POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

Master's Degree in Mechanical Engineering

Master's Thesis

Analysis and optimization of Zinc alloys die casting process

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April, 2021

Contents

Abstract

Process optimization to improve quality of parts, to enhance production times and, consequently, to reduce costs, is a crucial element in manufacturing companies. The aim of this Thesis, result of my five months internship at the Quality department of Dynacast Italia Torino S.p.A. in Grosso (TO), is to introduce efficient improvement actions to the current hot chamber die casting process of zinc components.

For this purpose, it is first necessary to provide a general introduction to Zamak alloys, offering an overview of their composition, mechanical properties and influence of alloying elements, outlining also the basic functioning principles of hot chamber die casting machines which, combined with the versatility of zinc alloys, allow the reaching of high quality performances within advantageous times and costs.

After a detailed casting defects analysis, considering all the possible formation causes and potential negative effects on the final product (reduced strength, aesthetic or functional problems), researches performed in Dynacast, during the internship experience, demonstrate that continuous quality improvement studies are necessary to define efficient action plans to prevent defects occurrence; for this scope, the thesis work reports practical corrections implemented that have resulted in tangible quality benefits, reducing waste during production and saving costs. Ishikawa diagram is the tool used during the internship to detect potential causes of a problem, in order to perform quality defect prevention.

At this point, the thesis work focuses on the importance of introducing automated technology in the production process and simulation software in the Research and Development activity as well as on the necessity of setting adjustments on the basic casting parameters. The enhancement of the melt injection phase, resulted from the optimization of parameters like nozzle temperatures, specific casting pressures and die temperatures, in fact, can determine a consistent improvement of the production final quality, reducing scrap parts.

All these considerations, as this work aims to demonstrate, are the evidence of the importance of ever-increasing process improvements in order to allow Zinc alloys die casting industry to have a competitive advantage in the market, especially in the automotive field, thanks to the benefits that casting components produced with this technology can offer.

1. *Introduction to Zama alloys*

1.1 Composition and mechanical properties

Zinc alloys are excellent materials for the production of resistant, aesthetically appealing and complex shaped components: they can indeed be used to meet the requests of various and different sectors, such as automotive, building, cosmetics, toys and so on, ensuring high performance standards, both from a functional and an aesthetical point of view. Taken into account the different characteristics required by each sector, it is therefore fundamental to conduct a thorough analysis of zinc alloys with the aim of identifying the most appropriate one for the purpose we would like to reach, examining product requirements and looking for an alloy with the right properties to meet these demands.

In order to conduct this analysis, it is essential to know zinc alloys classification; they can be divided into two main categories: ZAMAK alloys and zinc alloys classified with the prefix ZA, which have a remarkable higher percentage of aluminium compared to the previous ones and have therefore a greater resistance.

The New Jersey Zinc Company developed Zamak alloys in 1929. With the passing of time, ‘’Zamak’’ (or ‘’Zama’’ to abbreviate) has been chosen as the common name to define all zinc alloys for die casting process. Only with the introduction of several types of alloys, zinc alloys have been subdivided in ZAMAK and ZA alloys; however, ZAMAK is still considered the most common and conventional name to indicate a zinc alloy.

The name ‘’Zamak’’ is an acronym of the German names of the main metals that compose the alloys: Zink (Zinc), Aluminium, Magnesium and Kupfer (Copper); these elements occur in zinc alloys in different percentages, determining different characteristics that affect the die cast features and final applications.

Die casting alloys and die casted parts must respect quality specifications defined by UNI standards. Zinc alloys chemical composition standards differ according to the country [1], as shown below (*Table 1*):

Country	*Zinc ingots*	*Zinc casting*
Europe	EN1774	EN12844
US	ASTM B240	ASTM B86

Table 1: Zinc alloy chemical composition standards defined per country

The Short European Designation code is below explained using an example (ZL0430):

- Z indicates the material (Z = Zinc)
- Second letter (P or L) indicates the use (P in case of pressure die casting parts, L for ingots)
- 04 is the aluminum content (04 = 4% aluminum)
- 3 is the copper content (3 = 3% copper)

In the European context, composition and characteristics of the most common zinc alloys, used in die casting, are indicated in the EN 1774 Zinc and zinc alloys Ingot and liquid, whereas composition and characteristics of the die-casted parts can be found in the EN 12844 European Standard for Zinc Alloy Castings.

The main zinc alloys used in hot chamber die casting process are Zamak 5, Zamak 2 and Zamak 3.

1.1.1 Zamak 5

Zamak 5 is the most commonly used zinc die casting alloy in Europe; it conforms to EN 1774 1997 Ingot Specification [1] and is a versatile high-grade zinc alloy. It has excellent castability (therefore tends to be used for small intricate castings) and, compared to Zamak 3, it contains an higher copper percentage leading to higher strength and hardness and better creep resistance. On the other side, this greater copper quantity is responsible for higher price and a lower ductility that can affect the alloy formability during secondary operations. Similarly to Zamak 3, Zamak 5 is an excellent choice for products that require surface finishing treatments.

Alloying elements content is reported in *Table 2*:

	Min %	Max %
Al	3,8	4,2
Cu	0,7	1,1
Mg	0,035	0,06
Zn	Remaining to 100%	

Table 2: Zama 5 chemical composition according to EN 1774 1997 Ingot Specification

Limit values of other elements, considered impurities for Zama alloys, are contained in the below table:

	Max %
Iron	0,020
Lead	0,003
Cadmium	0,003
Tin	0,001
Nickel	0,001
Silicon	0,02

Table 3: Zama 5 impurities concentration limits according to EN 1774 1997 Ingot Specification

Lastly, *Table 4* reports as cast physical and mechanical properties:

Casting temperature	°C	405-425
Freezing Range	°C	379-388
Solidification	cm/m	1,17
Casting Shrinkage	mm/mm	0,006
Thermal conductivity	W/m·°C	108,9
Thermal Expansion Linear per °C	-	28x10^6
Tensile strength at 20°C	N/mm^2	328-270
Elongation at 20°C	% in 2in	7-13
Impact strength at 20°C	J	54-65
Hardness	BHN	92-80

Table 4: Zama 5 as cast physical and mechanical properties

1.1.2 Zamak 2

Zamak 2 is used selectively for small castings where high as-cast tensile strength and hardness are required: it is indeed the most resistant zinc alloy. Aluminum percentage is equivalent to that of Zamak 3 and Zamak 5; copper quantity, on the contrary, is definitely higher: it can reach 3,3%, providing an excellent strength to the alloy. However, this considerable amount can lead to the alteration of specific characteristics of the alloy over time: during metal aging it is indeed possible to observe a slight dimensional change as well as performance decrease, which can reach similar levels to those of aluminium alloys.

As a matter of fact, the main disadvantage when employing Zamak 2 is the performance reduction, especially ductility over time, induced by ageing. Despite this, the alloy remains an excellent material for die casting thanks to its exceptional castability.

Alloying elements content is reported in *Table 5*:

	Min %	Max %
Al	3,8	4,2
Cu	2,7	3,3
Mg	0,035	0,06
Zn	Remaining to 100%	

Table 5: Zama 2 chemical composition according to EN 1774 1997 Ingot Specification

Limit values of other elements, considered impurities for Zama alloys, are contained in the below table:

	Max %
Iron	0,020
Lead	0,003
Cadmium	0,003
Tin	0,001
Nickel	0,001
Silicon	0,02

Table 6: Zama 2 impurities concentration limits according to EN 1774 1997 Ingot Specification

Lastly, in Table 7 as cast physical and mechanical properties have been reported:

Casting temperature	°C	425-435
Freezing Range	°C	378-390
Solidification	Cm/m	1,08
Casting Shrinkage	Mm/mm	0,006
Thermal conductivity	W/m°C	105
Thermal Expansion Linear per °C	-	28·10^6
Tensile strength at 20°C	N/mm^2	338
Elongation at 20°C	% in 2in	8
Impact strength at 20°C	J	46,8
Hardness	BHN	100

Table 7: Zama 2 as cast physical and mechanical properties

1.1.3 Zamak 3

Zamak 3 is the most used zinc alloy in North America because of its excellent castability and dimensional stability over time. Zamak 3 has a superior dimensional stability compared to the other Zamak alloys, however this is only significant when very narrow tolerances are required. As far as resistance is concerned, Zamak 3 is characterized by a low percentage of copper that implies a lower strength compared to Zama 2 and Zama 5 but, at the same time, it reduces the likelihood of alterations due to material aging, thus avoiding dimensional shrinkage and maintaining a constant performance over time.

This zinc alloy is also suitable for the production of components that need surface finishing treatments.

The alloy mechanical and physical properties make it ideal for casting components for automotive industry, household and office equipment, hardware components, locks, toys, etc.

Alloying elements content is reported in the following table:

	Min %	Max %
Al	3,8	4,2
Cu	-	0,03
Mg	0,035	0,06
Zn	Remaining to 100%	

Table 8: Zama 3 chemical composition according to EN 1774 1997 Ingot Specification

Limit values of other elements, considered impurities for Zama alloys, are contained in the below table:

	Max %
Iron	0,020
Lead	0,003
Cadmium	0,003
Tin	0,001
Nickel	0,001
Silicon	0,02

Table 9: Zama 3 impurities according to EN 1774 1997 Ingot Specification

Lastly, in *Table 10* as cast physical and mechanical properties have been reported:

Casting temperature	°C	405-425
Freezing Range	°C	382-387
Solidification	cm/m	1,17
Casting Shrinkage	mm/mm	0,006
Thermal conductivity	W/m°C	113
Thermal Expansion Linear per °C	-	28x10^6
Tensile strength at 20°C	N/mm^2	283-241
Elongation at 20°C	% in 2in	10-16
Impact strength at 20°C	J	56,9
Hardness	BHN	82-87

Table 10: Zama 3 as cast physical and mechanical properties

Zamak 5 and Zamak 2 can be chosen for pieces that work at temperatures between 100 and 150°C [2].

1.2 Influence of alloying elements and impurities on zinc alloys

Each alloying element has different effects on material mechanical and physical properties, that vary depending on the quantity in which it's present.

1.2.1 Aluminium

First of all, aluminium reduces the melting point of the zinc alloy, lowering the thermal energy required by machines and granting energy saving. It also reduces chemical attack towards steel and, from the moment that both melting pot and die are made of steel, this means a longer tool life. Moreover, it improves the fluidity of the alloy, allowing the realization of thinner depths and ease molding. If an alloy loses aluminum, its fluidity lowers as well increasing the risk of hot cracking appearance.

Researches have demonstrated that an aluminium content of 3,8 – 4,2% allows the highest mechanical properties, combined with good castability. Indeed, undoubtedly, aluminum must be higher than 0,3% in zinc alloys, otherwise it would negatively affect creep resistance; for what concerns castability, the maximum peak can be reached with 5,1% of Al.

Considering most used alloys behaviour, Zamak 3 hasn't showed tensile strength variation or dimensional stability variation in the range of 4,1 – 4,8%; on the other hand, for values of Al higher than 4,4% it has evidenced a decrease in the elongation as well as in the resilience. Doing the same considerations for Zamak 5, a drop in resilience has been verified starting from 4,5% Al, as well as a drop in elongation from 4,2%. For these reasons maximum value of Aluminum has been set to 4,2%.

1.2.2 Copper

It is the third component in order of quantity in Zamak alloys. Its amount can vary from 0% to 3,3%. Differently from aluminium, which is always contained in the alloy, copper is optional: this because, even if its presence can improve mechanical strength, hardness and wear, at the same time, it can reduce elongation percentage at breaking point and alloys resilience. In addition, it can also cause dimensional instability, determining an increase in the cast dimensions with the passing of time.

The following analysis aims to show the effect of Cu addition in a zinc alloy with 4% of Aluminum.

- Mechanical properties improvement

Cu (%)	*Increase of resilience (%)*	*Increase of tensile strength (%)*	*Increase of hardness (%)*
0,06	+12	+4	-2
0,30	+8	+7	-2
1,0	+12	+16	+11
2,7	-20	+24	+23

Table 11: Mechanical properties with addition of Cu to Zn alloy with 4% of Al and 0,04% of Mg as alloying elements.

- Dimensional variation after 1 year ageing at 95°C

Cu (%)	*Linear expansion (%)*
0	0,0002
0,5	0,0004
1	0,0015
1,5	0,0020
2	0,0029
3	0,0038

Table 12: Linear expansion with addition of Cu to Zn alloy with 4% of Al and 0,04% of Mg after 1 year ageing at 95°C.

- Resilience reduction in the long term

Cu (%)	After 20 days ageing at 95°C	
	Rupture (%)	*Resilience (%)*
0	*-18*	*-7*
1	*-20*	*-43*
2	*-11*	*-77*
2,7	*-13*	*-92*
	After 10 years at environmental temperature	
0	*-16*	*-3*
1	*-18*	*-17*
2	*-10*	*-60*
2,7	*-6*	*-89*

Table 13: Resilience in function of Cu addition to Zn alloy with 4% of Al and 0,04% Mg after different ageing types.

For these reasons Zamak 5 has been developed with around 1% Cu, obtaining an alloy dimensionally more stable and more able to preserve resilience than Zamak 2.

1.2.3 Magnesium

Magnesium can be added as alloying element to contrast intergranular corrosion but, on the other side, if in quantity higher than 0,05%, it can negatively affect fluidity. Other effects linked to magnesium presence are: increased alloy hardness, higher risk of hot cracking and other problems related to surface finishing.

Considering the addition of Magnesium to a Zinc alloy with 4% of Aluminum, with values of Mg up to 0,05% it is possible to register an increase of tensile strength and life of 20% and a reduction of ductility of 50%; instead, for values higher than 0,06% the alloy shows a decreased resilience. Comparing tests performed at 95°C in dry or wet atmosphere, it’s possible to highlight Mg positive effect against intergranular corrosion. Moreover, Mg decreases the alloy fragility at low temperature and, when in quantity 0,1%, it determines the embrittlement at high temperatures.

1.2.4 Impurities

Concerning impurities, low amounts of Pb, Cd and Sn are admitted [3], due to their negative effect; indeed, the presence of impurities favours intergranular corrosion causing rapid ageing of the alloy and a reduction of the technological characteristics of die casted parts.

Since die casting process could cause alloy contamination, standards allow higher values of impurities in the die-casted parts, compared to ingots.

Impurities check is extremely important; foundry should therefore be structured to avoid alloy contamination. Spectrographic analysis is usually used to have rapid results.

1.3 New high strength zinc alloy: EZAC

When Zinc die casting was introduced, zinc alloys were considered a lightweight and low cost material in comparison to the other available die casting alloys such as tin and lead [4]. Although Zinc has always been known and used for its high strength, development of Zama family and later of EZAC for die casting process, has increased even more its application fields.

Before EZAC, Zinc was often overlooked for applications requiring high-temperature tensile strength. In fact, most zinc alloys have a low creep resistance when compared with other materials.

The EZAC alloy is the answer to a high strength, creep resistant zinc alloy for hot chamber die casting process. Its benefits include superior creep resistance, higher yield strength and hardness when compared with properties of the other zinc alloys. EZAC, indeed, tested in creep conditions (in this case, with a constant stress of 31MPa and temperature of 140°C) performs approximately fourteen times longer than Zama 2 and three times longer than ACuZinc5, achieving 730 working hours before failure [4].

Mechanical properties in standard conditions of some die casting alloys are reported in *Table 14*; EZAC is the most resistant material of the considered alloy; it is approximately 2,5 times stronger (considering yield strength) and 1,5 times harder (in Brinell scale) than A380 (the most common aluminium die casting alloy).

Alloy	Base material	Yield Strength (0,2%) *PSI x 10^3*	Hardness *Brinell (HB)*
Zamak 3	Zinc	32	82
EZAC	Zinc	57	120
A380	Aluminum	23	80
AZ91D	Magnesium	23	63

Table 14: Different die casting alloys mechanical properties comparison

In Table 15 EZAC has been compared with Zama 2 (the strongest Zamak alloy):

Alloy	UTS (*MPa*)	Yield (*MPa*)	Strain (*%*)	Charpy impact strength (*Ft-lbs*)	Hardness (*Rockwell B*)
EZAC	416,2 +/- 70,5	396 +/- 21,6	0,93 +/- 0,5	2	68
Zamak 2	332,0 +/- 15,3	278,8 +/- 9,5	4,0 +/- 1,6	3	57

Table 15: Mechanical properties of different hot chamber die casting zinc alloys

With an average yield strength of 396 MPa, comparable to that of ZA-27 (the strongest zinc alloy for cold chamber die casting), EZAC is 42% stronger than Zamak 2. Furthermore, considering EZAC hardness, it is 19% higher than that of Zamak 2.

Moreover, if on one side EZAC exhibits low elongation (approximately 1%) in comparison with Zamak 2 (see *Table 15*), on the other hand its impact strength is comparable with that of ACuZinc5 (about 2,2 Ft-lbs).

Lastly, compared with other high strength zinc alloys such as ACuZinc5 and ZA27, EZAC has shown excellent castability properties and a good resistance to wear [5].

1.3.1 Testing at high temperature

In order to deepen the comparison between zinc alloys for hot chamber die casting, results of tensile tests performed at 100°C (contained in *Table 16* and *Table 17*) have been analysed.

Outcome of the study has demonstrated EZAC tensile strength to be also higher at elevated temperature compared to that of Zama alloys.

Moreover, also in these temperature conditions, Zamak 5 has proven to have the highest strain percentage compared to the other two analysed materials (see *Table 16*).

Alloy	UTS (*MPa*)	Yield (*MPa*)	Strain (*%*)
EZAC	265,4	165,1	4,5
Zamak 2	212,7	150,7	10,5
Zamak 5	186,8	131,3	14

Table 16: Different zinc alloys tensile strength at 100°C [4]

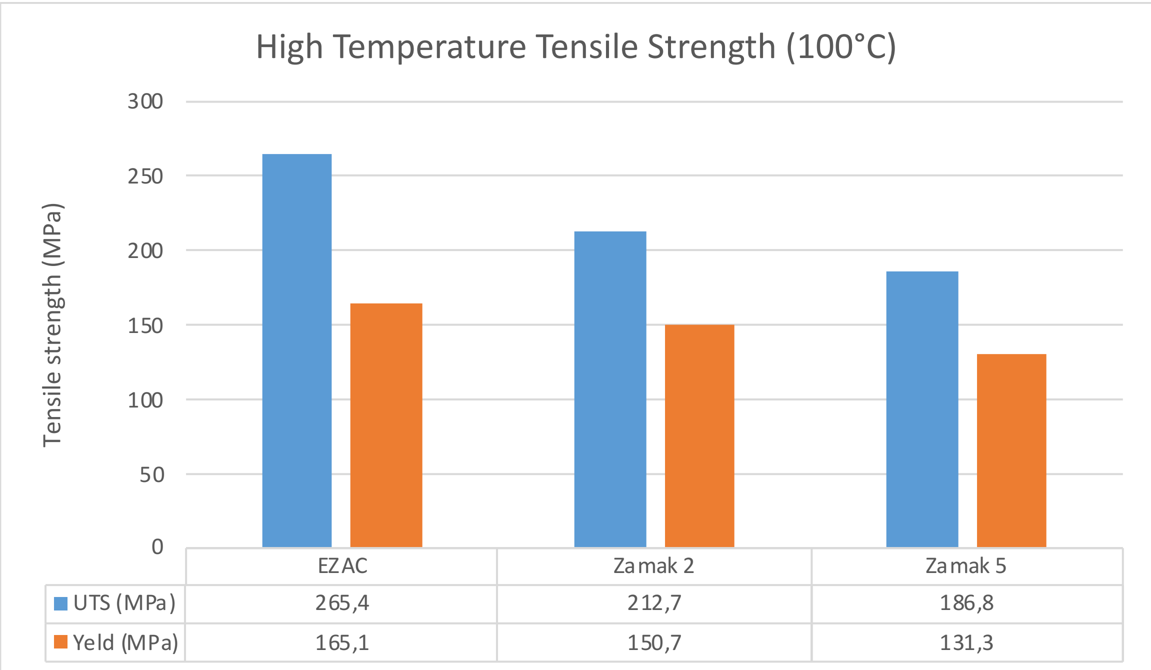


Figure 1: High temperature tensile strength diagram for zinc alloys

Evaluating data reported in *Table 17,* about EZAC and Zamak 2 creep properties, it is evident that the first has a superior resistance than the second one. Indeed, while EZAC takes more than 700 hours to fail, with a quite low creep rate (0,004 mm/hr), Zamak 2 time to failure is of 52 hours and its minimum creep rate is about 0,152 mm/hr. Furthermore, also elongation at failure, higher in the case of Zamak 2, has proven EZAC ability to better withstand high temperature test.

Alloy	Time to failure (*hrs*)	Minimum creep rate (*mm/hr*)	Elongation at failure (*mm*)
EZAC	731	0,004	6,7
Zamak 2	52	0,152	9,0

Table 17: EZAC and Zamak 2 behaviour in creep conditions

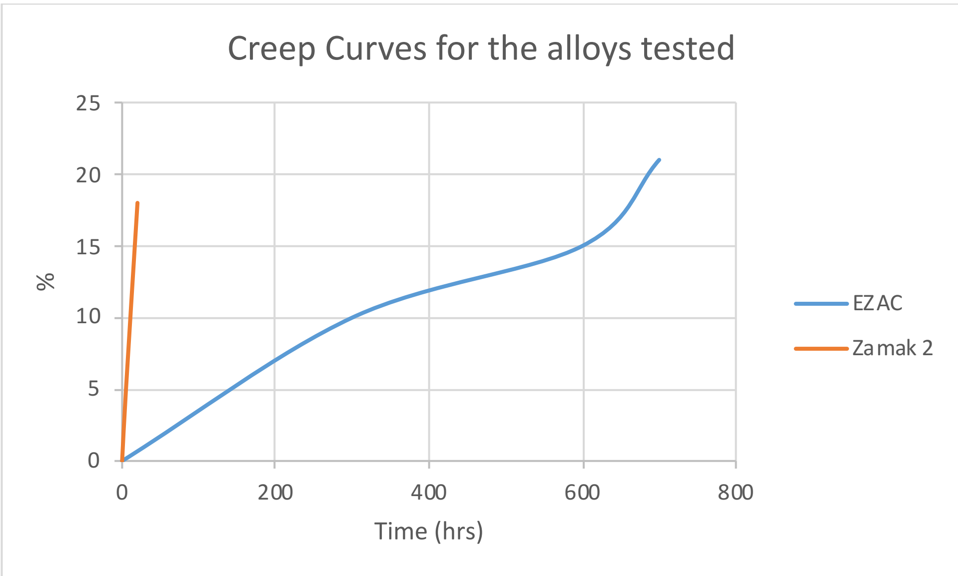


Figure 2: Creep curves for the tested Zinc alloys

1.4 Overview of ZA-27 alloy in cold chamber die casting

Zinc-aluminum alloys were first introduced for Gravity Casting; nowadays, they are used as materials for High Pressure cold chamber Die Casting.

