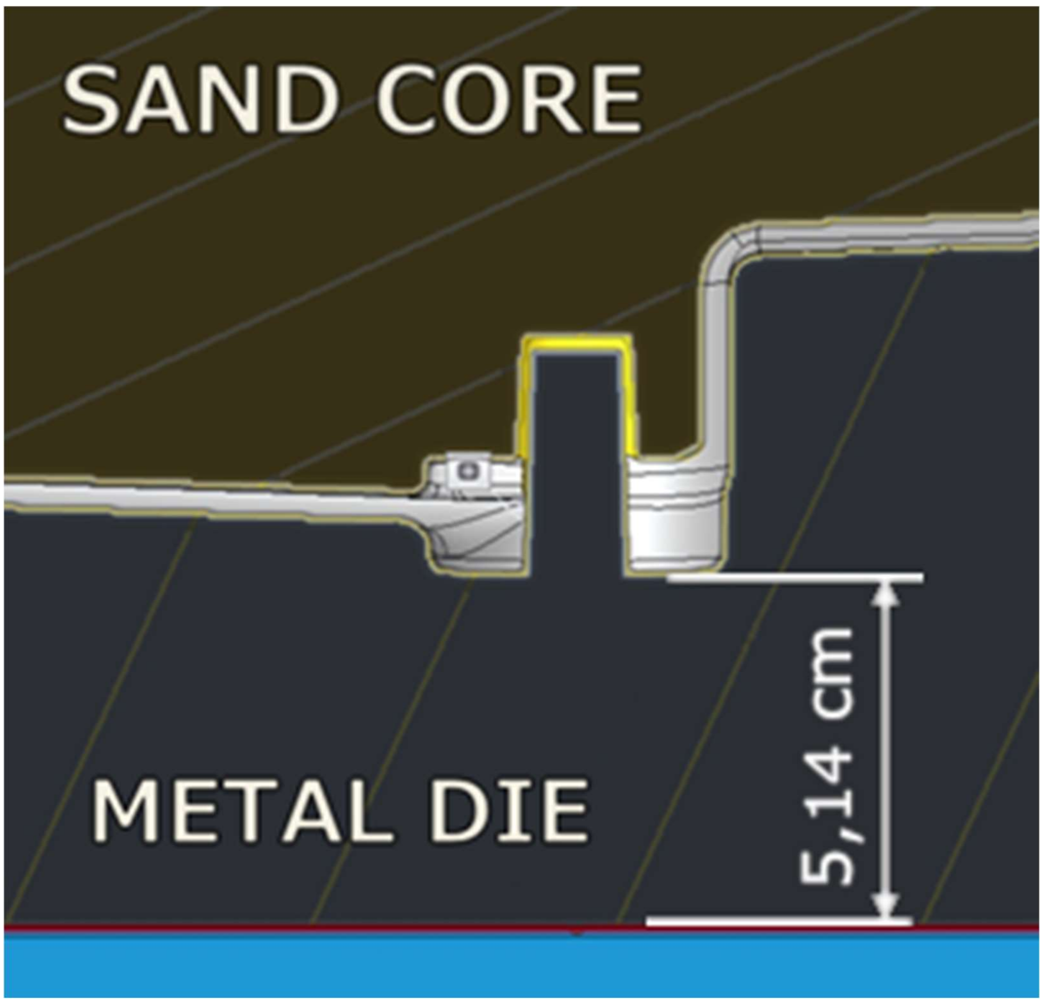


Figure 69: Distance of the critical area from the exterior of the mold. The amount of bulk material between the area and the exterior makes it impossible to cool the critical area from the outside without a having to modify of the mold first

No machining operations on the mold itself were necessary since the mold had already been altered beforehand (see Fig.70). The pin core, along with the cylindrical section around it, were not integral parts of the original mold's design but were added at a later time for different reasons:

- The pin core design was altered to act as a support for the sand core placed above it.
- The cylindrical surface was changed from a smooth to a rib configuration in order to further increase the heat transfer between the casting and the mold.

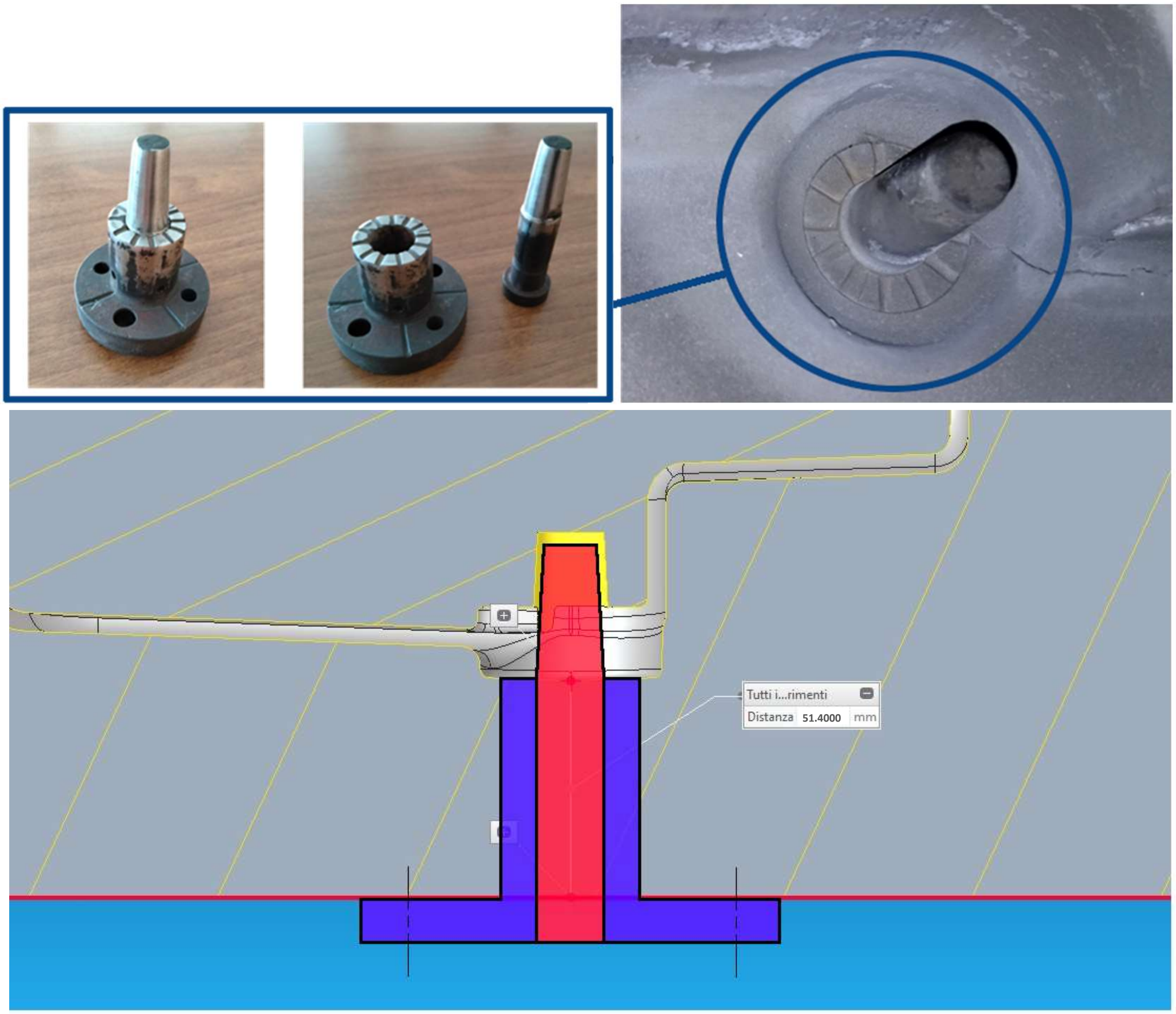


Figure 70: Picture of the assembly and how it looks once assembled (top), and a representative scheme of how the pin core assembly results installed on the mold (bottom). This was a modification performed beforehand, which made it convenient to disassemble the pin core to modify its configuration.

8.2.1 Cooling pin configuration

It was decided to substitute the two parts that constituted the pin core with a single unified piece. The new pin core, made out of H13 tool steel, would combine the function of the two previous parts while including a cooling channel for the compressed air to go through to chill the critical area (see Fig.71). The cooling channel was designed to reach just under the cylindrical surface, as the core pin was too thin for internal machining operations. The tube injecting compressed air is inserted all the way inside the cavity, with the wall between the tube and the cavity acting as the return circuit to expel the air.