ZA alloys have zinc as base metal and are characterised by higher Aluminum concentrations than traditional zinc alloys. An example is ZA-27, that is composed of 27% Aluminum and 2.2% of Copper. Easily machinable and efficiently recyclable, this zinc - aluminum combination is lightweight and is best suited for applications that require high tensile strength.

In addition to the already mentioned characteristics, other important benefits of ZA-27 alloy are:

- High hardness
- Good corrosion resistance
- Wear resistance
- Good bearing and creep properties

The high strength property of ZA-27, combined with its castability, enable to design resistant parts but at the same time, reducing the overall metal content that competing materials would require. The use of ZA-27, indeed, allows to cast stronger parts with thinner walls.

Dynacast customers that had failing parts of A380, made the switch to ZA-27 and more than doubled their yield strength.

1.4.1 ZA-27 alloy applications

ZA-27 is three times stronger than typical cast aluminum and can have the tensile strength of grey cast iron.

For previously described reasons, ZA-27 can be used for a variety of different projects but is best chosen in bearing applications. It is easily machined and castings can be readily polished, plated, painted, or anodized. Due to its high melting point, ZA-27 is suitable for projects with service temperatures of around 150°C [5]. Its anti-sparking property gives it the ability to act as a natural bearing, inevitably offering to the automotive industry cost savings as well as maintenance advantages over other metals use.

Other fields of application of ZA-27 include:

- Aeronautics
- Agricultural machinery
- Construction and building
- General engineering
- Textile machinery

1.5 Introduction to Aluminum die casting

Aluminum is one of the most versatile and largely available material on Earth; in addition to its low density, high strength-to-weight ratio and good corrosion resistance properties, it is 100% recyclable (with no mechanical or physical properties deterioration).
Its recycling process, further to the positive impact on the environment, uses about 5% of the energy required to produce primary material, allowing the elimination of costs that would otherwise increase the price of components.
While some sectors (aerospace, for instance) require properties of virgin aluminum, most industries can achieve the desired performances (in terms of durability, strength, and corrosion resistance) with recycled secondary aluminum.

A380 is one of the most common aluminum alloys and has significant benefits: in addition to offering the best combination of casting, mechanical and thermal properties, it exhibits excellent fluidity and resistance to hot cracking. For these reasons, it is used for a wide variety of products: chassis for electronic equipment, engine brackets, gearbox cases and hand tools.

1.6 Die cast alloys mechanical properties comparison

Stress - Strain diagram of die cast alloys has to be considered in the design phase of a component in order to know ultimate tensile strength and elongation properties. Indeed, the choice of the right material starts comparing mechanical characteristics of each alloy in consideration of the project needs.

Although the relatively high strength of Aluminum alloys, their low ductility represent a limit when it is necessary a more deformable material. In this case, Zamak alloys better meet the requirement (see *Fig. 3*).

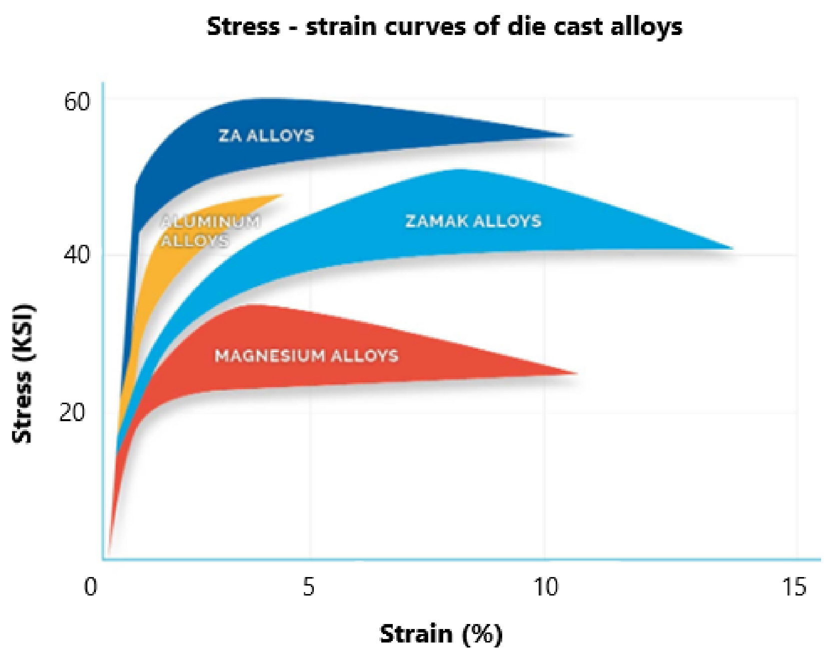


Figure 3: Stress and strain curves of die cast alloys [5]

ZA alloys, produced through cold chamber die casting technology, have higher tensile strength with respect to ZAMAK alloys, that are instead casted through hot chamber process. On the other hand, ZAMAK alloys reach higher elongation percentages during tensile tests (as shown in *Figure 3*).

1.7 Effect of ageing on Zama alloys

An important phenomenon to deepen is ageing and, in particular, the alloy phases tendency to achieve chemical equilibrium at environmental temperature [6].

Considering Zn-Al-Cu ternary diagram, it is possible to state that, while at elevated temperature the alloy can solve up to 1,2% Al and 2,8% of Cu, at environmental temperature, these values respectively drop up to 0,1% and 0,5%. Moreover, β phase, rich in Aluminum, transforms at 275°C in β', with precipitation of η phase. However, the reaching of the equilibrium conditions takes months or even years.

After ageing, Zama alloys evidence a decrease of mechanical properties; reduction of 20% can be reached in case of lower thicknesses components.

Artificial ageing at higher temperatures (in the range of 75 - 100 °C) accelerates mechanical and dimensional properties variation [7].

Most used Zama alloys have been tested in order to understand their resistance to natural and artificial ageing. *Table 18* and *Table 19* report some recorded data.

Elongation *(%)*:

	ZAMAK 2	ZAMAK 3	ZAMAK 5
After 6 months ageing in dry atmosphere	1,5	9	2,3
After 2 years ageing in dry atmosphere	1,2	7	2,2

Table 18: Zama alloys elongation (%) in function of ageing at 95°C in dry atmosphere

Fatigue resistance *(MPa)***:**

	ZAMAK 3	ZAMAK 5
After 6 months naturally ageing	48,2	57,5
After 6 hours ageing at 95°C	45,7	74
After 5 days ageing in dry atmosphere	41,9	40,1

Table 19: Zama alloys fatigue resistance (MPa) – 166 cycles/minute – 10^8 cycles

While natural ageing doesn't significantly influence zinc alloys fatigue strength, in dry atmosphere Zamak 5 resistance shows an important decrease, becoming lower than Zamak 3 (see *Table 19*)

In case of parts subject to vibrations, thin thicknesses and ribbed paths are adopted, allowing better quality (finer grains, no porosity), higher inertia (due to ribs) and lower stresses (reduced weight).

1.7.1 Results after 4 years ageing

In order to have a complete overview, in this section have been reported results of tensile tests performed to study the behaviour of three different Zamak alloys under the effect of ageing.

1.7.1.1 Maximum tensile strength

In *Table 20* maximum tensile strength values (σ_{max}) of three different Zamak alloys have been reported in function of ageing time (from 1 day to 4 years).

	Max. strength *(MPa)*		
Time	ZA2	ZA3	ZA5
1 day	441	383	410
8 days	454	371	405
14 days	439	365	391
30 days	430	343	376
61 days	414	342	365
183 days	402	327	347
1 year	403	319	338
2 years	403	313	343
4 years	420	313	331

Table 20: Zinc alloys maximum tensile strength in function of ageing time

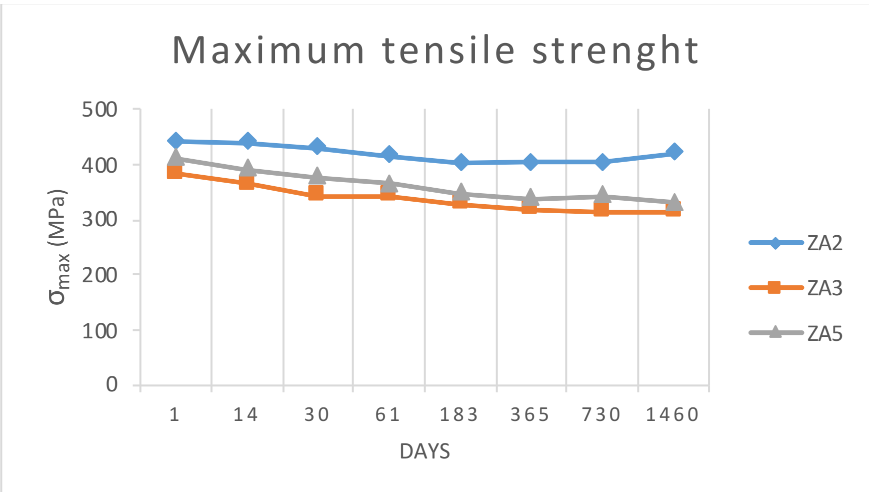


Figure 4: Zinc alloys maximum tensile strength in function of ageing time

1.7.1.2 Elongation at break

Table 21 and graph contained in *Figure 5* show elongation at break (ε_{max}) of three different Zamak alloys in function of ageing time (until 4 years).

Time	ZA2	ZA3	ZA5
1 day	4,2	2,38	2
8 days	2,1	2,96	2
14 days	1,5	2,78	1,8
30 days	1,6	3,2	1,9
61 days	1,6	2,5	1,84
183 days	1,7	2,79	2,18
1 year	2	2,87	2,03
2 years	2,1	2,68	2,4
4 years	2,36	2,33	2,15

Table 21: Zama alloys elongation at break (ε_{max}) in function of ageing time

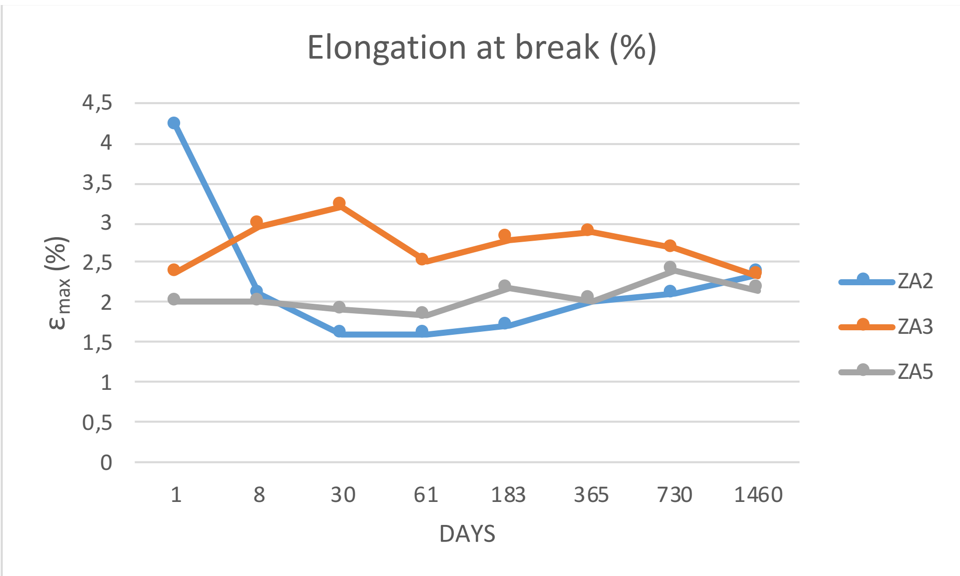


Figure 5: Diagram of Zinc alloys elongation at break (ε_{max}) in function of ageing time

1.7.1.3 Tensile strength at break

Table 22 and graph below instead show tensile strength at break in function of ageing time (from 1 day until 4 years) for three different Zamak alloys.

Specimens cooled in air have been tested.

Time	ZA2	ZA3	ZA5
1 day	422	369	406
8 days	436	351	394
14 days	395	324	380
30 days	385	222	362
61 days	334	203	340
183 days	342	165	291
1 year	386	190	289
2 years	391	176	283
4 years	418	142	254

Table 22: Zama alloys breaking strength of air cooled specimens aged until 4 years

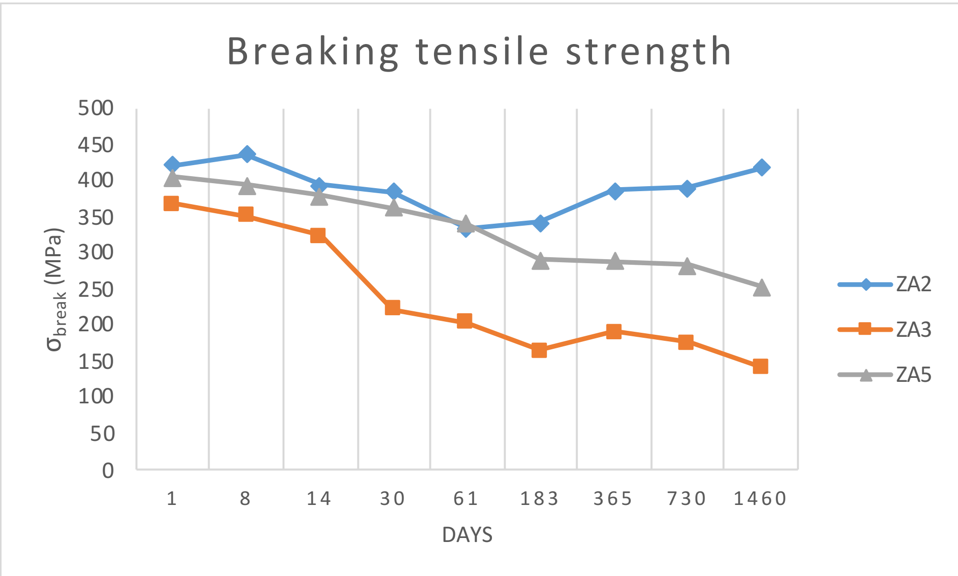


Figure 6: Zama alloys breaking tensile strength of air cooled specimens aged until 4 years

1.7.1.4 Vickers hardness

Hardness values of three different Zamak alloys in function of ageing time (from day 1 to the fourth year) can be found in *Table 23*. Hardness has been measured according to the Vickers test method.

Time	ZA2	ZA3	ZA5
1 day	149	119	136
8 days	148	115	134
14 days	146	112	132
30 days	141	103	125
61 days	139	105	119
183 days	133	102	117
1 year	128	97	110
2 years	131	94	106
4 years	133	96	105

Table 23: Zama alloys Vickers Hardness in function of ageing time of air cooled specimens

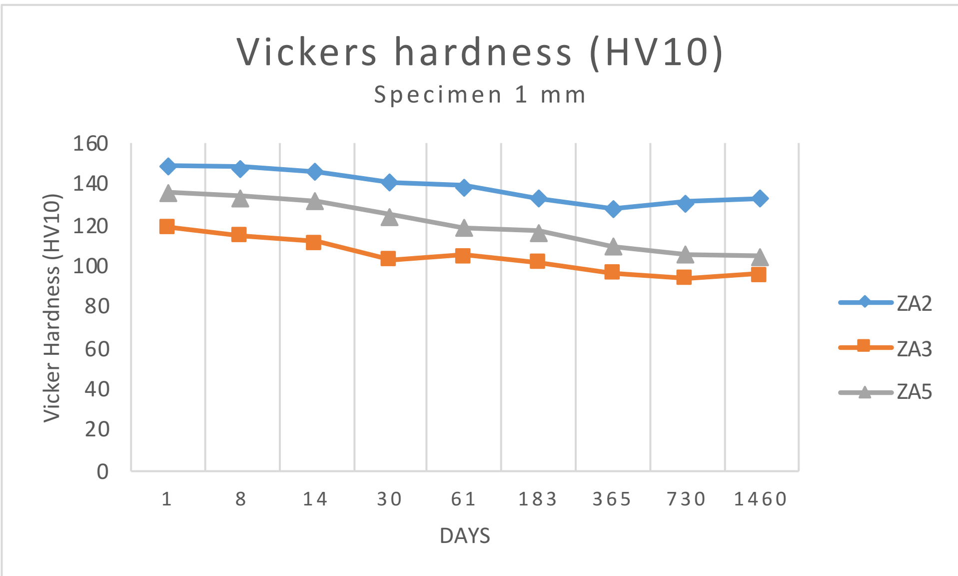


Figure 7: Diagram of Zama alloys Vickers Hardness in function of ageing time of air cooled specimens

2 Casting processes overview

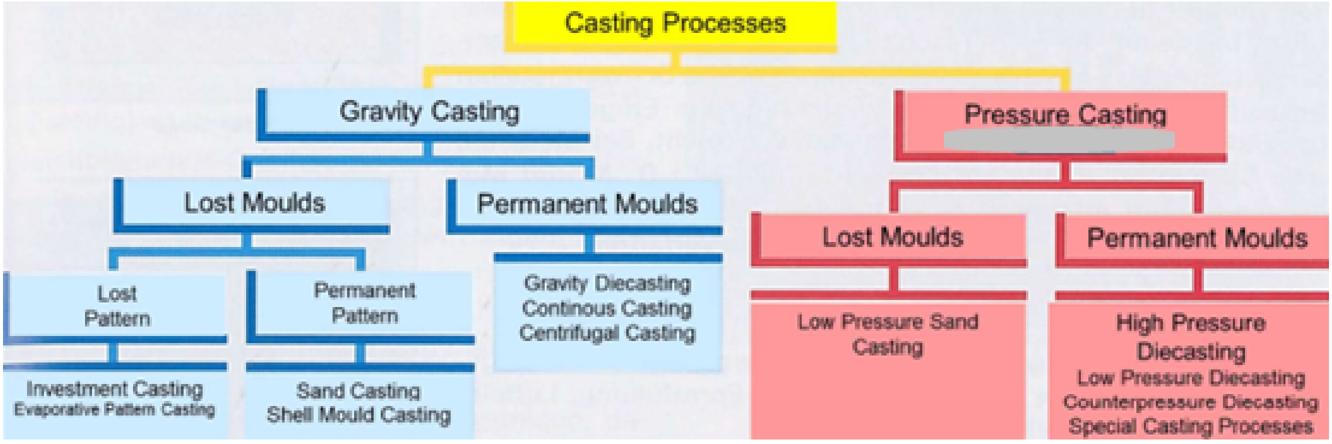


Figure 8: Casting processes – Gravity casting and pressure casting

Casting processes can be firstly distinguished in two main categories: Gravity Casting and Pressure Casting. The main difference lies on the mould filling methods: ''Gravity'' suggests that the melt is poured thanks to gravity force, while ''Pressure'' indicates the molten metal injection through a press. In both cases, moulds can be permanent (if they are reusable) or lost (if they can be used only once).

Focusing on the use of permanent moulds, gravity die casting process allows a lower surface finishing quality compared to high pressure die casting and doesn't enable to obtain complex geometries, that are easily achieved with pressure die casting.

<u>High Pressure Die Casting</u>

In High Pressure Die Casting, the alloy, previously liquefied in a furnace, is injected by hydraulic pistons at a high pressure (250 bar for hot chamber machines and up to 800 bar for cold chamber machines) into a hardened steel permanent mould. Filling is completed in an extremely short time (from 10 to 100 milliseconds, depending on part thickness, material to be injected and die properties).

The most widely-used materials in this process are aluminium, magnesium and zinc alloys; pure materials, instead, do not have the required properties.

Materials for high pressure die casting processes

Aluminium is a lightweight material, used in the 70% of total casting production thanks to its good elongation properties, corrosion stability and mechanical strength.

Zinc, instead, has a quite good elongation, a tensile strength similar to Aluminum and a low casting temperature (from 410°C to 430°C). Despite its high weight and problems related to high temperatures (creep phenomenon) and ageing, the possibility to produce high quality components with an easier process (in comparison with Aluminum), allows Zinc to be employed for several applications.

Magnesium is the lightest material that can be processed in a die casting machine, for this reason it is ideal for applications that require a low specific density alloy (mobile phone frames, to make an example). Furthermore, due to its low corrosion resistance, it can be used to cast indoor parts, painting the surface in order to protect them from oxides attacks.

Alloy	Material Designation	Brinell Hardness	Tensile strength (N/mm^2)	Casting temperature (°C)
Al DIN EN 1706	AlSi12(Cu)	90	240 - 300	640 - 770
Mg DIN EN 1753	MgAl9Zn1	75	190 -250	630 - 660
Zn DIN EN 12844	ZnAl4Cu1	92	280 - 330	410 - 430

Table 24: Die casting alloys comparison

Machines for high pressure die casting processes

Machines used for High Pressure Die Casting can be divided in two categories, that are mainly differentiated by the placement of the chamber in which molten material is collected just before the injection.

The reason of the existence of these two typologies is mainly due to the fact that traditional hot chamber die casting machines, that allow the production of zinc components, can't be used for all materials; indeed, considering liquid Aluminum, for instance, it would tend to attack injection system steel components, determining their destruction, and so the need to constantly replace them. Furthermore, released iron particles would increase melt contamination, directly affecting final parts properties. To overcome this problem, cold chamber machines, that work with a reduced contact time of steel components with high temperature melt, have been introduced.

3 *Benefits and drawbacks of Zinc die casting*

When designing components and selecting the right alloy to cast, most engineers base the material choice on the weight, which is why Zinc is often overlooked when it comes to lightweight applications. Indeed, since most industrial sectors require light parts (especially in automotive), Aluminum or Magnesium are preferred by designers, when Zinc could be a cheaper option with similar results.

- *Accuracy*

Zinc die casting process allows to achieve tighter tolerances, compared to those reachable with Aluminum and Magnesium die casting, without any secondary operation. If with aluminum alloys it is possible to cast an internal diameter within a tolerance of +/- 100 microns, with Zinc we can reach tolerances of +/- 25 microns [5]. Few other processes enable to have the same net shape performance.