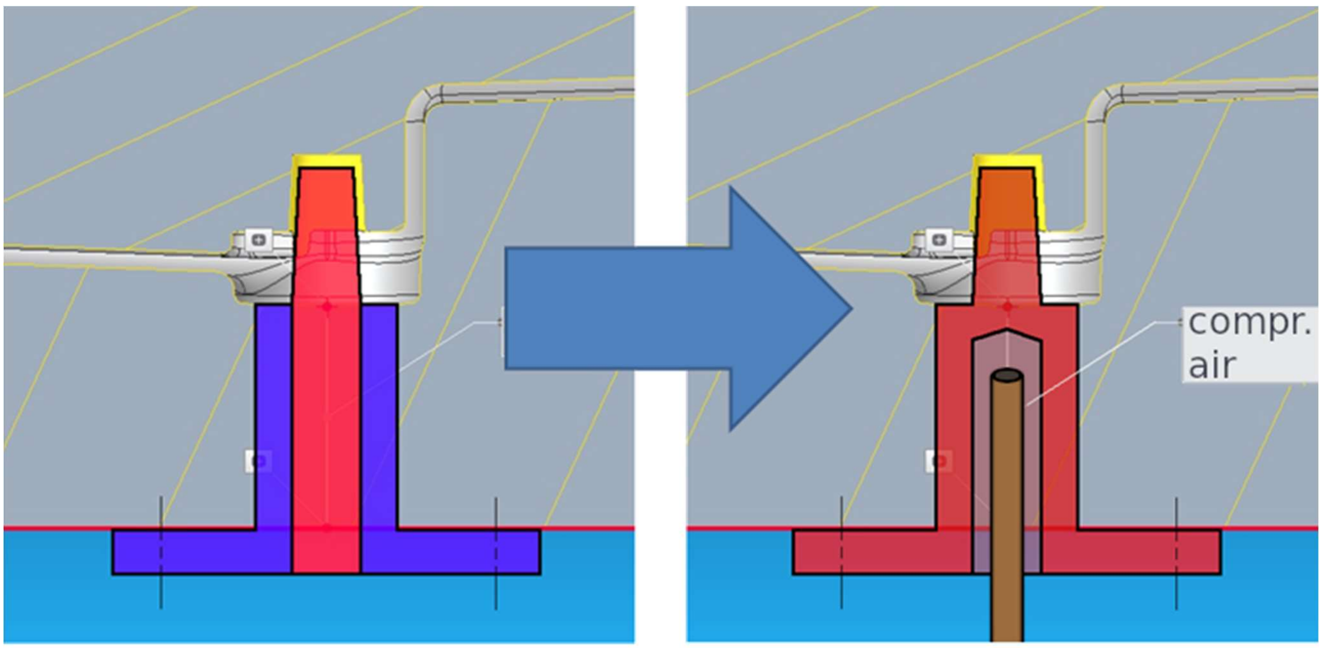


Figure 71: Proposed configuration to allow air cooling by the pin core area. The dimensions of the pin were quite small to accommodate a typical circuit with an injection path and a return path, so it was proposed to simply drill a hole where the injection tube could be inserted, and let the space between the tube and the mold to act as a return circuit instead

This new configuration solves all the problems presented by the direct water-spray bursts solution:

- It allows for a continuous indirect stream of air to cool down the critical area throughout the casting cycle, rather than an intermittent direct water spray in-between cycles, resulting in a much more homogeneously distributed thermal gradient with no thermal shocks.

- With the stream of air being applied indirectly from the exterior of the mold, the protective washes coating the casting cavity end up unaffected by the cooling action, lasting longer.

- No manual inputs from the operator are needed for this configuration, removing the human element and leading to reliable, consistent casting results.

An experimental run was planned where 30 test units would be produced to see the effects of this configuration. In regime conditions, after calibrating the pressurized air output, it was possible to detect a constant temperature of ~ 200° C in the oil cap area in between cycles, values similar to the ones obtained by the water spray bursts without any of the downsides coming from spraying water on the hot mold. From X-ray analysis none of the 30 produced parts displayed any internal defects or porosities, and a microstructural inspection shows an extremely fine, homogenous dendritic distribution.

Figure 72: New pin core configuration, machined out of H13 tool steel. Every dimension is the same compared to the old configuration, except for the compressed air circuit in the middle

9 Comparison between microstructures

In this chapter a metallographic analysis is performed on some of the samples coming from the 3 different experimental production runs, to compare the different microstructures and assess which of the corrective action has led to better results.
The analysis has been performed on 3 different units taken from each production run, in particular:

- Sample number 12 from the normal production run (see chapter 7.2)
- One random sample from the directly water-cooled production run.
- One random sample from the air-cooled production run

Sample preparation consisted in cutting off the oil cap area from the experimental units, sectioning it along a predetermined area, encapsulating it in bakelite, then grinding and polishing it for metallographic analysis. In order to be able to compare the results, the metallographic samples must come from the same area of the casting.

In this case, it was decided to compare the area highlighted in red in Fig. 73, which from experience turned out to be the area where the majority of the defects would occur more frequently.

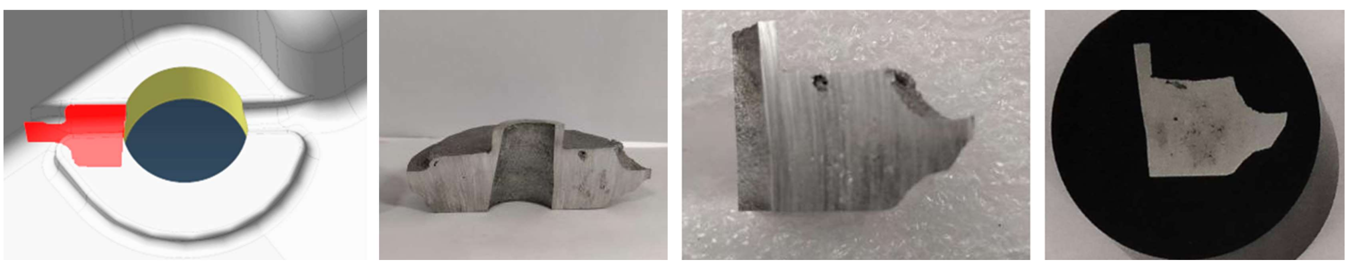


Figure 73: Sectioning of a sampled part performed to obtain a metallographic sample

The sample preparation process is standardized by normative ASTM E340-15, and consists in a series of steps followed in order to obtain a deformation-free, scratch-free, and highly reflective sample surface, in order to clearly reveal the microstructure of the metallographic specimen under microscopic examination [33].

The polishing has been performed with a manual metallographic polishing machine (see fig.74), where the specimen will be manually pushed with gentle pressure on the grinding disc mounted on the machine's electrically powered wheel, which will spin at constant speed to perform the mechanical abrasive action. A constant flow of refrigerant fluid is sprayed on the specimen to prevent the temperatures reached by the mechanical action to deform the specimen's microstructure. The grinding discs are named following Fepa's classification, going from the coarser P240 to the finer P4000.

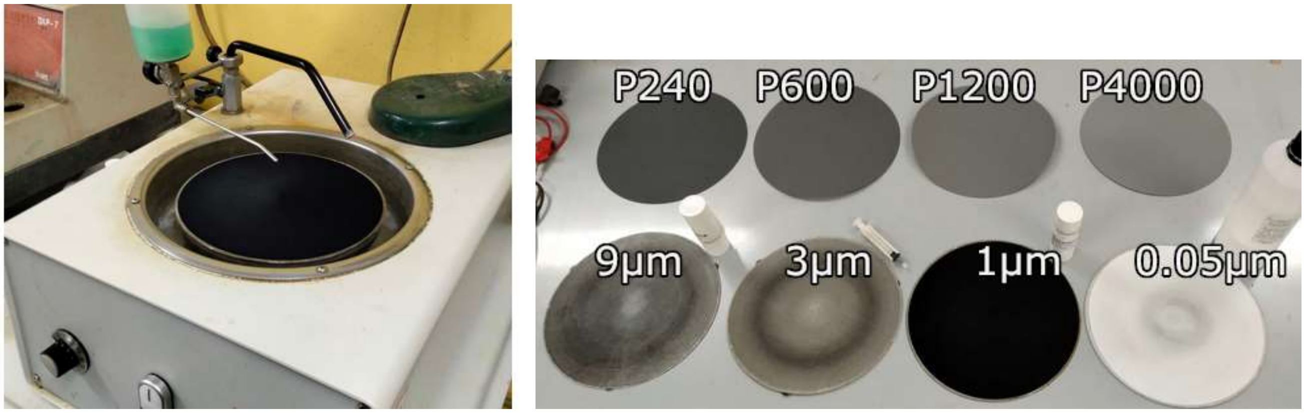


Figure 74: Polishing machine used (left), with each grinding and polishing disks used for the operation

The specimen preparation can be described in two main steps:

1. Mechanical grinding: gradual abrasion of the specimen through a series of increasingly finer grinding papers. An initial coarser grinding (P240 paper) is performed to obtain a flat surface, which will act as the basis for the subsequent operations. This is followed by a medium (P600, P1200) and a finer (P4000) grinding to prepare the specimen for the polishing operations. It's only possible to move from one stage the next when all of the scratches from the previous stage are completely removed.
2. Mechanical polishing: Finer abrasive action whose goal is to rid the surface of any scratches resulting from the grinding action. The grinding discs will be substituted by a series of fabric discs, where an increasingly finer abrasive solution is applied. The abrasive can either be diamond paste (from 9 µm to 1 µm) or alumina suspended in liquid solution (0,05 µm)

With this procedure 3 different specimens were obtained, one representative of the normal production conditions, one of the water cooled conditions, and one of the air cooled conditions. After the final polishing operation, the resulting microstructure was deemed clear enough to need no etching operations.