- *Castability*

The exceptional fluidity, typical of zinc alloys, allows the production of thinner, intricate and more complex parts, eliminating the need for secondary operations that are necessary for aluminum and magnesium alloys. Thin-wall components, being lighter, determine savings in material costs and energy.

- *Extended Die Life*

One of the biggest upfront costs in die casting is the investment in quality tooling. Tools used in die casting process are usually made of heat-treated steel. Their cost vary depending on the size and complexity of components to be produced as well as on the tooling type (conventional or multi-slide machines). Due to the low melting temperature of zinc die casting alloy, dies can last up to 10 times longer than moulds used for Aluminum and about five times longer than those used for Magnesium. When producing complex parts in very high quantity, Zinc becomes extremely cost effective, taking into account the tooling investment.

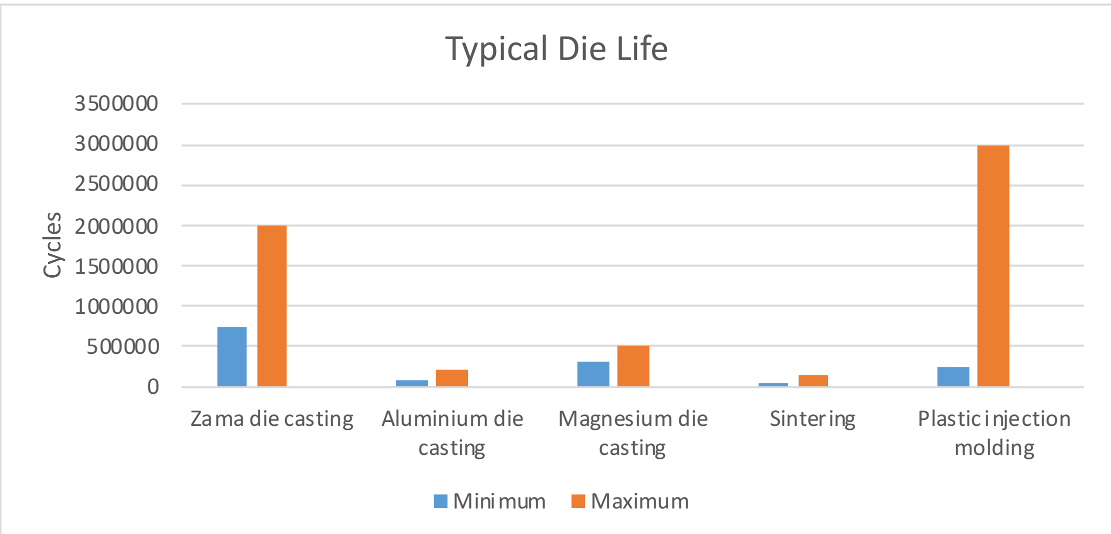


Figure 9: Die life diagram to compare different materials

- *Cycle Time*

In the die casting process the molten alloy is injected into the die to create the part. When metal solidification is completed, the component is ejected from the tool. Cooling time varies depending on the alloy and the part volume; often, it is dictated by the size of the runner system. Zinc hot chamber die casting process yields four to five shots per minute. Aluminum, instead, casted through cold chamber die casting machine, allows two or three shots per minute [5]. Since cycle time can determine up to 60% of the final part cost, choosing zinc can offer significant savings.

- *Mechanical Properties*

Standard zinc alloys are stronger than aluminum and magnesium alloys at room temperature. High strength can already be reached after die casting process, so secondary operations are not necessary (differently from Aluminum that require additional processing), saving on the overall cost per part.

Here below are listed most important Zinc die casting advantages [2]:

- Low melting temperatures, so long furnace and crucible life as well as low energy consumption
- Short melting times
- No environmental impact due to gases and vapours during melting or processing (Zinc is neither toxic or environmentally hazardous in any way)
- Very easy to cast with exceptional imaging properties, good die filling behaviour and an exceptionally small solidification interval
- High mechanical characteristics
- High pressure tightness
- Good storage and wear properties
- Good corrosion resistance
- Easy surface finishing by galvanizing or painting
- Easy to handle due to only medium thermal conductivity

3.1 Application fields

The versatility of zinc alloys and the hot chamber die-casting technology allow industries to obtain components for various fields of application, responding to different kind of requirements: aesthetic, technical or functional [2]. The components produced are part of everyday life.

Automotive: is the industrial sector in which die-casting technology is most frequently used. In the automotive field, zinc alloys are chosen for the combination of strength, ductility and malleability that they offer, which is very difficult to find in other metals. Car components that can be made of zinc alloy are numerous: details of the interior, sunroof components, mechanical elements, power steering and brake parts, for example. The only limitation is the impossibility to use Zamak parts directly in the engine, because of the metal low melting temperature (around 420°).

BLADE BEARING FOR ELECTRONIC AUTOMOTIVE KEY | CAPLESS FUEL FILLER | SEAT BELT LATCH

Figure 10: Automotive components in Zama

Electronics: Zamak products for electronics are particularly efficient and reliable. Made of a rigid and anti-vibration material, they are suitable for industrial and domestic applications. Furthermore, Zama characteristics, such as magnetic shielding property and the possibility of reaching extremely thin thicknesses (creating effective heat dissipation systems), make the material extremely appropriate for applications in this industry.

HANDLE FOR SECURE DOOR | CELL PHONE FRAME | HOUSING FOR EAR BUDS

Figure 11: Products for electronics in Zama

Lighting: Zama fluidity enables to create complex shapes and geometries with a high degree of detail. This allows designers to have a great creative freedom. Another important factor is the possibility of carrying out different types of surface treatments on the components: liquid and powder coating, chrome plating and gold plating, just to name a few. In this way, Zamak components for lighting can harmoniously integrate with the different styles and environments of furniture.

Small appliances & White Goods: Zamak components for household appliances and white goods have numerous advantages for both manufacturers and consumers. On customer side expectations in terms of aesthetics, quality, resistance and recyclability can be easily satisfied; on producer side, the added values are in the freedom of design as well as surface treatment, in the wide variety of finishing and assembly operations and in the reduction of costs allowed by the die casting process.

Building: in the building industry, both traditional and technological-innovative components can be made of Zamak, thanks to resistant and long lasting properties of this material. Zamak parts can be found in doors and windows, just to make an example. Furthermore, in the field of home automation and associated technologies, Zamak is proving to be a particularly suitable material for the production of electronic locks and automatic openings system components.

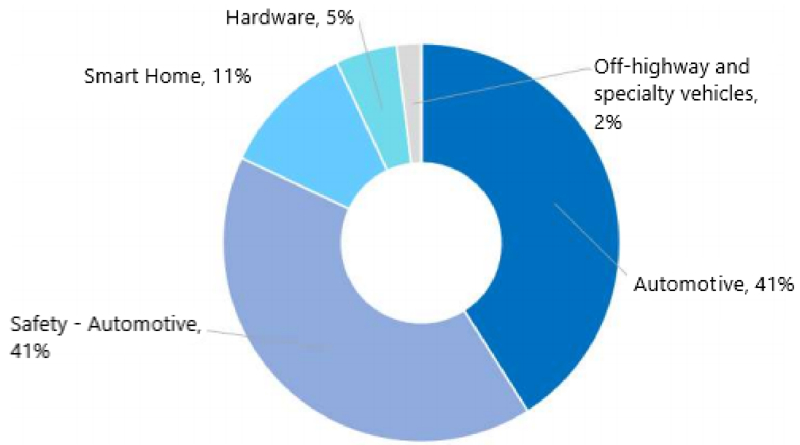


Figure 12: Percentages of Zama components for various fields of application

3.1.1 Zinc die casting in the automotive field

In general, the major reason for choosing Zama alloys is the chance of having high quality finishing, guaranteeing high mechanical resistance, in a cost-saving way.

Focusing on what concerns automotive parts, Zinc can be the right choice because its alloys, in addition to being cheaper, are more resilient compared to aluminum and magnesium alloys.

Automotive parts realized through zinc die casting [5]:

- Electronic equipment
- Sensor and airbag housings as well as other safety mechanisms
- Zero defect seat belt retractor spools
- Precision components for instrumentation switches
- Car doors locking systems
- Connectors for autonomous vehicles
- Sensor and Lidar housing for increased safety features
- Durable passive steering and braking systems

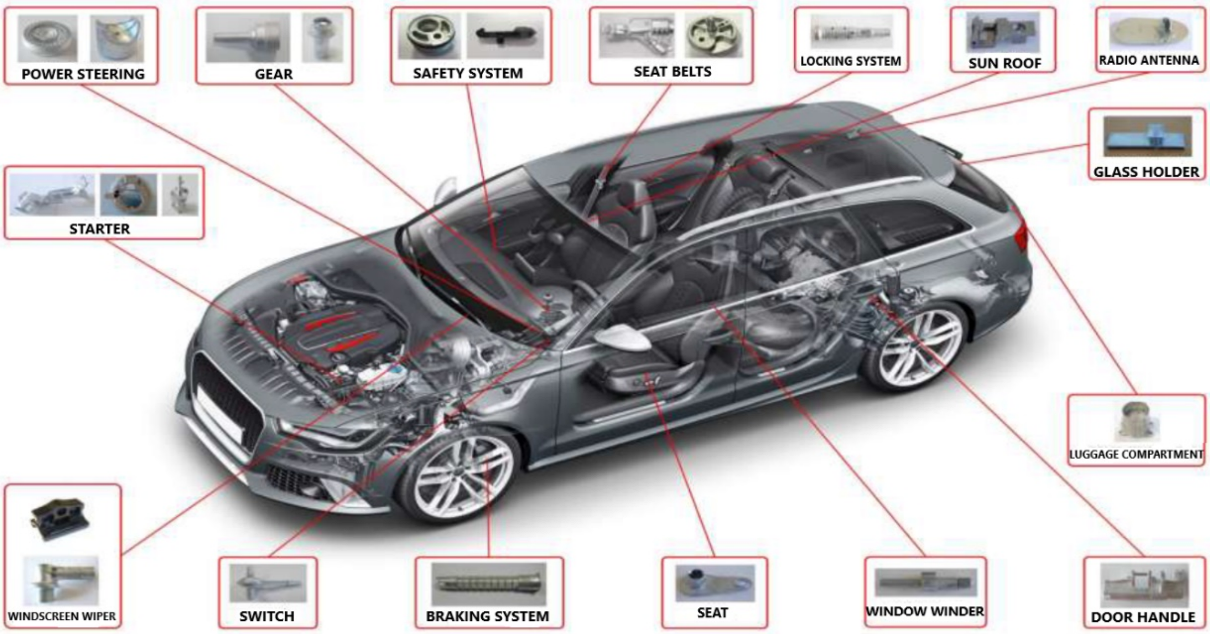


Figure 13: Zama components for automotive industry

4 *Hot chamber die casting process*

4.1 Introduction to hot and cold chamber die casting machines

Machines for High Pressure Die Casting can be divided in two categories, that are mainly differentiated by the placement of the chamber in which molten material is collected just before being injected.

Hot chamber die casting system: liquid melt, coming from an integrated furnace, is forced by the piston through the injection channel into the die. The chamber is located in the metal bath, surrounded by liquid melt and it is self-filling, allowing to arrange the system vertically, so as to save space (see *Figure 14*). Being not required an external pipe for the transport of the molten metal from the oven to the chamber, the distance from the furnace to the die is reduced, and so also the metal path, diminishing the risk of metal solidification.

Advantages of this system include fast cycle times (approximately 15 cycles per minute) and the convenience of melting the metal directly in the casting machine.

The disadvantage of these machines is that they are only suitable for low-melting point metals. Allowing low temperatures in the oven and not being aggressive towards steel, Zinc alloys are ideal for this kind of process. On the other hand, molten Aluminium aggressiveness would cause injection system wear and liquid alloy contamination, making these element not suitable for hot chamber machines.

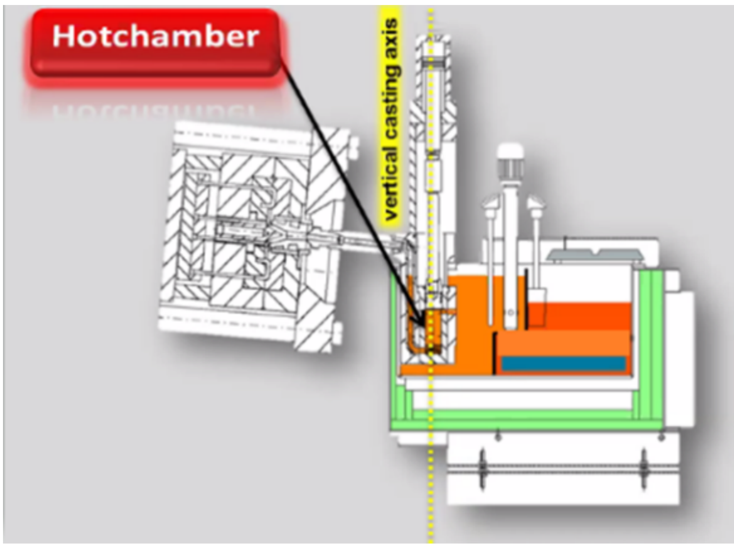


Figure 14: Hot chamber machines configuration

Cold chamber die casting system: the process starts with metal melting in a separate furnace. Then, a precise amount of liquid melt is transported to the cold-chamber machine where it is fed into an unheated shot chamber. This shot is then driven into the die by a hydraulic or mechanical piston.

The biggest disadvantage of this system is the slower cycle time due to the need to transfer the molten metal from an external furnace to the cold-chamber machine.

The chamber is defined ''cold'' because it is not in constant contact with the hot melt (like in the previously analysed case). Moreover, since it has to be filled from the outside (through an external source), the pipe for the metal transport is horizontally arranged (see *Figure 15*), requiring more space compared to hot chamber machines.

For aluminium, indeed, a separate furnace and a connecting ceramic pipe are necessary in order to avoid the attack of steel components, caused by the continuous contact with high temperature molten metal.

Moreover, it should be considered that when the plunger starts moving, involving high forces and speeds, the whole protections system, mainly made of ceramic coatings, can't last too long. For this reason, Aluminium contact time with steel components has to be reduced as much as possible [9].

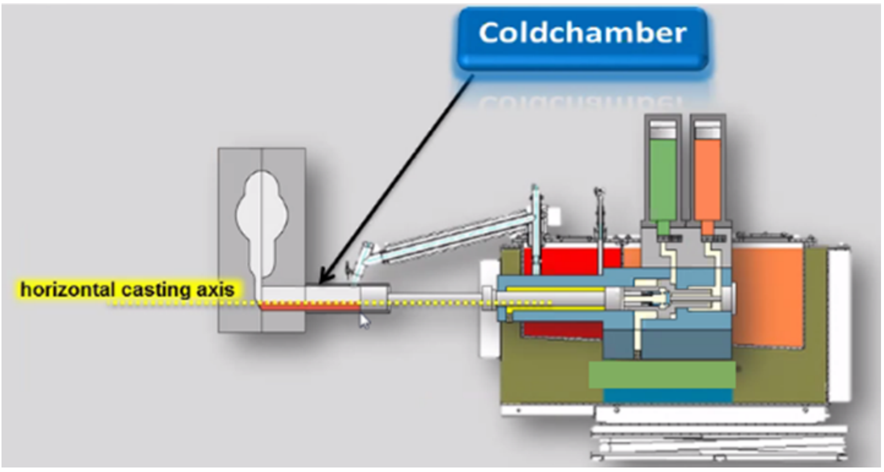


Figure 15: Cold chamber machines configuration

Both hot and cold chamber machines can be used for Magnesium that is the lightest metal for die casting process. However, it has to be considered that, when this metal gets in contact with oxygen, it can burn. Due to this fact, an inhert gas is necessary to protect the melt from contamination with air [11].

4.2 Components and functioning principles of the hot chamber die casting machine

Hot Chamber Die Casting can be used with Zinc, Magnesium and other low melting point alloys, using either multi-slide or conventional tooling.

Differently from cold chamber systems, in which the melting pot is separated and the molten metal has to be ladled into the shot sleeve, hot chamber machines contain the furnace unit directly into the metal bath. This internal mechanism makes hot chamber die casting the faster of the two processes. Other advantages include reduced porosity and longer die life thanks to the use of alloys that, also in high pressure and temperature conditions, do not attack the system.

The injection mechanism of a hot chamber machine is surrounded by molten metal. The furnace is connected to the casting unit by a metal feeding system called gooseneck [5].

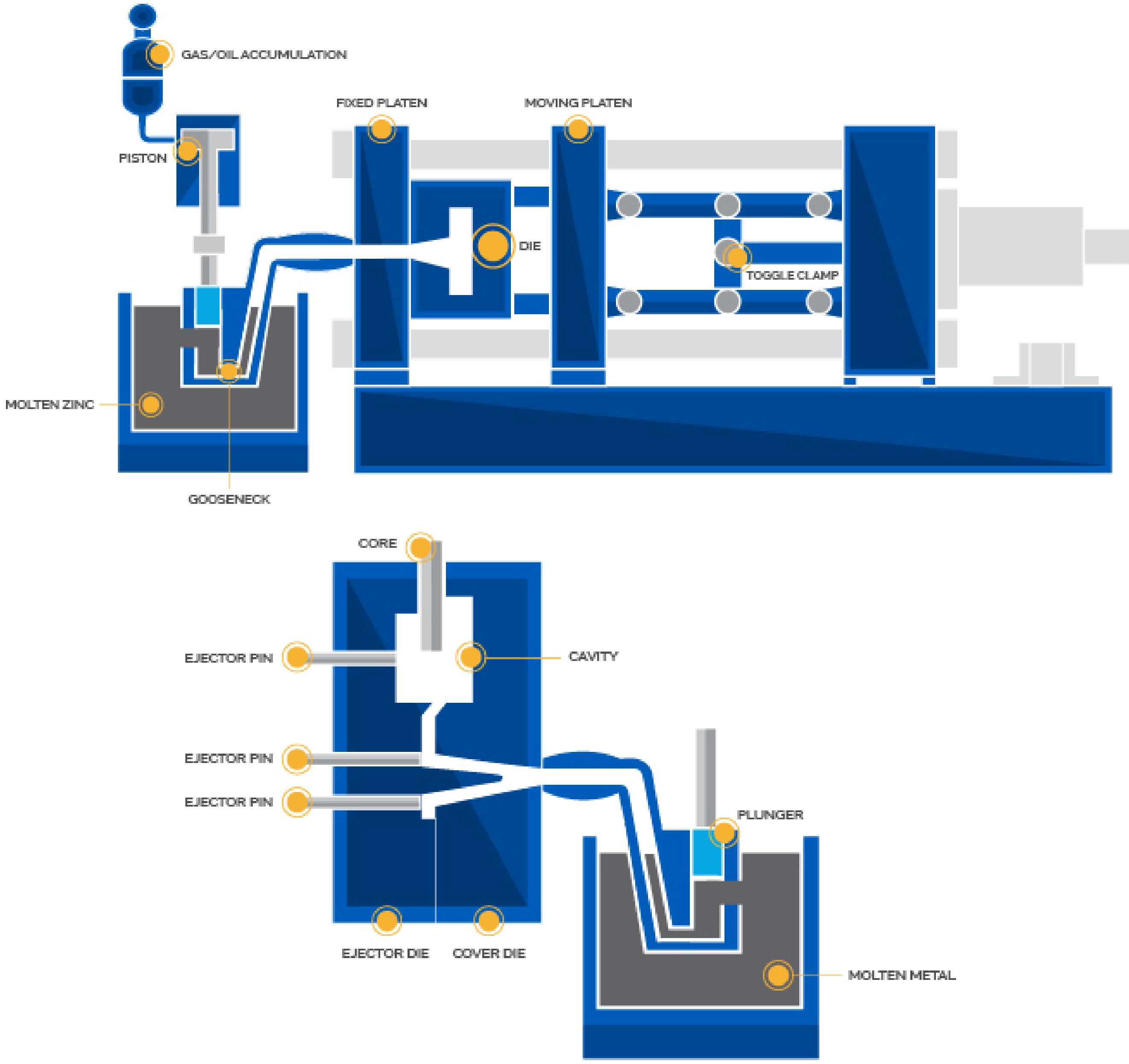


Figure 16: Hot chamber die casting machine metal injection system

The die is closed and the piston rises, opening the port, allowing molten metal to fill the cylinder (as represented in *Figure 16*).

Next, reversing its direction of motion, the plunger seals the port, pushing the molten metal through the gooseneck and the nozzle into the die cavity, where it is held under pressure until it solidifies.

At this point, the die opens and the cores, if present, retract (as visible in *Fig. 17*). The casting remains in the sliding die half (the ''ejector side''), in which are present the ejector pins. The cover side, represented in *Figure 16*, so called since it contains the sprue (which allows the molten metal to flow into the die), remains fixed [14].

Then, the plunger returns to start position, allowing residual molten metal to flow back through the nozzle and gooseneck.

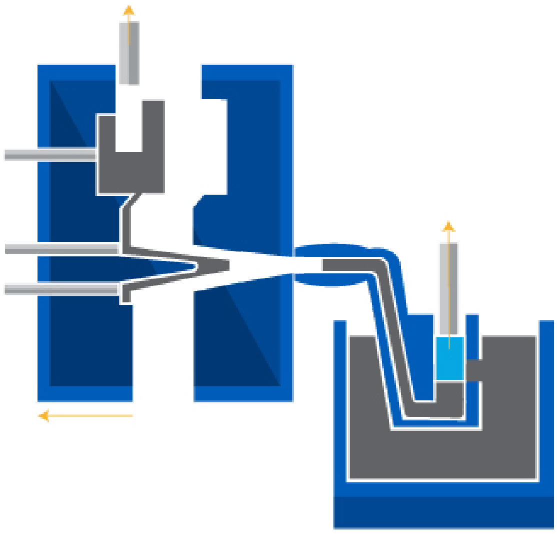


Figure 17: Die opening phase in the casting process

Ejector pins push the casting out of the ejector die (as represented in *Figure 18*). As the plunger uncovers the filling hole, molten metal flows in the injection cylinder to refill the gooseneck [5].