Figure 75: The final three specimens obtained for the metallographic analysis, with the normal-production sample on the left, the water-cooled sample in the middle, and the air-cooled sample on the right

9.1 Micrographs

To better compare the specimens, different micrographs at 50x magnification have been taken and merged together in order to provide a complete view of the specimen. These assembled micrographs are going to be used to compare the porosity fraction and dendritic arm spacing differences between the three samples. For the calculation of the porosity fraction the images need to be segmented, meaning they must be broken down into binary colors in order to be analyzed.

Figure 76: Micrograph assembly for the normal-production specimen

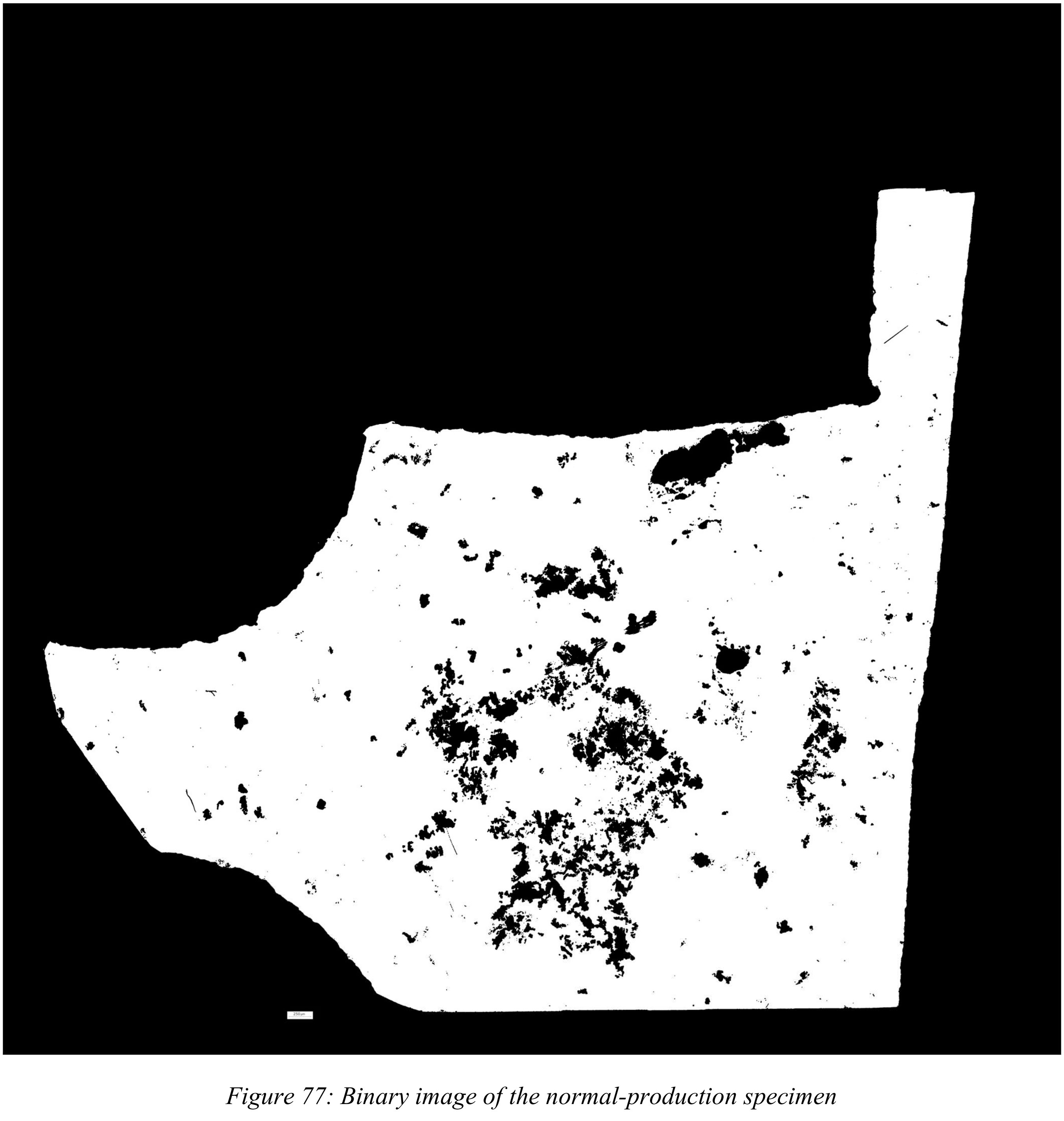


Figure 77: Binary image of the normal-production specimen

Figure 78: Micrograph assembly for the water-cooled specimen

Figure 79: Binary image of the water-cooled specimen

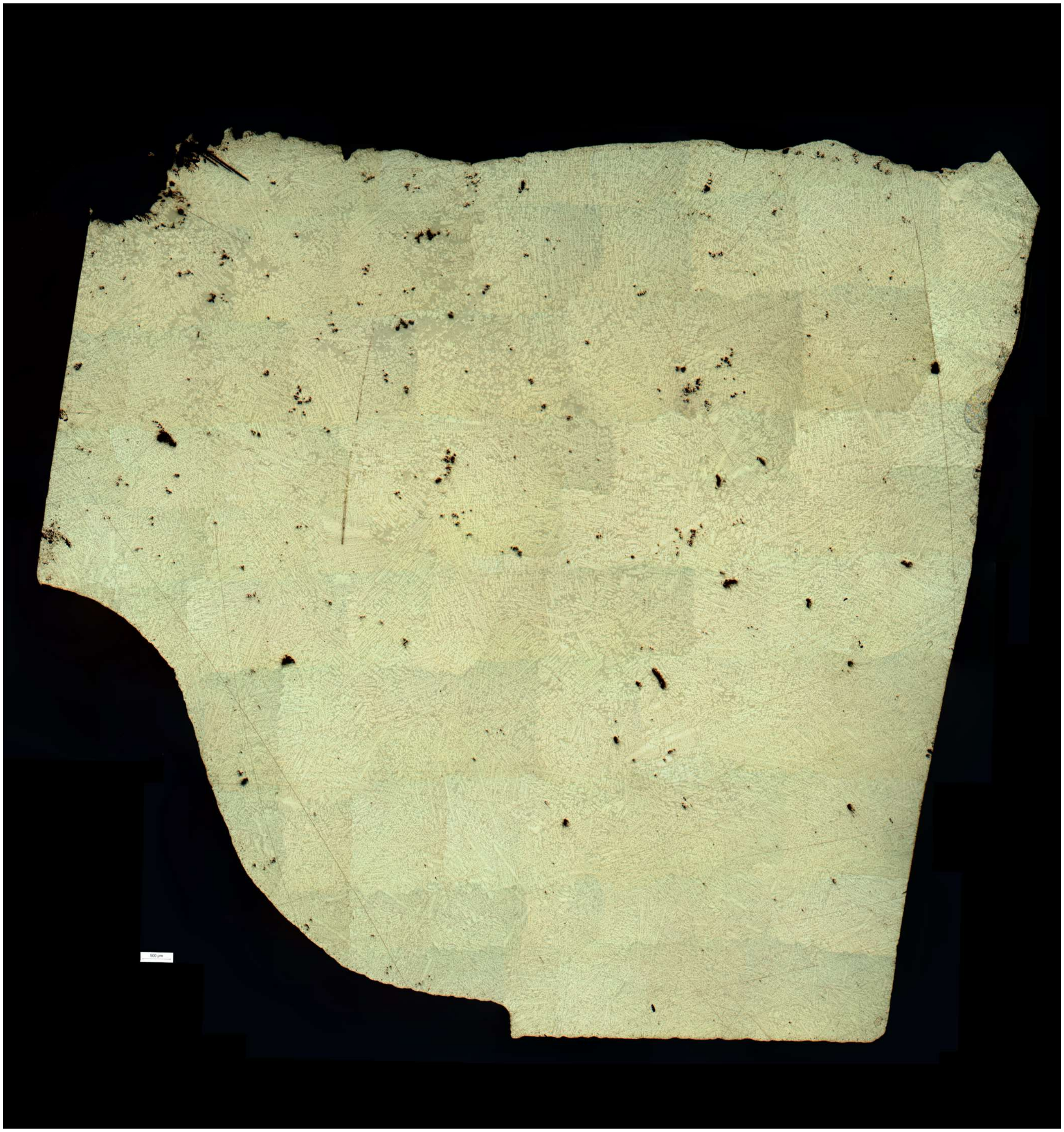


Figure 80: Micrograph assembly for the air-cooled specimen

Figure 81: *Binary image of the air-cooled specimen*

9.2 Comparison of porosity fraction

From the assembly of micrographs it's possible to compare the quantity of porosities in the sectioned area of the three specimens. All three samples display a different amount of shrinkage porosities, which can be quantified in percent of the occupied surface area by segmenting the images (see Fig.82).

Figure 82: Binary picture of the assemblies for the porosity fraction calculation

Given a reference length, the software ImageJ is capable to identify the full area of the section (as if it had no porosities) and identify the total surface area occupied by all the porosities combined (independently from the surrounding material).

With these two values it's possible to measure the porosity fraction percent of the three different sections. The software isn't able to distinguish between shrinkage porosities, gas porosities or inclusions, as it only uses the difference in color to identify the measured areas, but with proper practice the values obtained can still give a good indication on the quality of the casting itself.