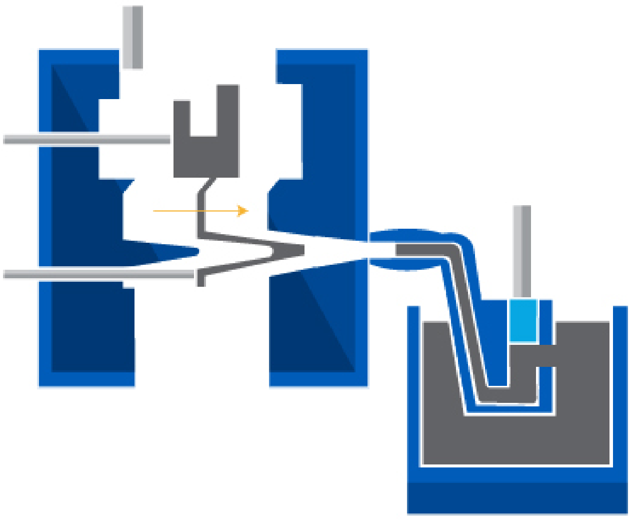


Figure 18: Casted component ejection at the and of the casting process

Figure 19 shows main constituent parts of a hot chamber die casting machine. Furnace and casting unit can be checked through the control desk, which allows to set and monitor casting parameters.

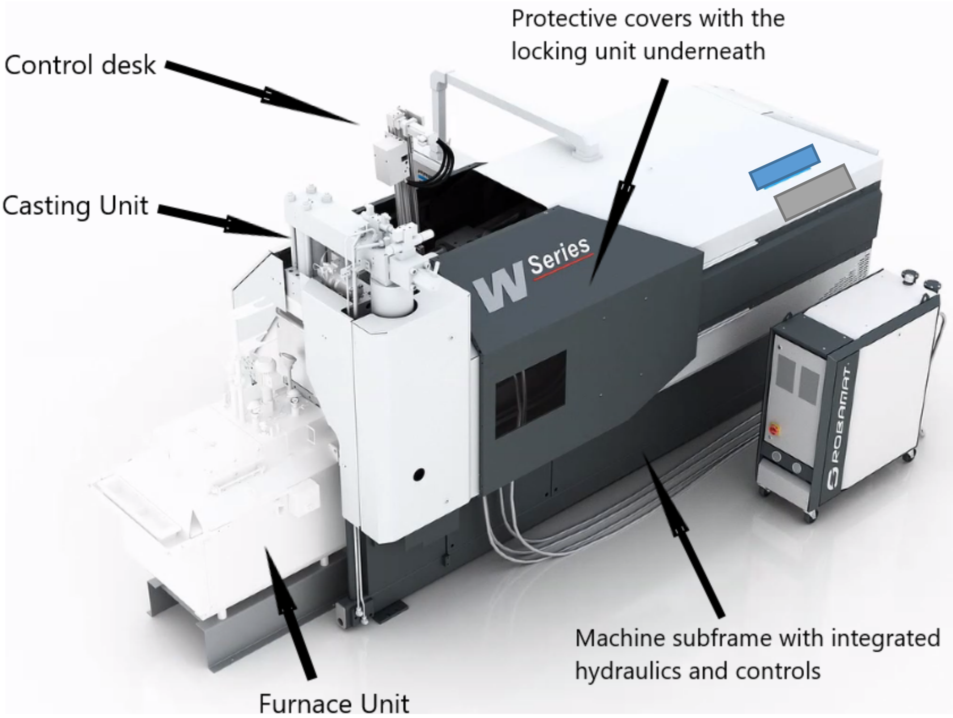


Figure 19: Schematic representation of hot chamber die casting machine main parts

Figure 20, instead, helps to better understand the casting unit functioning.

The melt, injected inside the die, is solidifying; for this reason, it is represented in blue colour. The molten metal that is still in the chamber and in the injection channel, instead, is depicted in red.

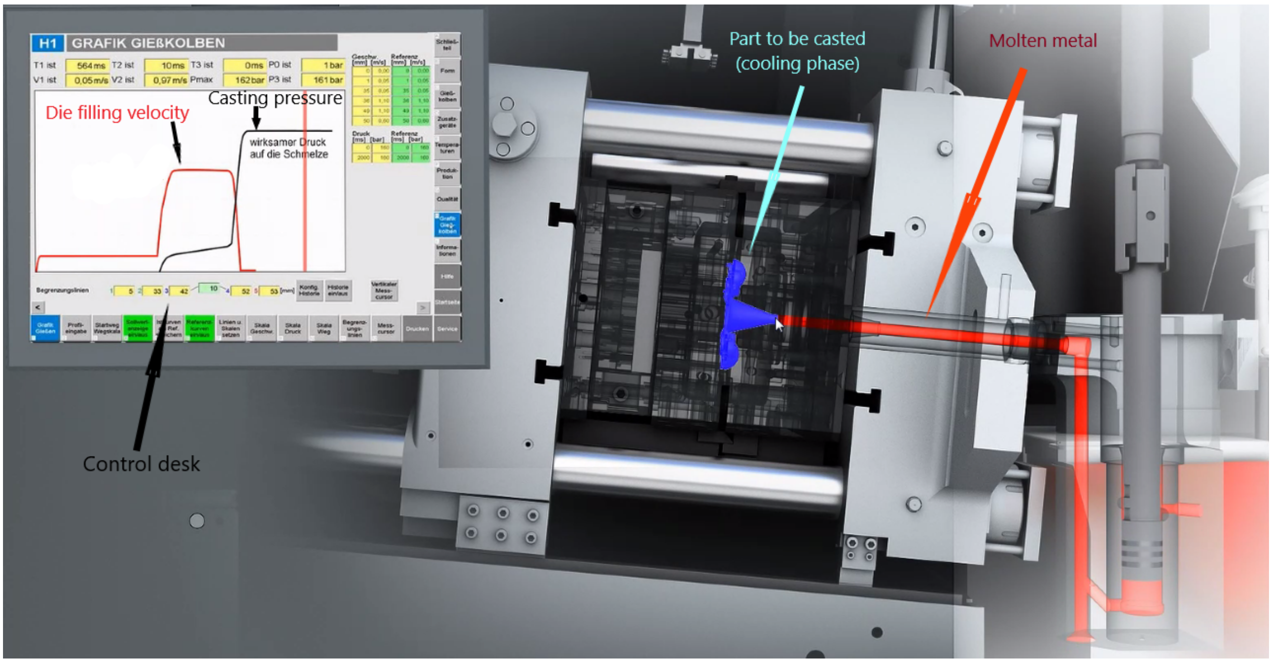


Figure 20: Internal view of the casting unit of an hot chamber die casting machine

4.3 Mould cavites configurations

Typical mould cavities configurations are different for the two die casting methods.

Dies for hot chamber machines are characterised by the sprue placed in central position with respect to cavities; a nozzle also located at the center allows metal filling. After every shot, it is possible to see a solidified drop at the sprue end.

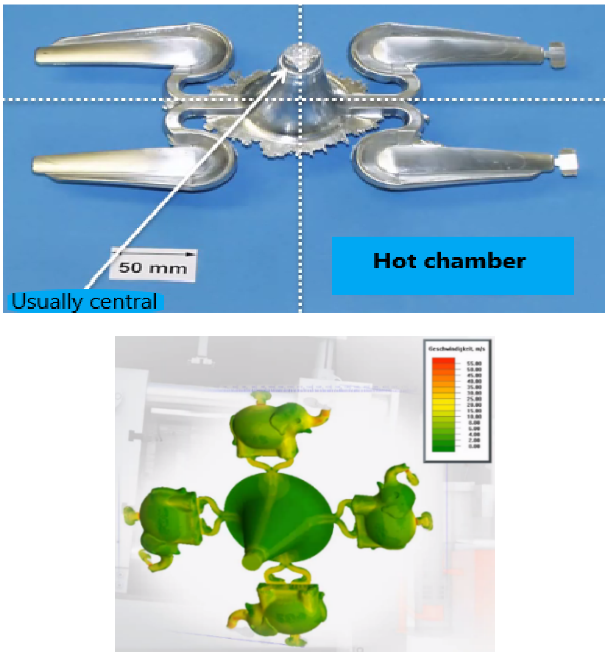


Figure 21: Illustrative images - Typical mould cavites configuration in hot chamber die casting process

Cold chamber, instead, is filled horizontally and works with dies characterized by a decentralised sprue [9].

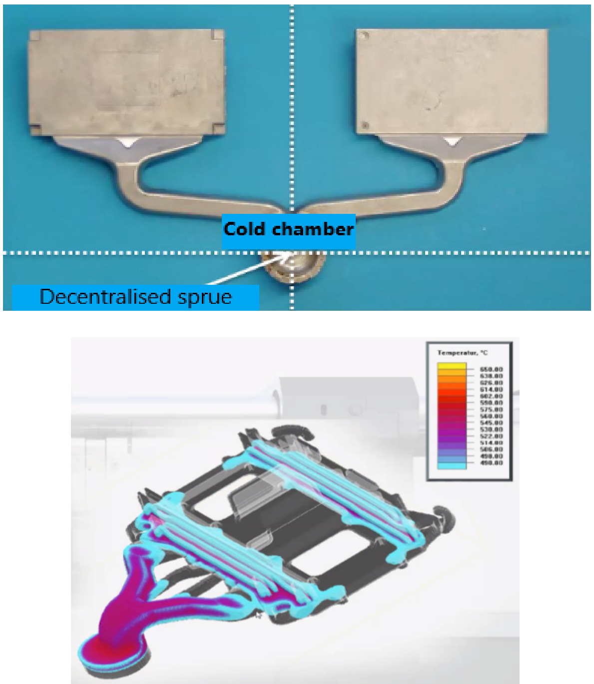


Figure 22: Illustrative images - Typical mould cavites configuration in cold chamber die casting process

4.4 Injection graph

The injection graph records the casting process from the injection piston start to the final pressure reaching time. In this plot, piston velocity (speed curve) and effective hydraulic pressure in the casting cylinder (pressure curve) are represented both in function of plunger stroke.

Injection values recording and casting parameters automatically computed are required for the exact setting of second phase starting point.

In the example below (*Figure 23*), ''P0 ist'' indicates the maximum pressure in the first phase, whereas ''P3 ist'' shows the pressure value at the end of the shot cycle (160 bar in this case).

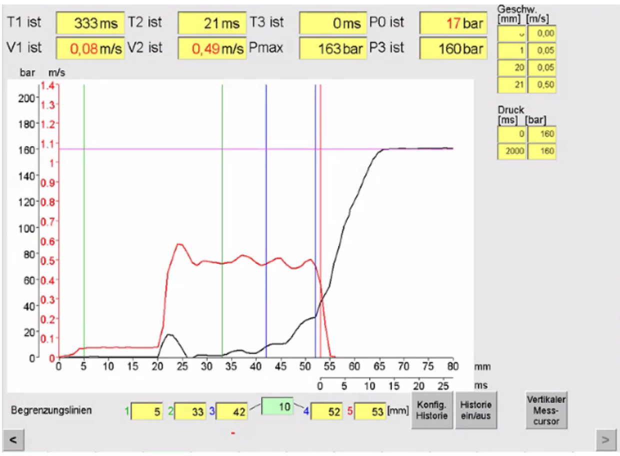


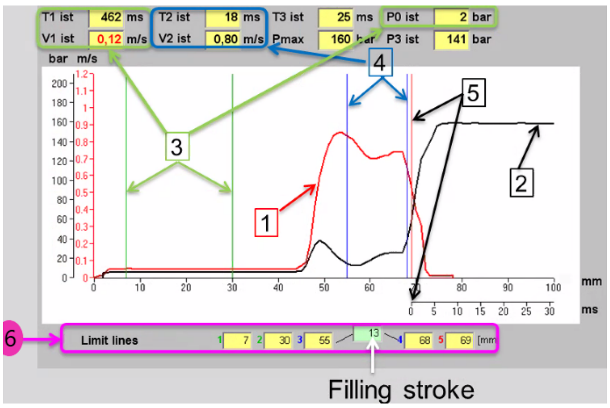
Figure 23: Injection graph example

Limit lines are used for measuring parameters and thus for monitoring the casting process.

Controls, indeed, take as reference the average value between consecutive lines; therefore, in order to get reasonable values, limits have to be placed in the right position [10].

An additional fact to consider is that every time the casting profile is modified, limit lines have to be checked.

The following figure shows the different limit lines location.



1) Speed injection piston (red curve)
2) Casting pressure (black curve)
3) Limit lines 1 and 2 (green), display of measured values between the two lines.
4) Limit lines 3 and 4 (blue), display of measured values between the two lines.
5) Limit line 5 (red), start of the scale in milliseconds
6) Display of limit lines position (mm)

Figure 24: Casting limit lines representation

4.5 Multi-slide die casting

The multi-slide die casting process uses four perpendicular slides in the tool, enabling to accurately realize very complex castings. In some cases, up to six slides can be used at angles less than 90 degrees. This casting process is mainly indicated for small components.

Multi-slide and conventional hot-chamber die casting differ for working operations as well as for tooling and machine configuration. Conventional hot-chamber machines use a two-part tool, making it difficult and expensive to create parts with complex geometries. Whereas, multi-slide tooling allows to design more precise and complex parts, thanks to the presence of four perpendicular slides in the tool.

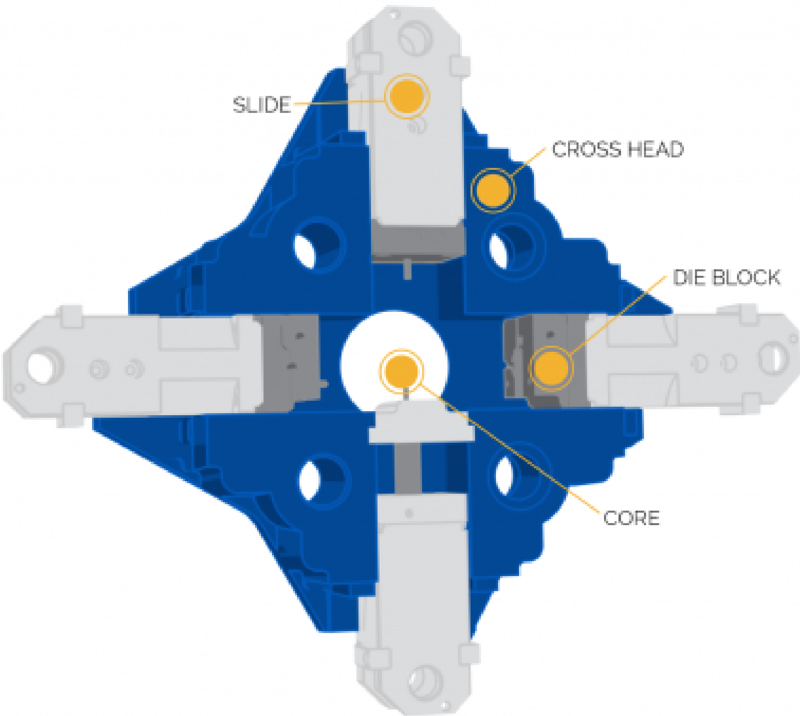


Figure 25: Multi-slide tool

A multi-slide tool (represented in *Figure 25*) is made up of die blocks, sliders, crosshead, and cover plate. Each die block has either a cavity and/or cores on its face, which together form the complete cavity and runner profile into which the molten metal is injected.

Multi-slide die blocks are mounted onto sliders, which precisely fit into a crosshead, ensuring repeatable opening and closing operations. A cover plate bolted onto the top of the tool holds all these components together.

Each slide moves independently on the other, during both the closing and opening sequences. This movement provides flexibility; in fact it ensures part integrity and prevents tool damage. The metal typically solidifies within seconds and is ejected with an air-blast that blows the shot out of the cavity into a padded collection mechanism [5].

This technology allows ranges of production of about 4,500 shots per hour [5]. This is achieved by using pneumatics, rather than slower hydraulics, in the machine.

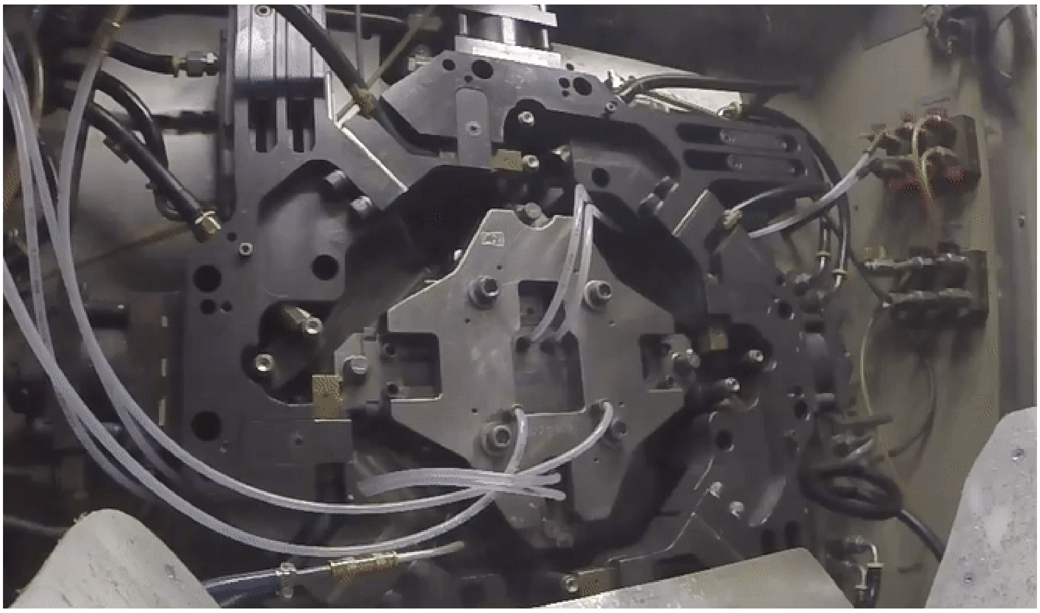


Figure 26: Multi-slide die casting machine

Multi-slide die casting has several advantages. Besides accurately creating complex parts, other benefits include [5]:

- Consistent part quality
- Elimination or reduction of secondary operations
- Excellent part-to-part repeatability
- Quick die changeovers
- Automatic separation of parts from runners
- Flash-free castings
- Rapid cycle speeds
- Cost savings in material, energy, and labour

With multi-slide process, net shape parts can be obtained typically without secondary operations. The result is a high-speed, temperature-controlled process that produces complex thin-walled components. Other manufacturing methods would need more than one operation to have parts with same geometries.

4.6 Die casting vs. screw machining

Screw machining and die casting are considered when a project requires exact tolerances, quick times and high production volume. These characteristics make a part a valuable candidate for these processes.

Since precision metal components are achievable through both methods, the choice often comes down to efficiency and cost. Below study helps to understand which process will add more value to a project.

Choosing screw machining (instead of die casting) leads some advantages:

1. This process allows to manufacture steel alloys that cannot be die casted. Indeed, die cast tools are made of hardened steel to withstand the high pressure and heat of the die casting process; since aluminum and zinc have significantly lower melt temperatures than steel, tools don't melt with them. Attempting to die cast a steel component, on the other hand, would yield one large block of compounded steel.

2. The second benefit is that screw machining holds exact tolerances at a lower initial tooling expense.

Moving from screw machining to die casting brings other advantages: in addition to offering higher efficiency at a lower overall part price, die casting also allows greater design freedom, exact tolerances and material waste reduction. Here below, a more detailed analysis.

<u>Design freedom</u>: die casting enables the production of extremely complex shapes that are impossible to achieve with screw machining. Screw machining, indeed, allows to take out parts that can be machined from bar or tubular stock on a rotating axis; for this reason, complex inner geometries, for example, are not achievable.

<u>Exact tolerances</u>: generally, if screw machine is carried on slowly enough, narrow tolerances are achieved; however, this slows down the entire production process.

Often, tolerances that a project requires can be accommodated by multi-slide die casting, in fast times. Indeed, with this method it is possible to produce precision components with tolerances of +/-0.02mm, guaranteeing short cycle times and increasing part performance. In a two-cavity tool, 9000 parts per hour can be manufactured; a reduced cycle time contributes to a lower overall cost per piece.

<u>Reduced scrap/raw material waste</u>: die casting drastically cuts down wasted material.

Screw machining works by cutting away material from a solid piece of metal. This means customers to pay for the raw material transformed in final part and even the scrapped one.

In contrast, in a four-cavity die casting tool, the gating system only produces a minimum waste quantity (for example overflows), since robots at the end of every casting cycle throw the sprue in the furnace unit in order to immediately remelt and reuse the material.

Lastly, while screw machining requires low tooling costs, die casting process uses more expensive tools. Nevertheless, considering manufacturing process of a part, the tool is totally ''paid back'' after 10-14 months of production.

In conclusion, die casting is the ideal match for high volume projects that require tight tolerances and high speedy delivery.

5 *Casting process monitoring*

SPC Charts allow the analysis of process performances by plotting data points recorded during hot chamber die casting machine functioning.

Regular monitoring of a machine can save unnecessary inspections.

Process control is an important tool, indeed, it allows potential issues detection and, when necessary, corrective actions implementation through parameters adjustment. In this way, the consequences of an incorrect setting can be limited, also in terms of costs.

Below charts report data related to a die casting machine (Frech 80). The following parameters have been recorded on the basis of 200 casting cycles:

- Piston stroke:

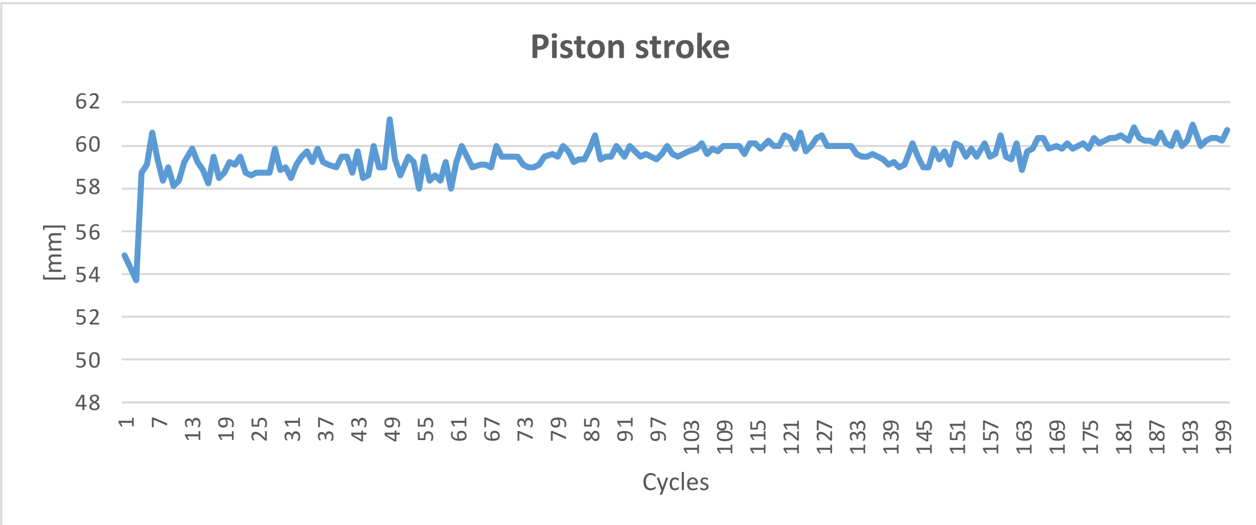


Figure 27: Piston stroke

- First phase velocity:

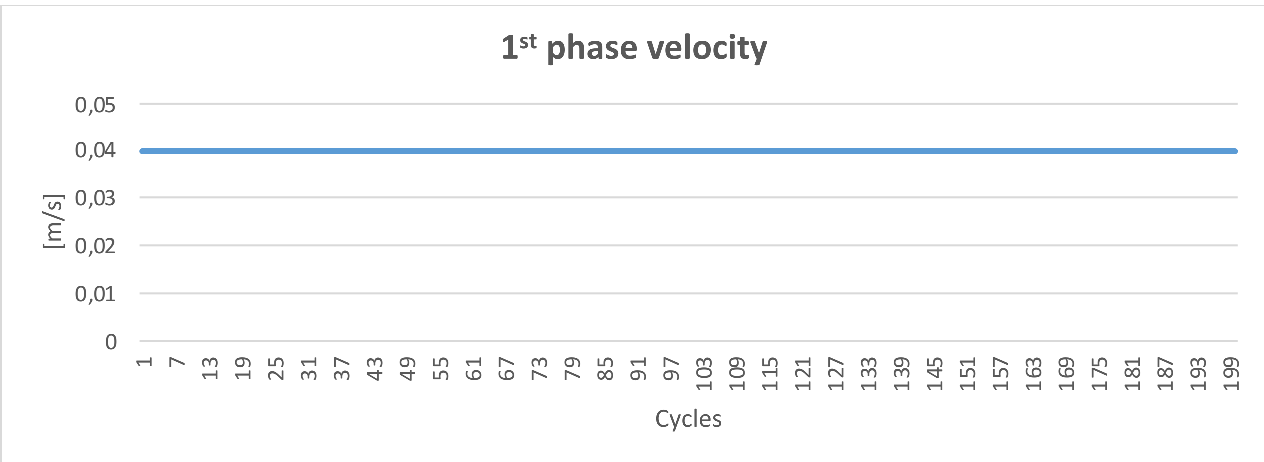


Figure 28: First phase velocity

- Second phase velocity:

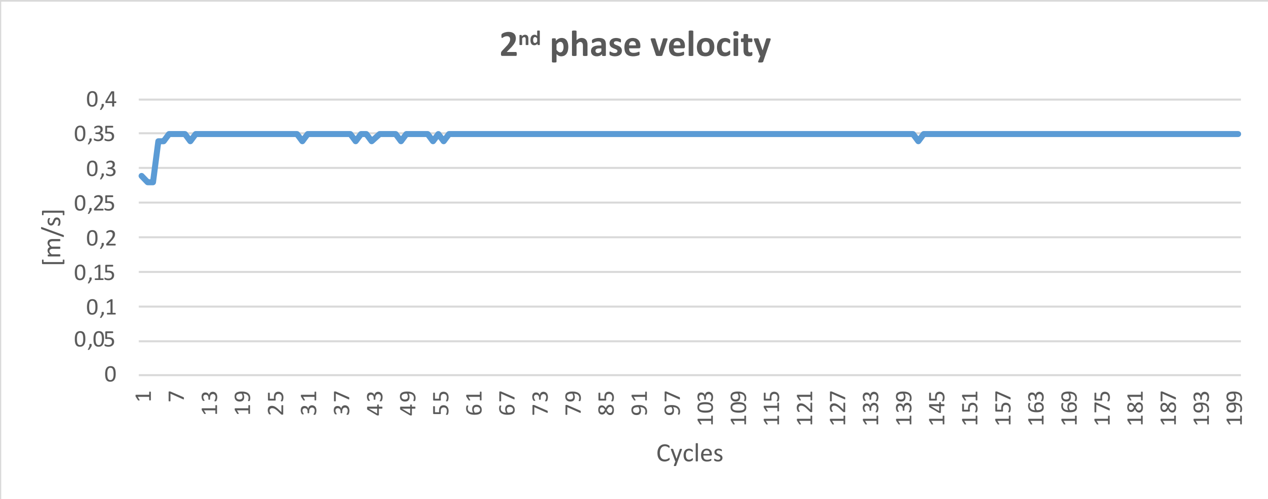


Figure 29: Second phase velocity

- Injection pressure:

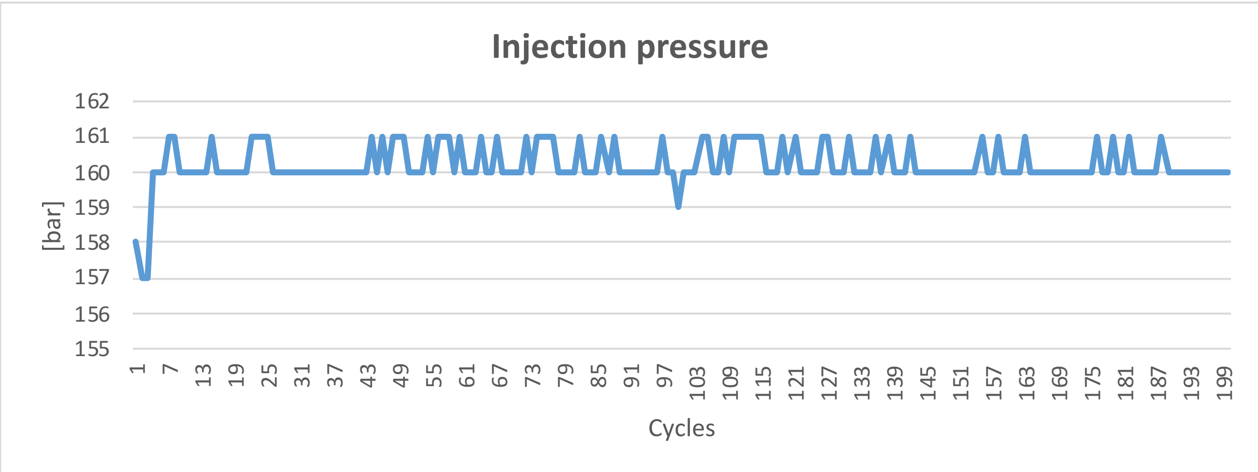


Figure 30: Injection pressure

- Cycle time:

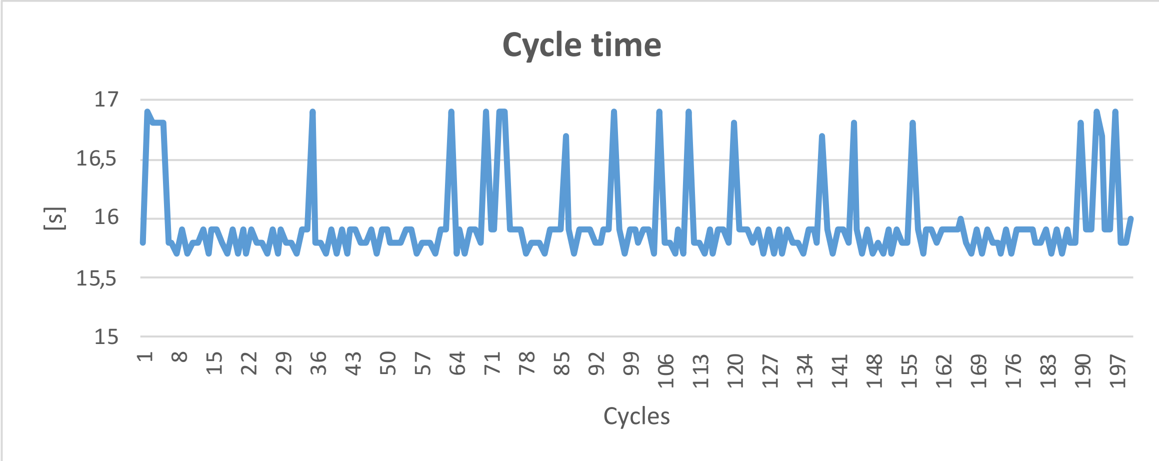


Figure 31: Cycle time

- Furnace temperature:

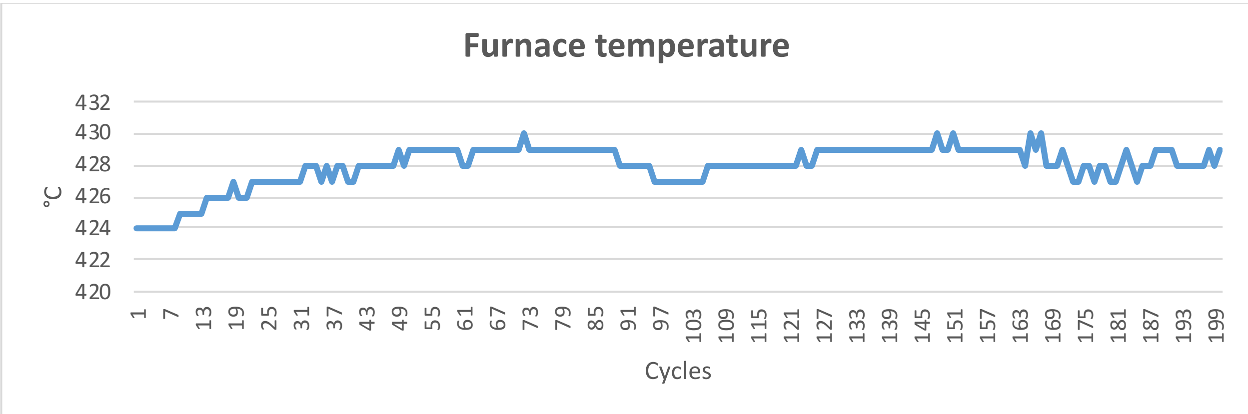


Figure 32: Furnace temperature

- Nozzle temperature:

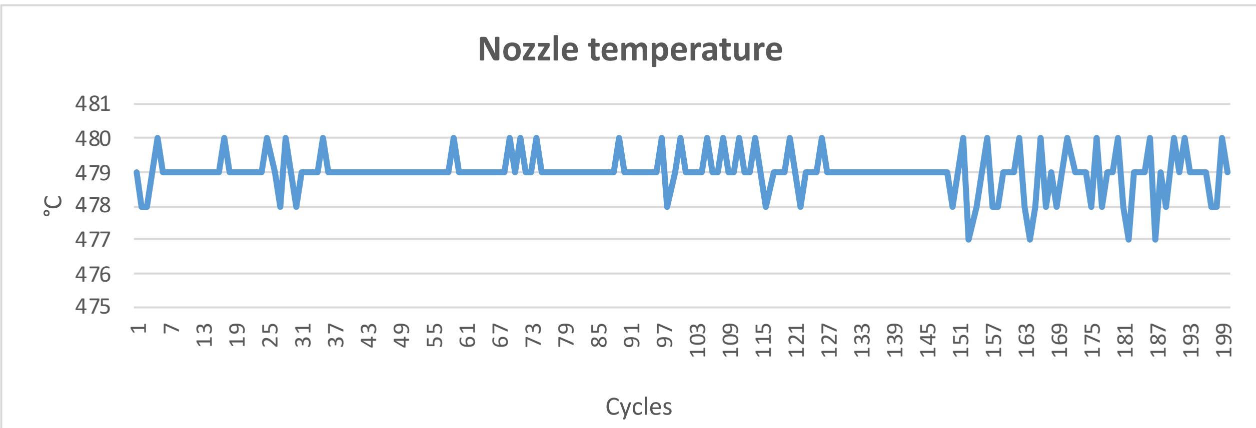


Figure 33: Nozzle temperature

6 *Casting defects*

Defects are intrinsically generated by casting processes. Castings final properties and in-service behaviour are always related to microstructural features and to defects. Both microstructure and defects are the result of process stages, alloys properties and tools design.

Defects analysis allows quality parts monitoring with respect to reference standards (usually defined by customers); moreover, correlations between defects type, distribution and origin, helps to define corrective actions to take in order to improve the overall die casting process.

6.1 Die casting process defects description

The hot chamber die casting process, is a trustable way to produce parts. Sometimes the whole system can fail, causing defects on the final parts.

<u>Part not completely filled</u>

Certain areas of the cast part are not entirely filled. This defect can be recognised from the part not clearly defined contours.

Potential causes could be:

- Temperature of melt too low
- Temperature of die too low
- Nozzle and gooseneck temperature too low
- Casting unit wear
- Shot valve irregularly operating
- Too low specific casting pressure
- Maximum casting volume too small – reduced plunger diameter

Figure 34: Not completely filled parts

Flash development

Flash, also known as casting fin or burr, is an unwanted excess of material that remains attached to a cast, which occurs at the level of the separating plane of the two die halves.

Possible causes are:

- Too weak die locking force / die frame
- Die related problems
- Die frame not parallel to mounting plate
- Guidance from movable to fixed die half too weak
- Specific casting pressure is too high
- Gate velocity is too high
- Casting force higher than locking force of machine

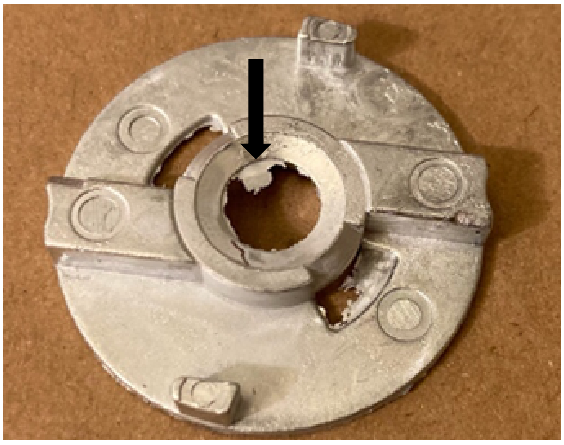


Figure 35: flash defect

Inclusions

Inclusions are particles that do not belong to the standard melt.

Potential causes could be:

- Too high furnace temperature
- Use of too much remelted material
- Prolonged holding phase in the furnace - overheated material
- Too much die lube
- Too early remelted material (must stand for approx. 20 min before it is used again)
- Smallest quantities of lead and cadmium that can destroy the zinc melt.

Surface deposit

A surface deposit can be a layer of various chemical composition, thickness, distribution and adhesion, which has been deposited on the surface of the casting during production process.

A deposit appears as a surface region (extended for several mm) covered by particles of different chemical composition respect to the casting. The deposit can be detected by means of visual inspection and metallographic tests.

A lubricant excess, which can be transferred from the die to the casting, can cause a surface deposit formation.

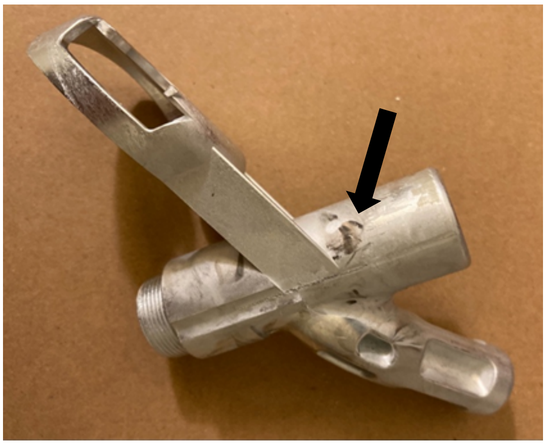


Figure 36: Surface deposits on the component

Hot cracks

Since cracks occur as the casting cools, towards the end of solidification alloys with a wide solidification range are especially subject to hot cracks. If the solidifying metal does not have sufficient strength to resist tensile forces during solidification, hot tears will appear.

Potential causes could be:

- Complicated design
- No radiuses on edges
- Not homogeneous shrinkage
- Large differences in wall thicknesses

Heat checks

They result from permanent damage of the mould in the form of cracks. These fine cracks on the surface of the die steel are localized in areas with especially high temperature. Potential causes are listed below:

- Large die temperature fluctuations.
- Preheat die instead of 'warm-up shots' (use heating and cooling units)
- Excessive use of die lube

Flow marks

Flow marks are clearly visible patterns on the cast part surface. They forms after that solidified melt is covered by incoming liquid melt and are the preliminary stage of cold laps formation.

The potential causes could be:

- Temperature of melt too low
- Turbulent flow in the gate
- Too low gate velocity
- Time for die filling too short
- Temperature of die too low

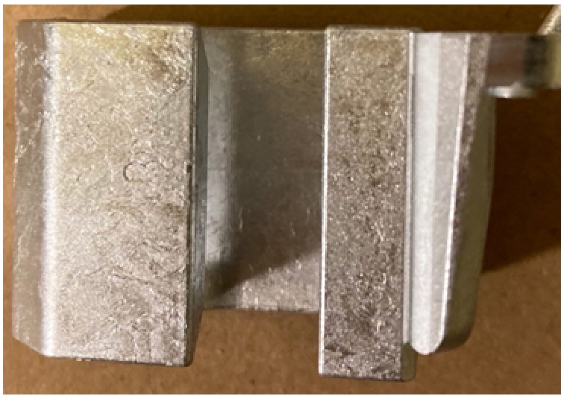


Figure 37: flow marks defect

Surface waves

Similarly to flow marks, surface waves are clearly visible patterns on the cast part surface and are often determined by an incorrect die lubricant application. Possible causes are:

- Too much die lube
- Uneven application of the die lube
- Unsuitable die lube
- Temperature of melt too low
- Vents blocked or inadequate ventilation
- Die temperature too low
- Time for die filling too short
- Unsuitable spraying device

Cold flow

Cold flow is characterized by areas on the cast part surface in which the melt has partially solidified during die filling. It forms when the turbulent flow of metal rapidly solidifies when in contact with the surface of the die.

They are patterns representing the borders of different feeding flows on the casting surface.

The already solidified and the still liquid metal flows incompletely fuse together.

Potential causes:

- Too low die temperature
- Temperature of melt is too low
- Time for die filling too long
- Gate incorrectly designed
- Too late 2nd phase starting point

Figure 38: cold flow defect

Discoloured surface finish

The surface of the cast part is discoloured with a yellowish to brownish hue, instead of the normal grey colour.

Potential causes:

- too low die temperature
- Unsuitable die lube
- Too much die lube
- Too high die lube concentration
- Die cooling leaks
- Unsuitable spraying device

Sink marks

A sink is a surface depression towards the interior of the casting, related to the presence of a sub-surface shrinkage porosity.

A sink occurs when, during the casting solidification, a hot spot localizes close to the metal/die interface. The skin layer is not able to sustain stresses arising from the contraction of the sub-surface solidifying region and plastically deforms.

They are more easily recognizable after polishing, painting or galvanizing and potential causes could be:

- Thick sections
- Extremely different sections
- Specific casting pressure too low

Draw points

Draw points are shiny scratches and striae on the cast part surface, generated by moulds component that are moving during opening phase

They appear parallelly to moulds components direction movement.

Potential causes:

- Cooling time too long
- Die temperature too high, local hot spots
- Too much die lube
- Unsuitable die lube
- Draft angle too small
- Damaged/worn die cavity

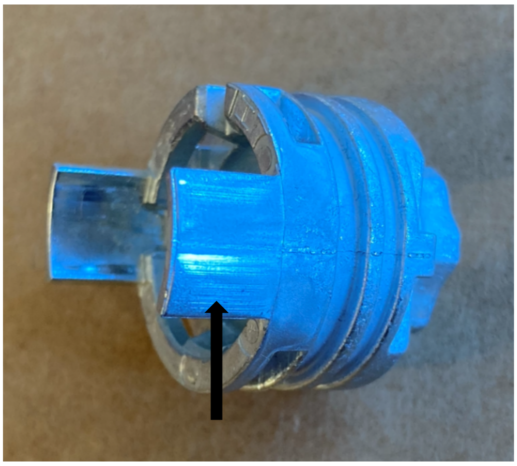


Figure 39: Striae visible on the part

Welds

Welds on the surface are nearly always recessed. They occur due to welds of sections on the die surface from which the cast piece breaks off. Welds tend to occur shortly before the gate, as this location is struck directly by the casting steam.

Potential causes:

- Velocity too high in gate
- Gate too small or unfavourable
- Unsuitable die lube type
- Too little die lube at critical points (localized dosing)
- Temperature of melt is too high

6.1.1 Defects not directly related to die casting process

Other defects not directly related to die casting process can reduce the final part quality. Here below, they have been briefly explained.

Dents

Surface damage of the cast part due to mechanical impact.

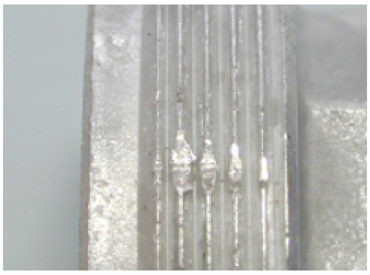


Figure 40: Dents on a cast part

Potential causes:

- No rubber support over the die casting machine slide
- No rubber on the lateral walls of the conveyor belt
- Height of drop between the conveyor belt and the box of cast parts is too high

Intercrystalline corrosion

This particular corrosion phenomenon is often visible after one or more years (it depends on air humidity) and determines a brittle casting. Preventive actions:

- Rule out any contamination of the melt, otherwise purity according to the standard DIN EN 1743 is no longer ensured
- Never place brazing solder or plumber’s solder in the crucible. 10 g are enough to completely contaminate the crucible contents of a DAW 80
- Don’t put dirt or chips into the crucible
- Tin, brass and lead must be processed separately

6.2 Porosity

Porosity can be defined as the presence of material discontinuity inside the casted part.

It forms in two ways:

- As result of natural shrinkage of melted material during cooling and solidification phase → Shrinkage porosity
- As result of trapped air presence in mould cavities, during injection phase → Gas porosity

<u>Shrinkage porosity</u>

Shrinkage cavities depend from the metal thermo-physical properties during solidification.