Specimen	**Full Area** $[mm^2]$	**Area occupied by porosities** $[mm^2]$	**Porosity fraction** [%]
Normal production specimen	55,09	4,43	8,04 %
Water cooled specimen	41,64	0,295	0,71 %
Air cooled specimen	57,07	0,188	0,33 %

Table 10: Porosity distribution % results

From the results displayed on table 11 it's possible to see how the air-cooled specimen displays the least amount of porosities between the three, both in absolute value and in percentage. Despite the unfavorable casting conditions, this modification allows to achieve acceptable porosity levels, which helps preventing the crack from occurring.

9.3 Secondary dendrite arm spacing

Secondary dendrite arm spacing, referred as DAS or SDAS is the distance between dendrite secondary arms of a casting. This parameter allows the quantification of the casting's microstructural properties (see chapter 1.3). It can be measured in different ways, in this thesis it has been measured directly from the micrographs through the intersecting line method according to the normative ASTM E112-13 [34]. This method consists in drawing a line which intersects some clearly defined secondary growths of a dendritic structures, as illustrated in Fig.83 below, then dividing its length (L) by the number of dendrite arms intercepted. The bigger the SDAS measure, the slower the solidification will have been.

$$SDAS = \frac{L}{n}$$

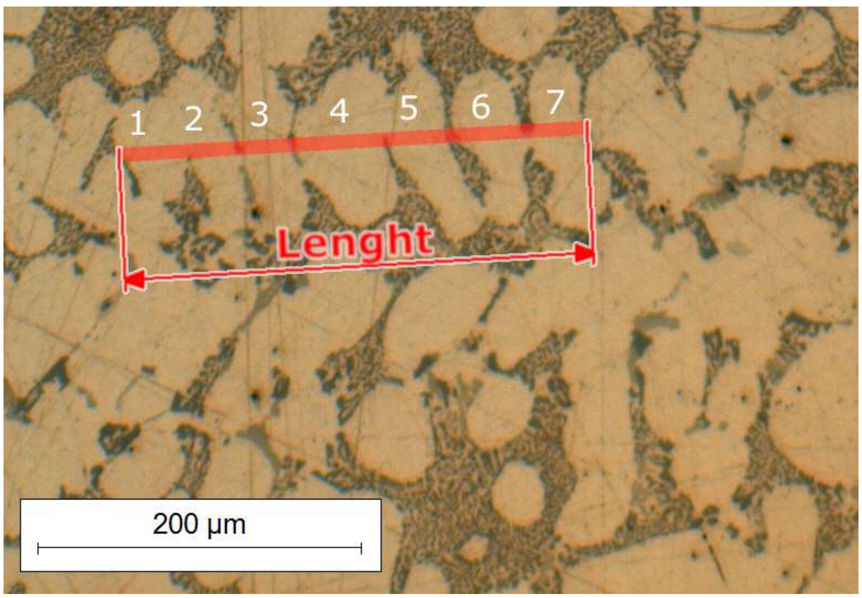


Figure 83: Intersecting line method to measure the SDAS

From the micrographs taken of the 3 samples, it's possible to compare the SDAS parameter for the three different production runs. But due to the complex shape of the feature, some areas near the mold surface will solidify differently than the areas in contact with the pin core, or the ones with the sand core at the top. Therefore, it's important to compare areas that will occupy the same volume in space between the three different samples.

For a better comparison of the microstructures, the picture assemblies have been superimposed on top of each other, and a grid has been traced to identify 15 significant areas possible to compare, as shown in the Fig. 77. These 15 areas allow to identify where the SDAS parameter should be measured for each of the three different specimens.