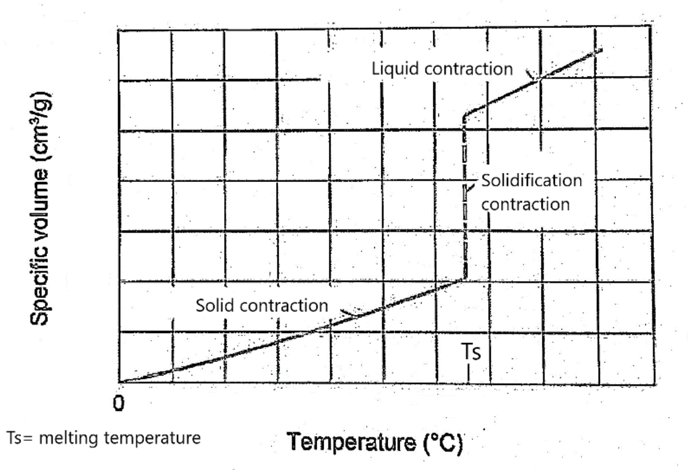


Figure 41: Specific volume in function of temperature

Alloys always shrink when changing their state, passing from molten to solid. This happens because the density of a casting alloy in the molten state is lower than that in the solid state. There is a reduction of the specific volume of the material during the transition from the liquid to the solid state (solidification contraction). Shrinkage cavities have a more or less fissured, cavern type shape.

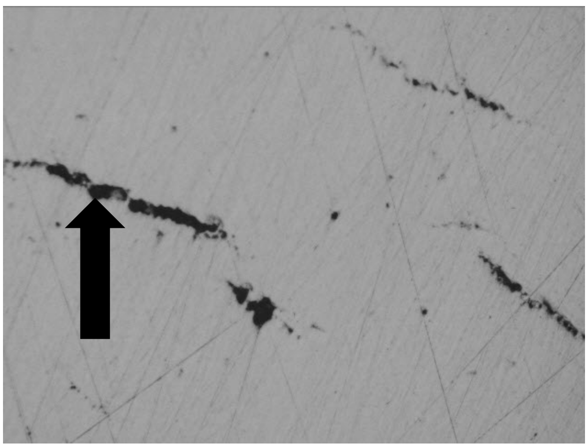


Figure 42: Shrinkage cavities on a component

It is impossible to manufacture castings that are completely free of shrinkage cavities but by means of a suitable design of the casting, for example, avoidance of harsh differences in the wall thickness, and optimal design of the casting system, this volume deficit can be minimised.

Potential causes could be:

- Secondary compression pressure too low for thick-walled dies
- Intensification pressure too low for thick walled areas
- Gate too thin for intensification pressure
- Runner cross-section too small
- Cross-section too small for filling

<u>Gas porosity</u>

Gas pores are distributed air inclusions, also called 'microcavities'. Due to the almost always turbulent flow in the die casting process, this type of porosity cannot be prevented, but rather at most reduced. These pores are likewise generally rounded in shape due to the interfacial stresses between gas and melt.

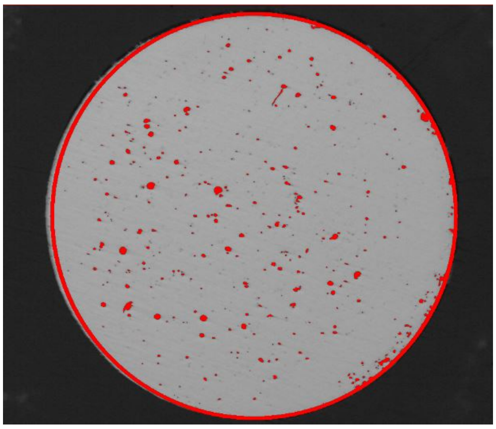


Figure 43: Pores in the circular section of a sample

They can result for:

- Fluid-mechanic causes, indeed during mould filling, a turbulent flow determines air gases inclusion in the molten metal
- Process related causes, indeed a thermally activated contact reaction between molten metal and mould with die lubricant can produce release of gases, which can spread into the melt and be included during solidification

Other important parameters that can cause gas pores appearance are:

- Specific casting pressure too low
- Velocity of 2nd phase too high
- Wrong starting point of 2nd phase
- Incorrect gate velocity

In general, both porosity due to shrinkage and gas occur together. Moreover, generally shrinkage cavities also contain gas. Gas pores are usually enlarged by shrinkage and frequently lose their round shape as a result.

6.2.1 Potential effects of porosity

Depending on the type and properties of the component as well as the load case, pores in castings can affect the strength, leak tightness under pressure, surface characteristics, and/or appearance of the component.

For technical components, the effect of porosity on the component strength must be considered. Points of force application, stress intensity, and areas with the greatest stress concentration must be known in order to ensure suitable selection of pore classes.

The same porosity can have different effects on statically and dynamically stressed components.

Static strength: when a force is applied to a component, the stress is proportional to the force divided by the cross-sectional area. If the cross-section is reduced because of pores, the stress increases. As soon as the resulting stress exceeds the elastic limit of the material, permanent deformation occurs, potentially leading to fracture. Moreover, a notch effect arises, depending on the pore geometry.

Under bending and torsional load, the position of the porosity in relation to the neutral axis must be observed. Especially in the case of shrinkage pores, the porosity is located in the excess material area and therefore near the neutral axis. As a result, the strength reduction in the total cross-section is proportional to the areal porosity content with good approximation.

Dynamic strength: the strength of a component under cyclic loading is determined to a large extent by notch factors in addition to the material. Geometric contours (for example small edge radii) as well as inhomogeneities caused by oxide films and non-metallic inclusions or unfavourably shaped phases (for example intermetallic phases) can lead to notches having greater notch factors than those of pores.

Pores have different notch effects depending on their shape, their position relative to the casting surface, and their arrangement relative to each other. The notch effect:

- increases with the areal porosity content
- decreases with increasing roundness, greater radius, and increasing distance of the pores from the casting surface.

If the components have been coated, electroplated or heat treated, porosity on or just below the surface can cause points of discontinuity. During heat treatment (annealing, thermal drying of paints), the elevated temperature causes a strength reduction of the material. As a result, gas-filled pores can lead to deformation or blistering at the surface of the casting due to the internal pressure, which rises with increasing temperature. Blistering can be minimized by applying forced venting or vacuum to the die.

Porosity can be classified in two main categories: with the term ‘‘macroporosity’’ are considered pores with a minimum extent of about 0,5 mm; ‘’microporosity’’ instead includes pores with an extent up to 0,5 mm.

6.2.2 Porosity tests

Porosity of complex components varies depending on the position of the examined cross sections. The porosity is often not evenly distributed with a cross-sectional area. The positions of the reference areas must be selected in such a way that they cover the cross sections that are highly relevant to the functional capability of the component. Main test procedures are the following:

The *radiographic test* (X-ray test) is a non-destructive test. A two dimensional projection of the casting is generated in the X-ray test. This causes restrictions on pore localization and identifications. Defects of 0,5 mm in size are at the lower resolution limit.

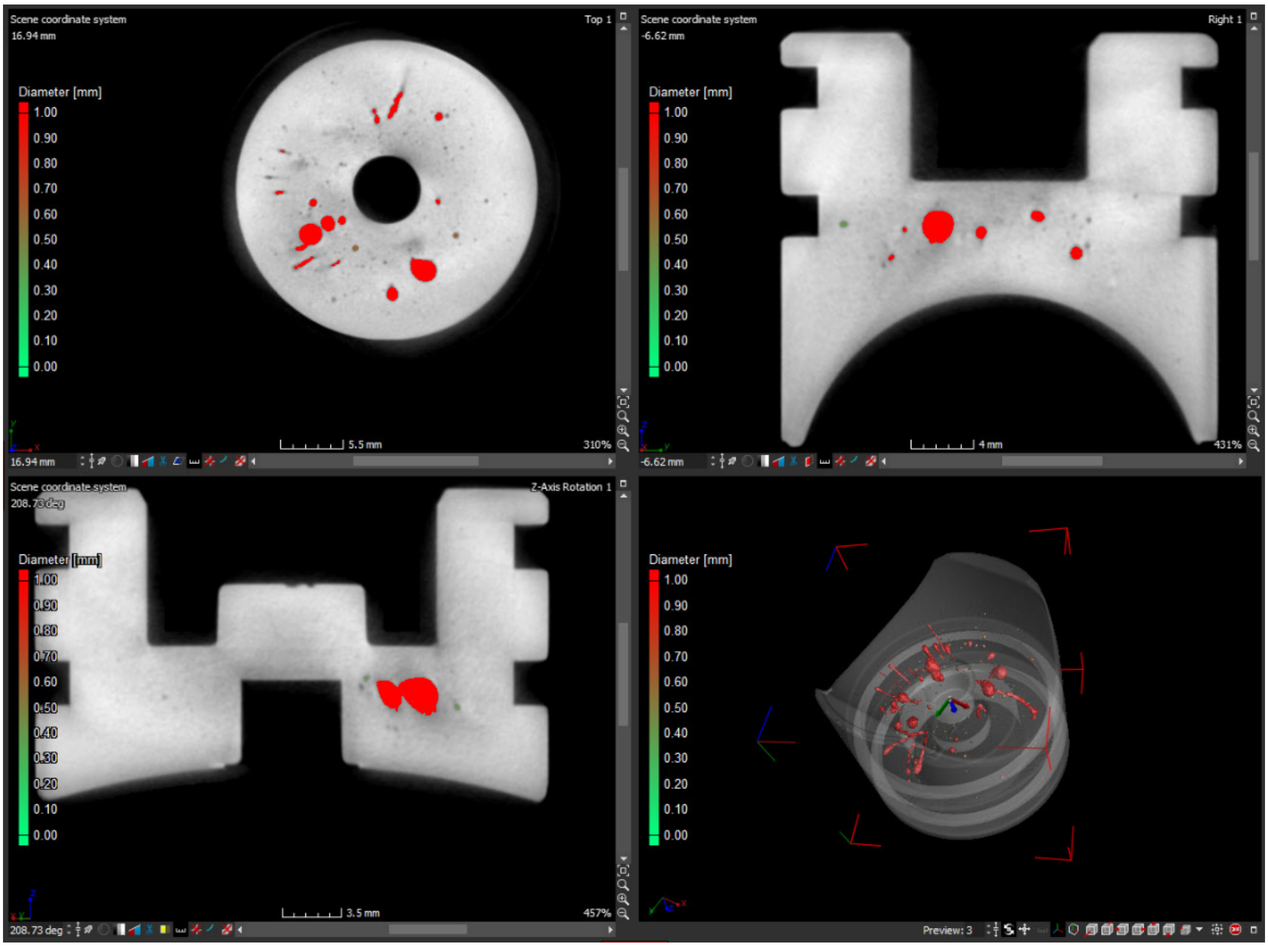


Figure 44: Pores on Zama casted component detected with a tomography

The *ultrasonic test* is a non-destructive test. A one dimensional projection of the casting is generated in the ultrasonic test. A complete overview of a component can be generated only by scanning the entire component.

Density test (generally performed by dipping part in water and applying Archimedes' principle) is a non-destructive test that allows the definition of the overall porosity volume over the total component volume. This test is just an aid for production optimization.

Microsection test is the method with the greatest informational value regarding porosities in critical component areas. In addition to porosity evaluation, other microstructure characteristics (for example the dendrite arm spacing) can be examined with this method. Since evaluation is performed on a saw-cut section, this is considered a destructive test method, therefore only random samples are taken. Furthermore, costs to perform this kind of analysis are high.

Here below are reported the images of a destructive porosity test: samples to be tested have been sectioned, subsequently embedded in resin and finally polished in order to improve porosity visualization and evaluation.

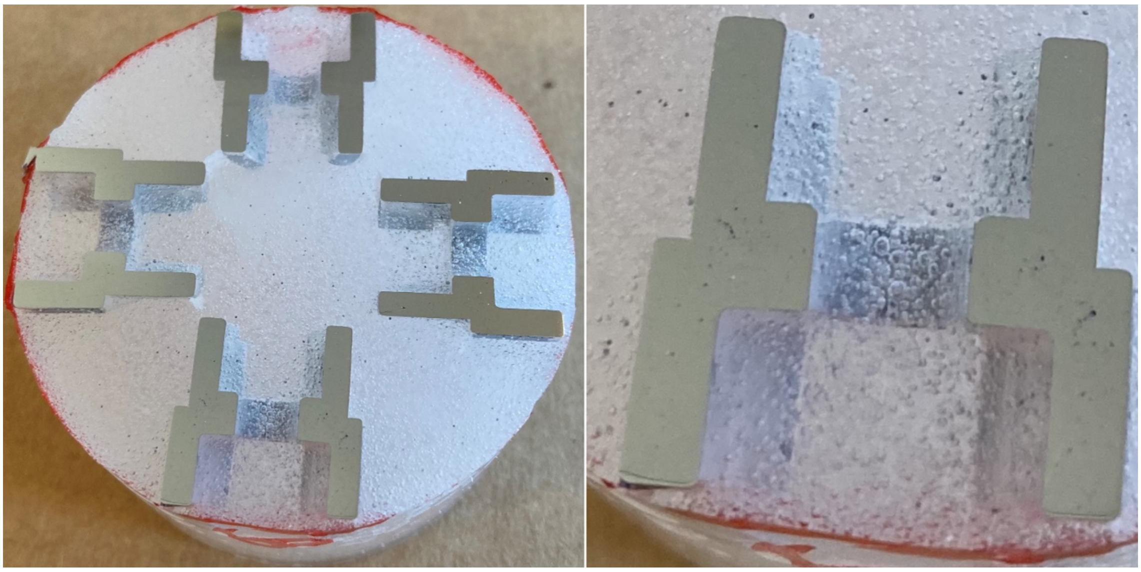


Figure 45: Destructive porosity test on Zama die casted samples

6.2.3 Porosity designation

A permissible porosity is specified in the form of a key, composed of several parameters. The designation of the reference sheet is indicated in the first position, the individual parameters follow. The parameters and the associated values are placed in square brackets. The various parameters are separated from each other by slashes.

Example of a porosity key: VDG P202-[Parameter 1][Value]/[Parameter 2][Value]/…

The designation of the pore classes consists of the following parameters:

<u>Pore content [%]</u>: is the maximum permissible pore surface percentage for the agreed reference areas.

<u>Pore diameter/pore length Ø</u>: is the maximum permissible pore diameter (indicated in mm) that is possible to find into the sample. The following figures graphically clarify these definitions.

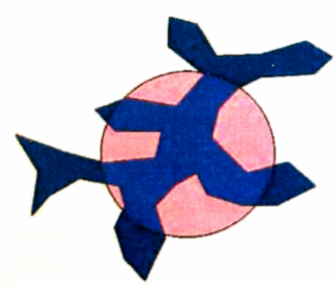


Figure 46: Equivalent diameter (diameter of a circle of equal area) [$Ø_F$]

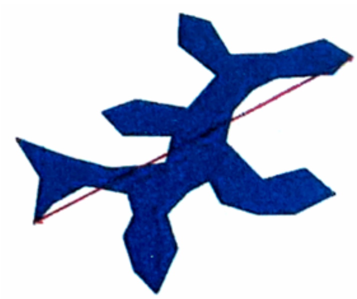


Figure 47: Pore length or analogy diameter [$Ø_L$]

<u>Distance of adjacent pores [A]</u>: This parameters indicates the minimum edge distance between two adjacent pores.

<u>Number of pores [Z]</u>: The integer value specifies the maximum permissible number of individual pores in a reference area. Pore accumulations are treated as individual pores.

Pore accumulations [H], [H_R], [H_K]: A pore accumulation is existent if the distance between two adjacent pores is less than the diameter of the smaller pore.

[H]: pore accumulation in the entire reference area

[H_R]: pore accumulation in the edge area of the reference area

[H_k]: pore accumulation in the core area of the reference area

[H], [H_R], [H_K] can have the following binary values:

0 = pore accumulations impermissible

1 = pore accumulations permissible

Localised aggregated porosity [N], [N_R], [N_K]: if the diameter of a pore accumulation exceeds the maximum permissible pore diameter)

[N] refers to localised aggregated porosity in the entire reference area

[N_R] refers to localised aggregated porosity in the edge area of the reference area

[N_k] refers to localised aggregated porosity in the core area of the reference area

If [N], [N_R], [N_K] is listed in the pore key but a value is not indicated, the value 1 automatically applies, this means that localised porosity is permissible in the corresponding area

Examples:

- VDG P202 – %15/ $Ø_L$ 3/ N_k1

A porosity of 15% is permitted for the agreed reference areas. A pore length of 3 mm must not be exceeded. Localised aggregated porosity is permitted in the core area.

- VDG P202 – %5/ $Ø_L$ 1/ N_k0

A porosity of 5% is permitted for the agreed reference areas. A pore length of 1 mm must not be exceeded. Localised aggregated porosity is not permitted in the core area.

- VDG P202 - %10/ $Ø_F$ 3/ R_Z15

A porosity of 10% is permitted for the agreed reference areas. An equivalent diameter of 3 mm must not be exceeded. The reference area has a surface quality with a roughness depth R_Z of approx. 15 µm.

It is important to consider that, keeping the international standard VDGP202 as reference, many customers define their own standards in terms of limits, test methods, measurement and classification parameters and so on.

7 *Continuous process improvement and problem solving methodologies*

7.1 Deming's Plan-Do-Check-Act Cycle

In the 1950s, W. Edwards Deming developed a quality system for the continuous improvement of business processes. Deming's quality system contended that business processes should be analysed and measured to identify the sources of variations that cause products to deviate from customer requirements. He proposed that business processes were placed in a continuous feedback loop so that managers could identify and change the parts of the process that needed improvement. To illustrate his continuous improvement system, Deming developed a diagram using four arrows in a cyclical pattern.

This diagram is commonly known as the PDCA cycle.

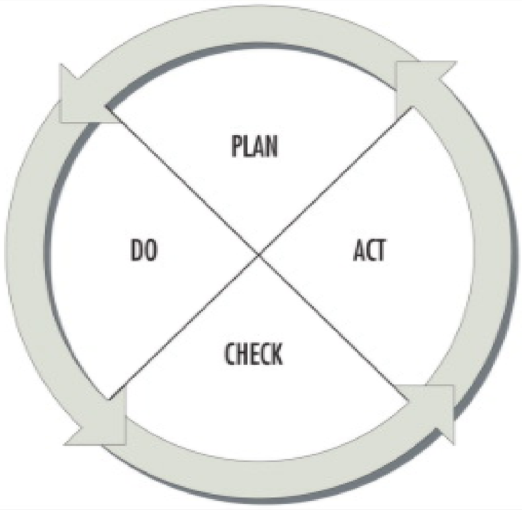


Figure 48: PDCA Cycle

The sections of the diagram are defined as:

- PLAN Design or revise business-process components to improve results
- DO Implement the plan and measure its performance
- CHECK Assess the measurements and report the results to the decision makers
- ACT Decide on the changes that are needed to improve the process

Although Deming's focus was on industrial production processes, his method and philosophies just as easily applied to modern business practices

Advantages

The PDCA cycle provides precisely continuous improvement because it works in a cyclical way. Each part of a project or activity will go through the same stage several times, ensuring that errors can be corrected and adapted to the needs and the actual situation.

Disadvantages

A major disadvantage of PDCA methodologies is its inherently reactive nature. Although PDCA has a circular paradigm, it assumes that everything starts with Planning. This need not always be the case in real-life situations, where at times changing the rigid circular order might deliver better results.

7.2 Ishikawa diagram

Ishikawa diagram, also called cause-and-effect diagram, is another problem solving methodology, and is the one used during the internship to detect potential causes of a problem, in order to perform quality defect prevention.

Each cause or reason for imperfection is a source of variation. Causes are usually grouped into major categories to identify and classify these sources of variation.

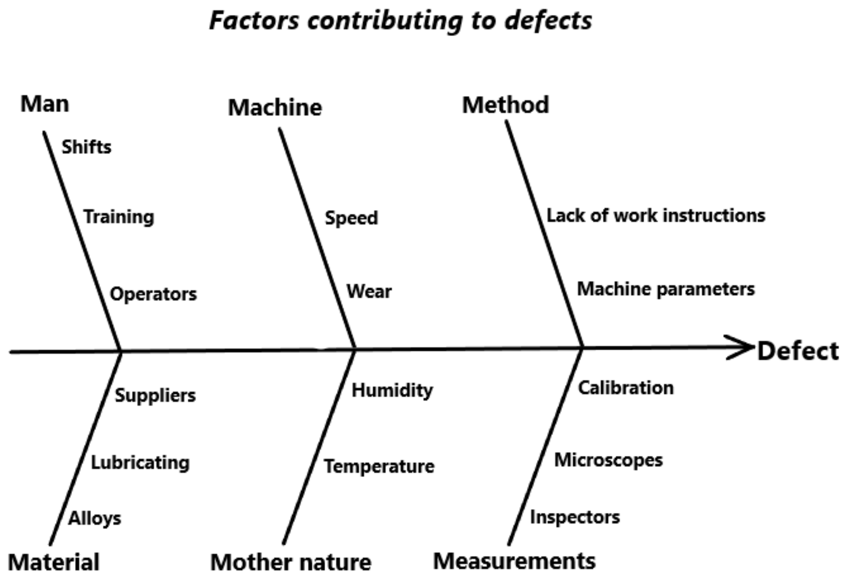


Figure 49: Example of an Ishikawa diagram

Originating with lean manufacturing and the Toyota Production System, the 6 M model is one of the most used frameworks in manufacturing for root-cause analysis. 6M represents initial letters of the six families in which a potential cause can be placed:

- Man (physical or knowledge work)
- Machine (equipment, technology)
- Material (raw material, lubricating systems)
- Method (process)
- Measurement (inspection)
- Mother nature (environment)

Advantages

- Highly visual brainstorming tool which can spark further examples of root causes
- Quickly identify if the root cause is found multiple times in the same or different causal tree
- Allows one to see all causes simultaneously
- Good visualization for presenting issues to stakeholders

Disadvantages

- Complex defects might yield a lot of causes which might become visually cluttering
- Interrelationships between causes are not easily identifiable

8 *Quality parts improvement*

Process improvement is a crucial element that leads to production costs reduction and shorter working cycles. With the aim of reaching sensitive decrease of scraps and cycle time, it is therefore necessary to introduce automated technology and simulation software in the production process.