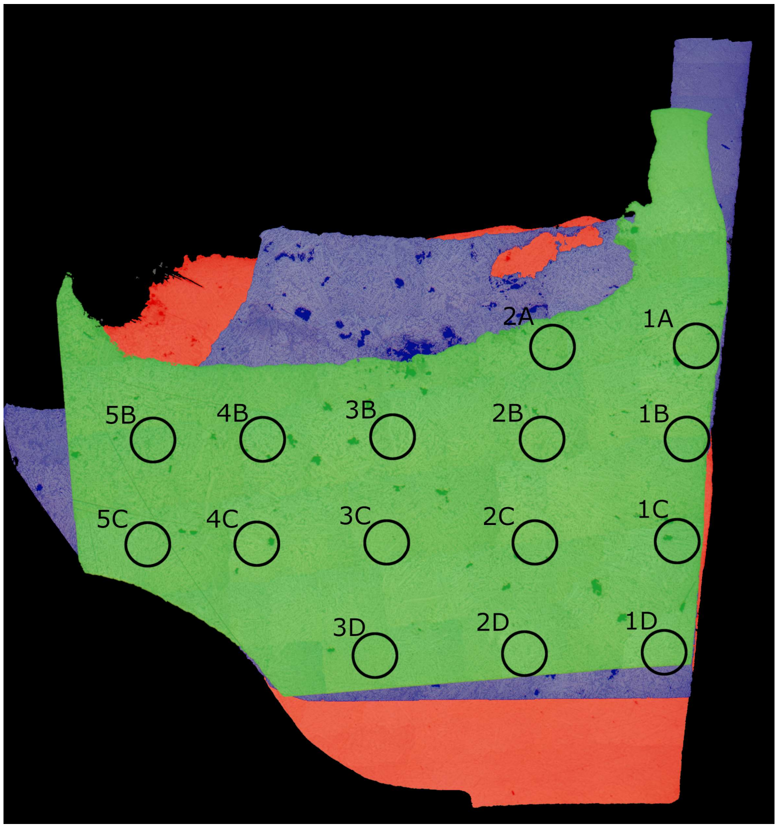


Figure 84: Overlap of the three specimen micrographies

Area	SDAS [micron] Normal production	Water cooled	Air cooled
1A	24,18	26,89	19,63
1B	23,00	22,88	19,33
1C	24,11	21,11	19,17
1D	22,20	19,67	15,86
2A	24,31	23,67	21,86
2B	24,10	21,00	24,00
2C	24,91	18,25	22,58
2D	24,00	17,30	19,90
3B	26,50	20,20	22,14
3C	29,40	21,36	23,33
3D	28,50	16,13	19,60
4B	32,00	21,67	19,45
4C	32,14	19,70	17,80
5B	21,55	19,86	19,57
5C	25,14	16,00	11,30
average	25,74	20,38	19,70

Table 11: SDAS of each grid area

Due to the small size of each grid area, it was only possible to take a single representative SDAS measure for each of the defined areas. From their comparison (see Table 10) it's clear how the cooling techniques yield far better result than the simple conductive coatings do in the normal production. Recalling that the air-cooling technique will bring the temperature of the mold in the affected area down to a steady 200°C, while the water-cooling technique will bring it temporarily to 250° C then allows it to raise to 300° ~ 350° C, it's of particular interest how little this seems to affect the dendritic arm size, with both techniques displaying similar results.

In any case, both techniques result in a far better SDAS parameter than the normal production would have, where the temperature of the mold in the affected area used to hover around 380° ~ 400° C.

10 Conclusions

The experimental analysis performed on the oil pan allowed to identify the source of its casting defect to be due to the high temperatures reached by the mold in regime operations, especially in the oil cap area where, due to the particular geometry of the casting cavity, it's not possible to install a riser even though it should be needed. It was concluded that, at the end of the production run, when the mold coatings are consumed and wore down, the thermal gradient imposed by the coatings themselves is lost, losing also the imposed directional solidification which causes the occurrence of hotspots, leading to shrinkage porosities.

Different solutions may be devised to solve this problem, from more economical ones like the use of more resilient coatings, to more extreme ones like the redesign of the mold itself from scratch. Before taking more extreme corrective actions, an experimental run was performed in order to see whether a localized cooling of the critical area could lead to the solution of the problem or not. The logic behind this solution was due to the nature of the shrinkage porosities nucleation, which occur when a section of the casting solidifies around a molten area (hot spot), which can't be fed with material anymore and will slowly contract due to the volumetric shrinkage associated with the solidification process, leaving empty spaces between the dendritic structures. If it was possible to cool down the affected area fast enough to impose a solidification gradient from pin core towards the feeding channels, so that the thicker section could be continuously fed until it fully solidified, then the resulting structure would not display shrinkage porosities and result defect free.

Therefore, an experimental run was planned in order to quantify the effects of a localized cooling of the mold in the corresponding affected area of the casting with a nebulized water spray. From the specimens obtained in the experimental run it was possible to see a stark reduction of shrinkage porosities presence. The dendritic structure resulted much finer and homogeneously distributed, improving the mechanical properties of the affected area as well.
After validating the concept, a more consistent and viable solution was adopted by modifying the mold in order to incorporate a compressed air cooling channel trough the mold near the pin core, which would bring down the temperatures of the affected area to values near to what the nebulized water spray would obtain, but in a more consistent way and without the thermal stresses resulting from a room-temperature water spray hitting a 400° C hot mold.

The air-cooled solution proved to solve the manufacturing problem for this particular part, opening the door for alternative solutions to different products that display similar problems. The air-cooling circuit has been fully implemented to the casting cycle of the oil pan production and has been in use on this particular product since then.

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