Process improvement can be developed through a well-defined action plan, which takes into consideration the complexity of elements and relations that characterizes parts manufacturing. For the realization of a component it is not required machinery only, but also product design, technologies, quality checks and planning activities, to mention some of the most important elements of this structured system.

Planned actions for enhancing manufacturing process can be grouped into two main categories: *simulation* of die casting and *automation* systems integration in foundry.

Simulation of the die casting process represents an essential element that impacts on process improvement: with simulation software it's possible to foresee material reactions inside the mold. This is feasible thanks to a thermo-fluid dynamic analysis of the mold, known as CFD simulation (Computational Fluid Dynamics), which allows to detect potential defects, such as cold laps and hot spots, on the die cast. The simulation stage proves especially helpful to obtain an optimised die design before starting the production process; it allows also to select casting parameters that best suit a specific cavity shape, reducing the occurrence probability of previously detected potential defects as well as the necessity of further mechanical operations and, as a consequence, determining lower production costs.

The introduction in a production system of automated machinery, equipped with state-of-the-art technologies, allows to obtain a faster process for high quality production, reducing the whole lead time and costs. In addition, the replacement of manual operations with robots, leads to a reduced likelihood of error. A relevant production costs reduction is further increased thanks to lower energy consumption (for the higher productivity ranges) and material saving (thanks to reduced scraps).

Consequences of the application of previously described planned actions are *scrap* and *cycle time* reduction.

It is necessary to carry out process analysis that focuses on the causes of scrap. To identify these causes simulation software help to foresee every stage of the production, from design to finishing operations. Simulations, firstly permit to reduce the possibility to have defected parts that must be scrapped. Secondly, they allow to study the best tool-design so as to optimize cavities positioning, evaluating also the necessity or not to introduce overflows. Indeed, since overflows can not be refused after diecasting, due to high grade of contamination, their presence would consistently increase material scrap.

Once scrap causes have been figured out it is possible to proceed to the outlining of potential solutions to apply, identifying the most relevant steps in the production process and constantly checking and correcting them.

Cycle time represents a central variable in the production of a component because a reduced cycle time results in a reduced lead time. First of all, as already mentioned, it is important to simulate production and to define the best die casting parameters. In this way potential defects will be avoided from the very beginning and, consequently, it will be possible to eliminate further corrective mechanical operations.

Another core element for cycle time shortening is the technological system of the foundry, whose technological innovation level can generate relevant time reduction during the production process. As a matter of fact, automated machines lead to optimized cycle times and to more accurate operations, discriminating factors for the achieving of performances requested by customers. Furthermore, periodical checks on machinery help understanding how cycle time can be further improved.

8.1 Improvement action practical application

A process improvement project, for production of a small appliances component, has obtained excellent results in terms of increased productivity and decreased operators manual activities. The project has solved a situation of misalignment between production demand and production capacity. Through the introduction of automated systems this gap has been narrowed, thanks to the achievement of optimal cycle time. After several studies and researches it has been possible to apply some changes to the process, which have brought to significant benefits: an increase of 33% of production capacity and a decrease of 95% of manual activities made by operators.

8.2 Casting process simulation software to optimise mould design

Mould design optimization

The start of a new project requires, after a feasibility analysis, an accurate mould design phase. In hot chamber die casting processes, design and optimization of the die and so, of injection channels for example, is extremely important and can be realised with the help of simulation software.

The first requirement for producing high-quality die cast components is the use of high-quality tooling. The die cast tool determines not only achievable tolerances, but also shots number, repeatability, strength, and complexity that is possible to get with the process.

It is possible to choose between a single cavity mould or a multi-cavity mould. When considering this second option, it is necessary to keep in mind that not only the complexity of filling and ejection phases would increase, but a higher productivity (thanks to multi-cavity dies) would affect also aspects like the daily quantity of metal required for the process. To decide the number of cavities in a mould indeed, it is important to consider hypothetical cycle time, total number of pieces to produce and surface quality requirements. Indeed, increasing the number of cavities, there is a higher probability to reduce the surface finishing quality.

When designing the tooling, it is important to consider all aspects of the mould and of the end-part itself: from material selection, potential runner sites, tolerance to reach, and more. State-of-the-art magma flow software helps to analyse the castability of certain design features and the best sites for runner systems and cooling ports before the tool manufacturing. Elements like cooling ports limit the amount of tool wear, prolonging the life of the die cast tool and ensuring an even porosity and high strength in the final casting.

Use of simulation software

The use of software to simulate phenomena regarding die casting process, has become increasingly common in recent years. This because of the inherent complexity of the process, considering melt flow, thermal effects as well as metal phase change (from liquid to solid).

Simulation is a mean of understanding molten metal behaviour inside the mould. It allows the overall process optimisation, in order to produce parts with the desired properties, at the lowest cost, using available materials.

Numerical modelling for die casting is a challenging task since it has to consider fluid flow phenomena (as viscous flow), heat flow in the metal and in the mould, and change of phases (from liquid to solid state).

Studies show that the final strength of a casting can be increased (by an order of magnitude in case of Aluminum [13]) improving the die filling phase. Thanks to simulations, injection parameters can be better set at the beginning of tool life. With a correct die filling it is possible to avoid, for example, metal splashing on the mould lateral surfaces and free turbulences that would cause air porosity, not reducing final piece resistance expected value [13].

One goal of the thesis is to show that an appropriate numerical model can accurately predict metal flow behaviour. ProCAST has been used here to show output of filling and solidification simulations.

8.2.1 Die filling simulation

On the basis of the final part geometry, it is possible to proceed with a die filling simulation using ProCAST.

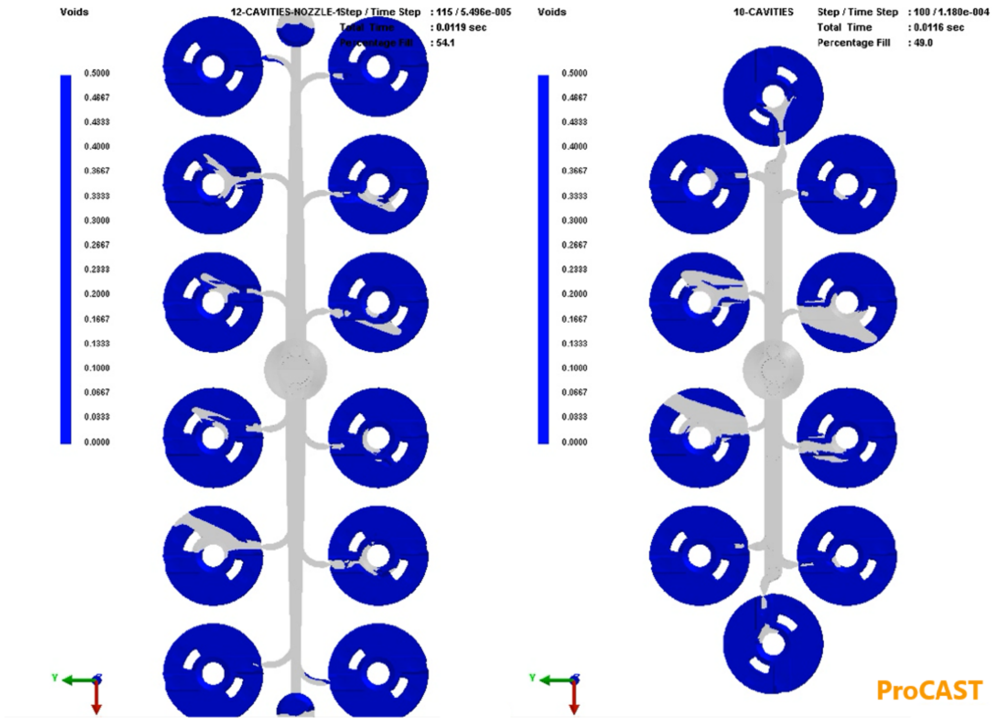


Figure 50: Representation of die filling initial phase

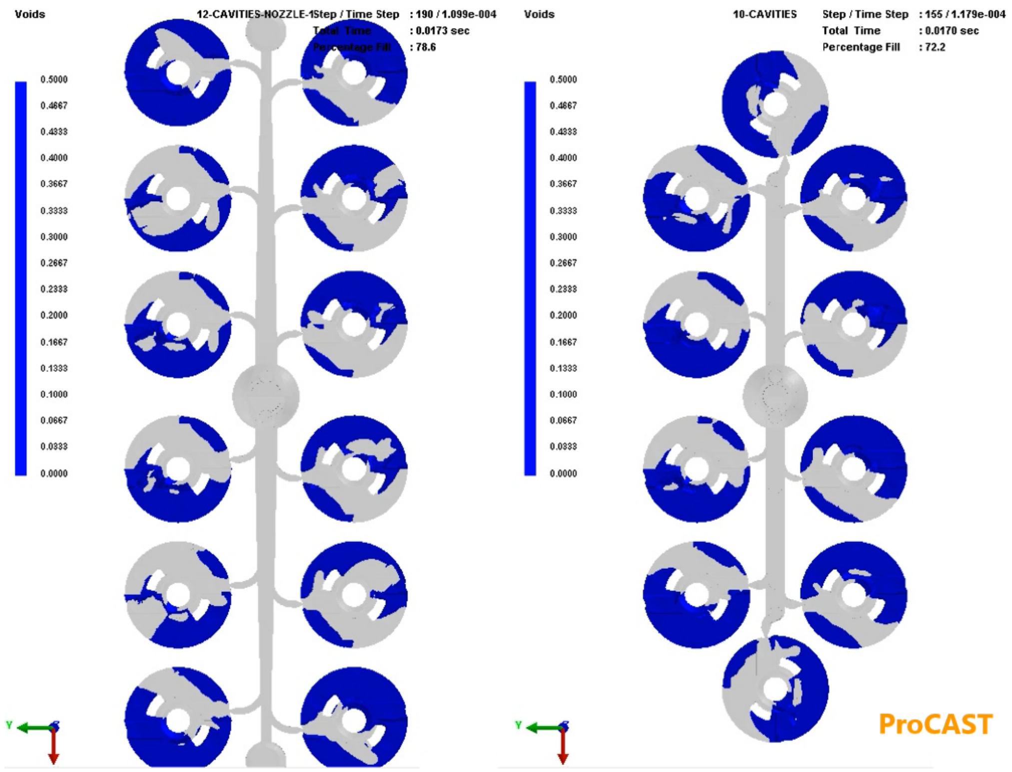


Figure 51: Representation of die filling intermediate phase

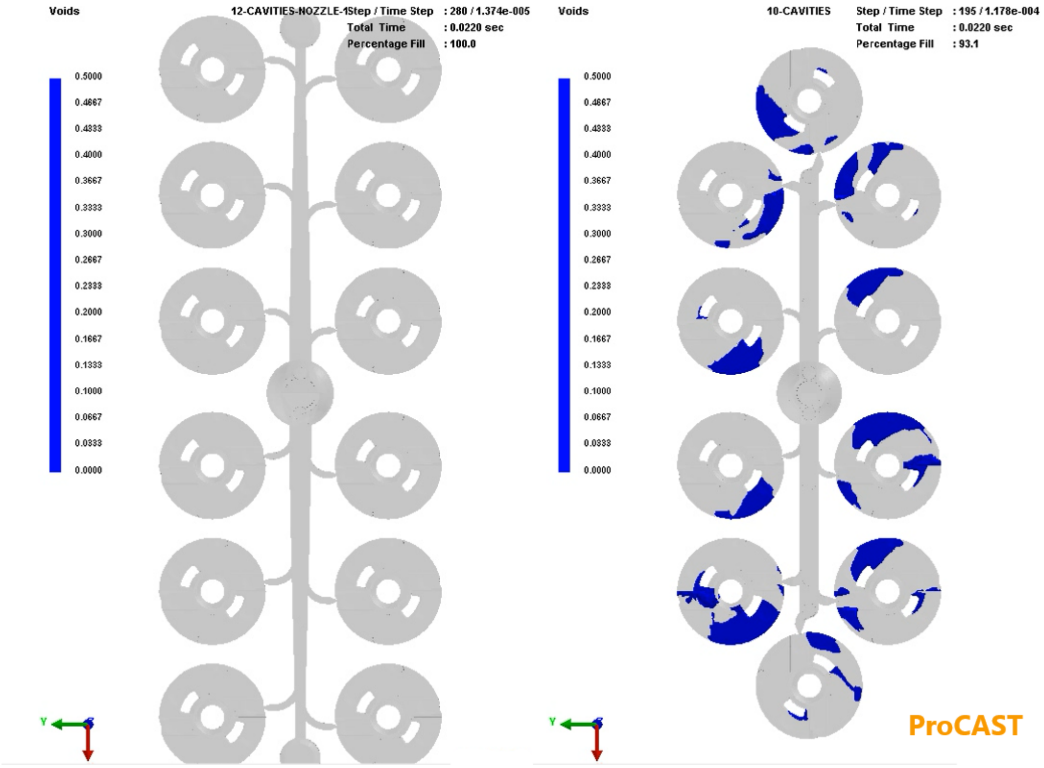


Figure 52: Representation of the end of die filling phase

Figures above, extracted from the video realized with the simulation software ProCAST, represent the filling process in three consecutive stages of a 12 cavities die (on the left) and 10 cavities die (on the right).

This simulation helps to best design the die, choosing for example the optimal number of cavities, in order to reach the ideal filling.

The software suggests the optimal filling velocity and injection gate cross section. With these parameters fixed, filling time varies in relation to part wall thickness and die surface temperature.

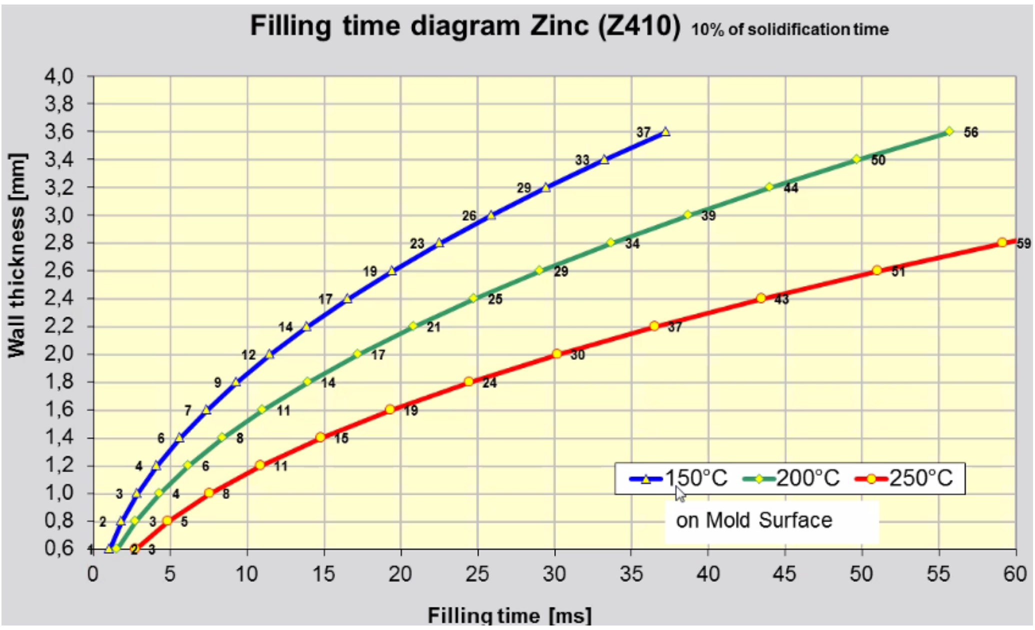


Figure 53: Filling time diagram of a Zama alloy

Figure 53 contains a diagram in which the filling time of a Zama alloy is represented in function of the wall thicknesses to cast for different mould surface temperatures. To work with higher die temperatures is necessary to increase filling time. Indeed, considering for example a wall thickness of 1,8 mm, while with die temperatures of 150°C the filling phase takes 9 milliseconds, increasing it to 250°C, the time required is 24 milliseconds (15 units higher).

For what concerns the molten metal flow rate (casting capacity), it depends on the filling volume (parts and overflows) and the time required to fill the die cavity. Here below some useful formula that allow to compute the injection gate cross section.

$$Metal\ flow\ rate = \frac{Filling\ volume}{Filling\ time}\ \ (l/_{s})$$

$$Gate\ cross\ section = \frac{Metal\ flow\ rate}{Gate\ speed}\ \ (mm^2)$$

In practice, filling mode can be different depending on components geometry (walls thickness for example) as well as on final parts quality requirements.

Generally, for components with a structural role, the focus is on mechanical resistance, trying to avoid for example internal porosity; for aesthetic components, instead, it is important the surface finishing, and so the reduction of any superficial defect [12].

Considering a practical case, to produce thin walls components, a quicker die filling (that means reduced filling time, achievable with higher plunger speed) could grant a better surface finishing but, at the same time, possible undesirable effect can be the formation of porosity, due to generation of fluid turbulences, and burrs appearance, caused by high filling speed.

8.2.2 Solidification phase simulation

The simulation of metal cooling and related solidification starts when the filling process simulation finishes [13].

Figures below contain the images extracted from the video realized with the simulation software ProCAST; they represent the solidification process in three successive moments.

To produce high quality parts, a correct design of water-cooling passages in the die and vents arrangement along the parting lines are necessary. To do this, simulations, allowing the identification of critical areas in which the molten alloy solidifies later, are fundamental.

Vents, in particular, are usually wide and thin (approximately 0.13 mm), so that when the molten metal starts filling the die, it quickly solidifies [15].

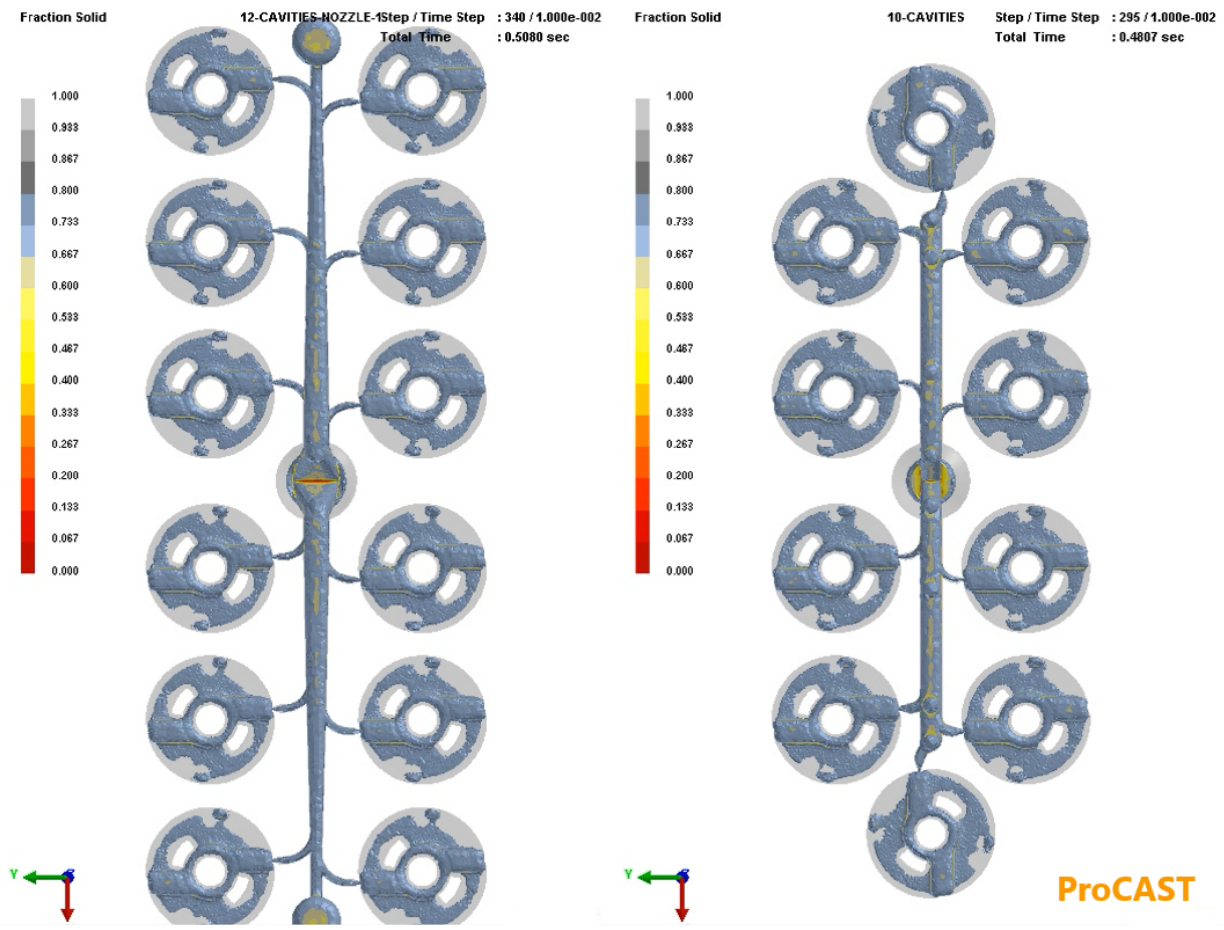


Figure 54: Representation of the first stage of solidification

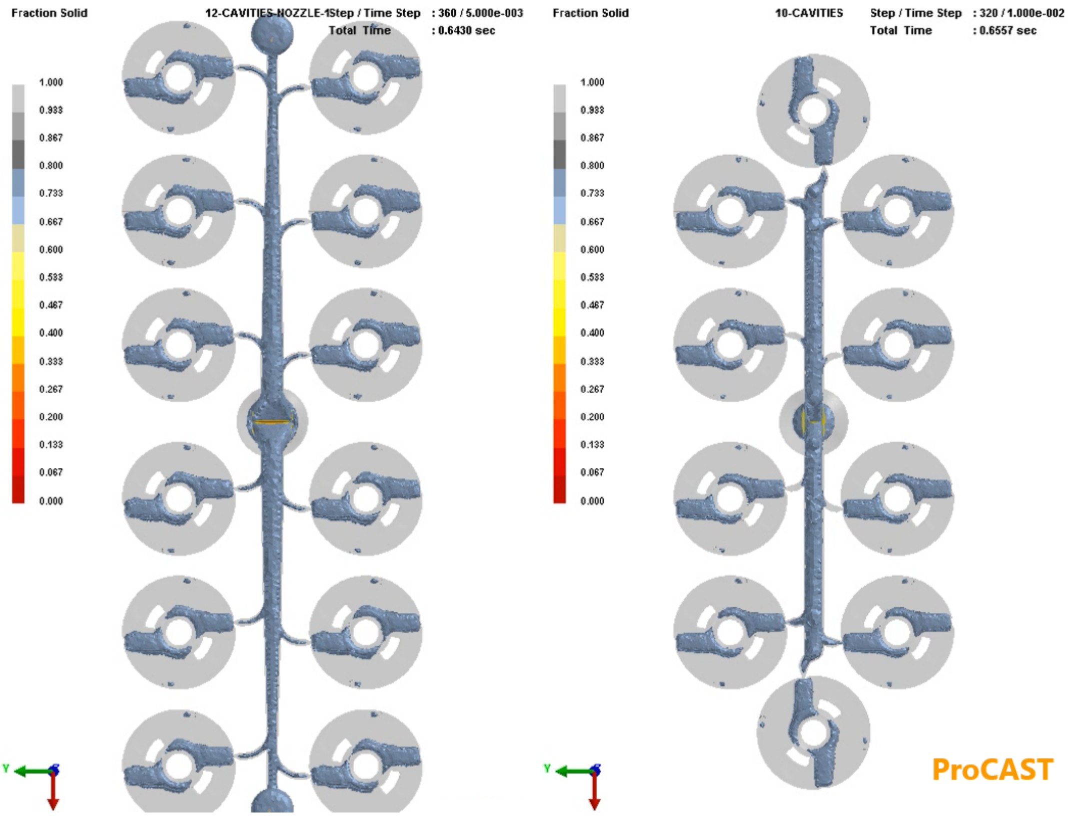


Figure 55: Representation of intermediate phase of solidification

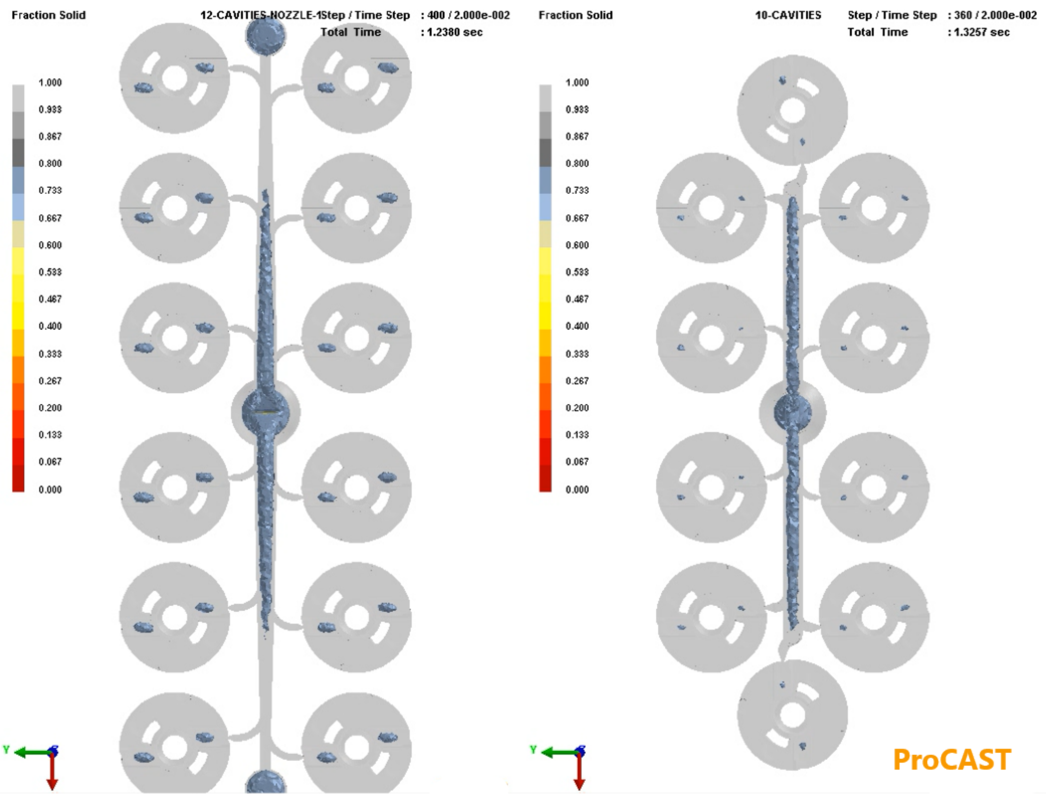


Figure 56: Representation of the end of solidification

8.2.3 Practical application example

A detailed analysis has been conducted on a component that is part of a hinge for a door, in order to optimise mould configuration. After several years of part production with the same mould, the latter was worn out causing superficial defects on the product, such as cold laps, lack of material and porosity. After the analysis of the parameters and of the geometry of the mould, the leading cause of the defects has been identified as the incorrect filling of the cavities. For this reason, the design of a new mould has been evaluated as a necessary action. Aiming at reducing casting defects, the design department has therefore modified mould design, more specifically the feeder design.

In the first phase of design, software simulation of the filling of the cavities allowed different parameters analysis, such as temperature of the metal in every stage of the filling, air pressure in the cavity, material speed and presence of areas with air entrapments.

To define the corrective actions, product shape has been analysed: the component has a thicker upper section and a thinner lower section. The feeder must be carefully designed because, in order to achieve a symmetrical and regular filling, the addition of further elements to facilitate the dynamic behaviour of the filling fluid was necessary.

Simulation phase has revealed that the filling of the upper section was asymmetrical and therefore caused air entrapment in the die cast, with consequent air bubbles presence on the component surface. The cause of the asymmetrical filling was ascribed to the different speeds at which the material started to fill the cavity. As a matter of fact, the fluid entered from the injection point with a high kinetic energy and continued its way by following the cavity geometry, which drove the material to fill specific areas that were thus quickly and more filled, reaching instead only at a later stage those areas that were not in the direction of the main flow.

The first problem to solve was therefore related to the asymmetrical entrance of the material in the gate: in order to symmetrize material entry in the cavity, designers have added a damper at the end of the main feeder. With the new configuration the flow, before dividing, fills the damper while losing kinetic energy and continues its way towards the cavity at a constant speed.

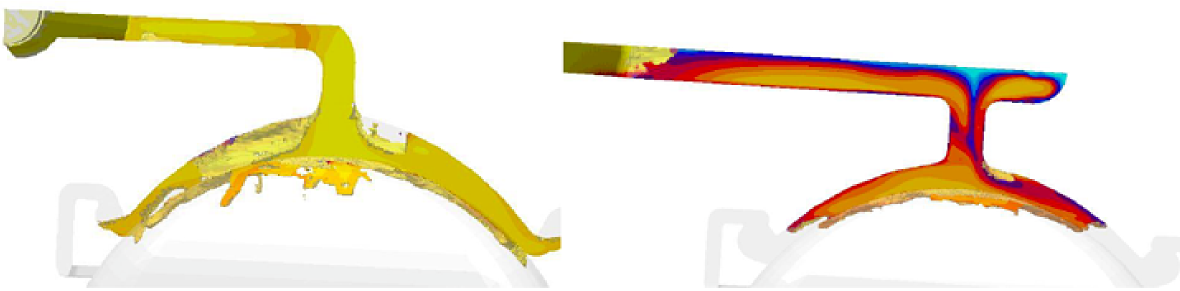


Figure 57: Asymmetrical filling without damper (left) and symmetrical filling with damper (right)

The second problem, still concerning the upper section of the die cast, was related to the divergence of the feeder in specific sections, thus causing turbulences. Consequently, a convergent feeder has been implemented, helping the filling of the cavity, reducing boundary layer separation.

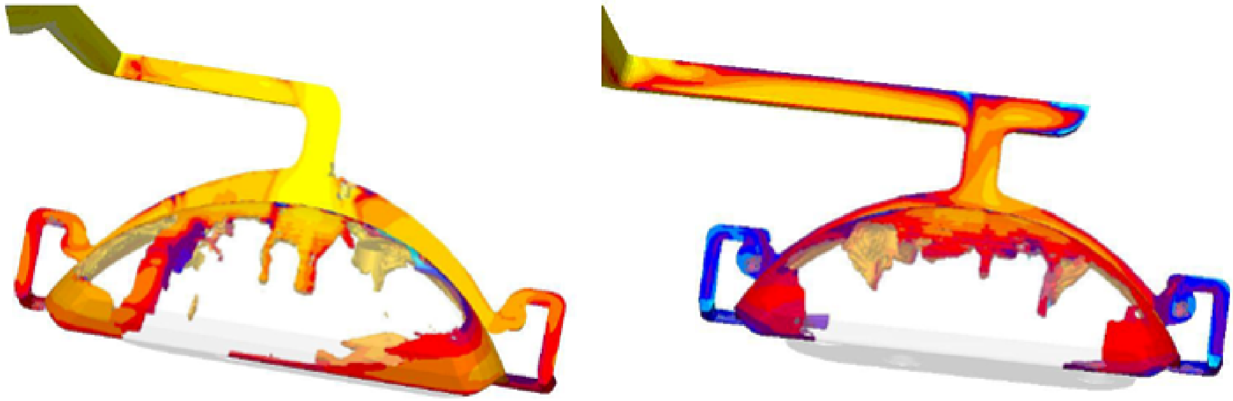


Figure 58: Divergent feeder (left side) and convergent feeder (right side)

In addition, the lower section of the product is visibly different from the upper section. Indeed, being initially filled with material at low temperatures, cold laps and lack of material appeared. Observing the component shape, it was indeed clear that a uniform filling was difficult to obtain, particularly in the lower section: in the first stage there was the upper section filling, only after melt material reached the lower section. Consequently, the filling material reached the lower section at a lower temperature, not guaranteeing an appropriate level of superficial quality.

With the aim of solving this problem, feeding system has been modified with the addition of two auxiliary runners for the lower section of the component in order to achieve a regular filling, by maintaining a stable material temperature in the entire die cast. The two auxiliary runners, as well as the main feeder, have been designed in order to obtain a symmetrical flow: to achieve this result, two further dampers have been added to the auxiliary runners.

Moreover, considering the particular shape of the product, in order to further facilitate the filling in the whole cavity, a partially tangential in-gate has been designed, able to direct material in critical areas. The lower section presents, indeed, some inserts that, without this type of gate, could potentially obstruct the material flow, thus impacting on filling uniformity. This kind of solution therefore determines a better material distribution, by facilitating its entrance in the cavities and the reaching of the most critical areas.

Excellent results have been obtained: the previously observed critical issues remarkably decreased. Mould design and ProCAST allowed to test various solutions before proceeding with the actual production of the component, thus obtaining relevant benefits in terms of quality, time and costs.

8.3 Injection parameters influence on defects formation

The final result of a die casted part is influenced by a wide variety of factors.

Firstly, while developing a new project and defining the production process, an important step is the choice of the most suitable casting unit because it significantly influences the final outcome.

Secondly, since casting machine parameters greatly affect the manufacturing process, an accurate evaluation before the start of production allows to carefully set and adjust them.

Properly analysing and modifying parameters, die casting process considerably improves, offering high quality components.

8.3.1 Choice of casting units according to casting requirements

Various casting units with different characteristics are available on the market and can be chosen, mainly, according to the part to-be-casted requirements.

The highest demands are met with the real time controlled ''RC'' casting unit, that for this reason is the most used one.

Following, the description of the most common casting unit types.

8.3.1.1 Standard casting unit

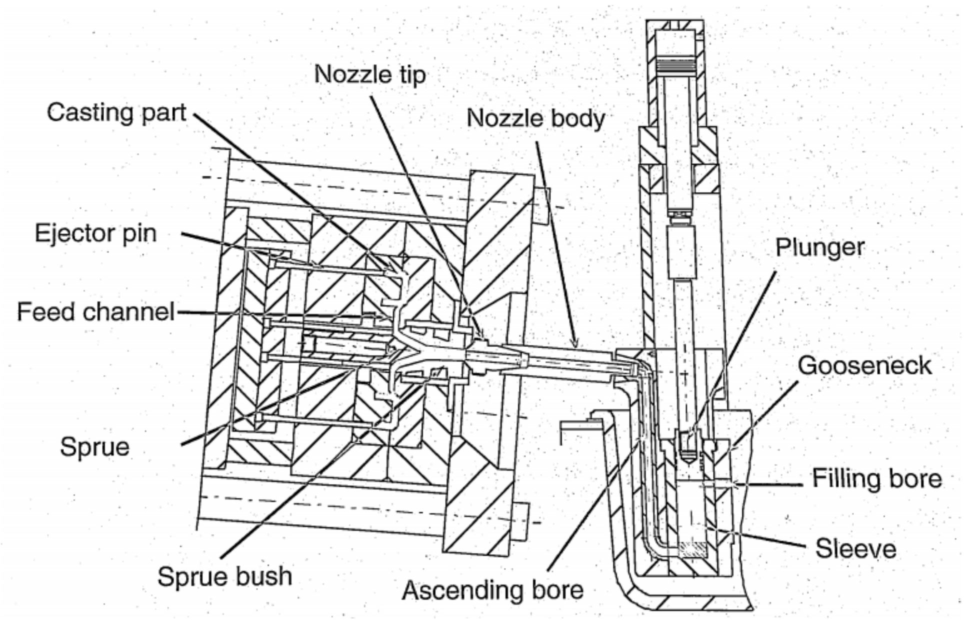


Figure 59: Standard casting unit representation

Its functioning principle has been reported below through a graphical representation; valves behave in function of the casting pressure and rule the melt metal motion in the standard casting unit, allowing the definition of a two-phase profile.

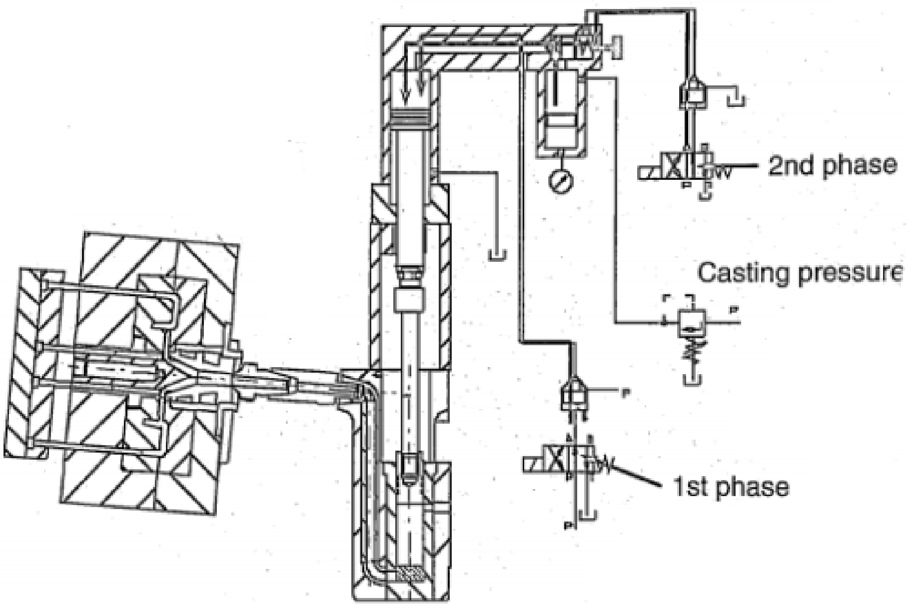


Figure 60: Schematic representation of Standard casting unit functioning

8.3.1.2 Shot Stop casting unit

This unit allows to stop the injection at the end of die filling by controlled braking in order to reduce flash development [6].

The resulting injection cycle is a 3-phase profile, as it is possible to see in the table below.

Phase	1	2	3
Piston displacement (mm)	0	35	71
Velocity (m/s)	0,1	0,9	0,2

Table 25: 3-phase metal injection profile

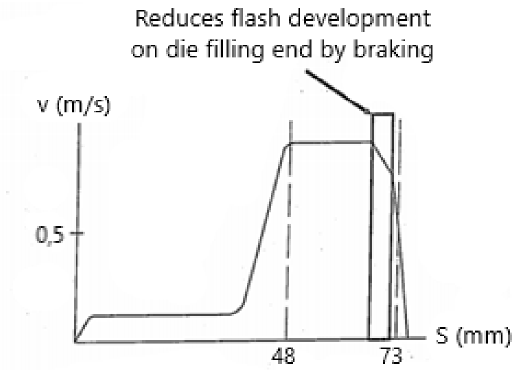


Figure 61: Representation of braking at the end of die filling

Plunger input profile

Phase number	1	2	3
Piston displacement (mm)	0	80	120
Velocity (m/s)	0,2	1,2	0,35

Table 26: 3-phase metal injection profile

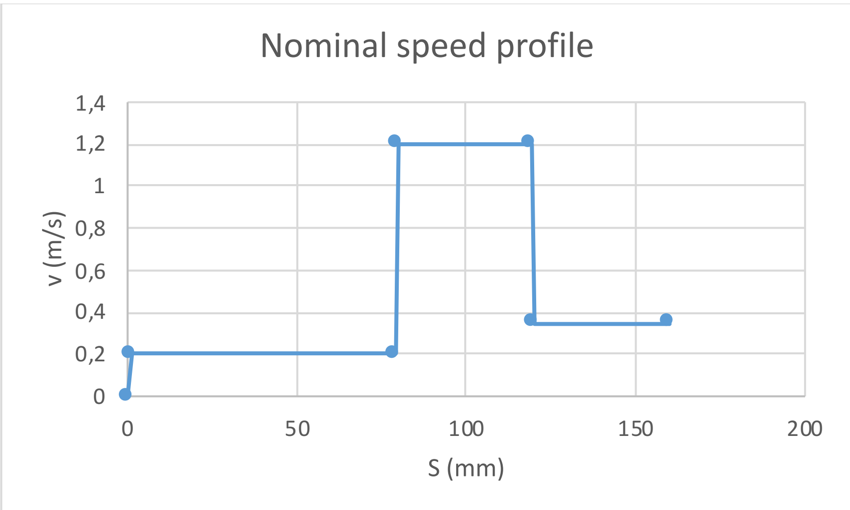


Figure 62: Representation of casting speed in function of plunger movement

8.3.1.3 Real-Time-Control casting unit

Real-Time Controlled casting unit with servo valve in outlet allows a freely programmable profile, best meeting the needs of today's casting industries.

Plunger input profile

Piston displacement (mm)	Piston speed (m/s)
0	0
15	0,2
55	0,2
60	1,25
103	1,25
106	0,3
120	0,3

Table 27: Casting profile – Piston displacement and speed

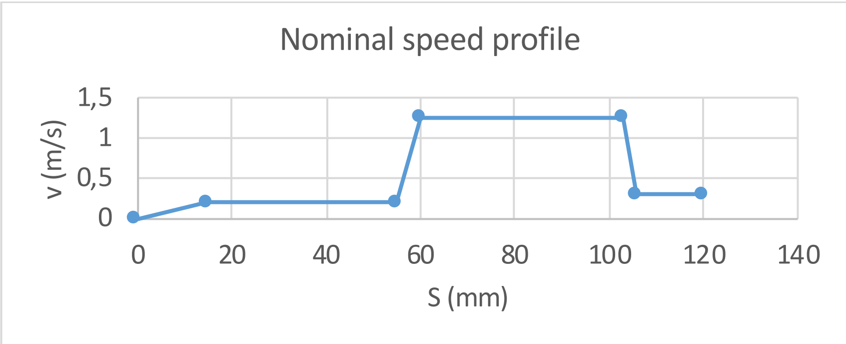


Figure 63: Representation of casting speed in function of plunger movement

Injection time (ms)	Pressure (bar)
0	80
200	140
500	140
1000	100
0	60
1000	60

Table 28: Casting pressure in function of time from piston start

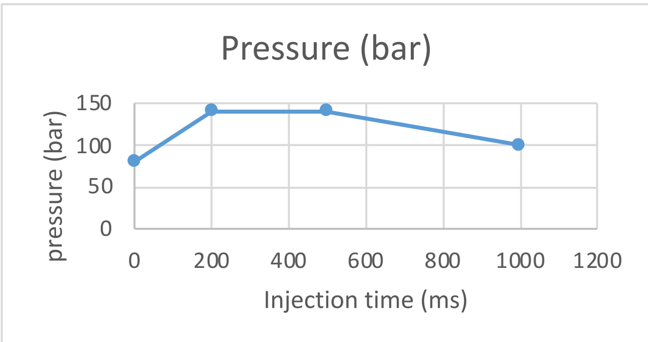


Figure 64: Representation of casting pressure in function of time (milliseconds) from piston start

8.3.2 Quality-related temperature parameter

The current temperatures of a heating casting unit for Zinc are continuously monitored, because it is important to keep them into a previously defined range; an example of working temperature values in case of an hot chamber die casting machine is displayed below:

	Nominal (°C)	min. (°C)	max. (°C)	act. (°C)
Temperature in the metal bath	420	415	430	419
Temperature in the gooseneck	430	410	450	429
Temperature on the nozzle	490	480	570	519

Table 30: Working temperature values of an hot chamber die casting machine

Each listed temperature has a proper influence on the production process.

8.3.2.1 Nozzle temperature

A sufficient and stable temperature difference between the nozzle tip and sprue bush is necessary to obtain a correct die filling. Nozzle temperatures operative range is from 450°C to a maximum of 580°C. Casting standard temperature is from 430°C to 450°C.

In the nozzle tip, the melt should rapidly cool down in a very short region (1-8 mm), so that the casting plug solidifies and can be easily pulled out of the sprue bush when opening the die. The remaining melt in the nozzle must stay liquid so that it can flow back into the furnace thanks to the inclined position of the machine after the end of the secondary compression [6].

This required temperature difference is difficult to achieve without cooling the sprue bush.

Considering factors that influence temperatures variation in the nozzle:

1. The larger the nozzle diameter, the greater the heat transferred from nozzle to the melt that flows inside. Nozzle diameters lower than 6 mm are critical.
2. Condition of the cone in the nozzle tip is important, indeed, if the cone is internally damaged, the casting plug can stick in the nozzle causing unintentional flow interruptions.
3. As regards contact surface between nozzle and die: the smaller the contact between the nozzle and the sprue brush, the lower the heat loss in the nozzle, favouring temperature stability.
4. Size and position of cooling channels can influence the temperature in the sprue bush and in the distributor cone.

Other aspects concerning possibility of temperature variation are the fact that shorter cycle times increase the frequency of the hot melt flow through the nozzle and larger and heavier cast parts require greater quantity of hot melt flow through the nozzle, both determining higher heat exchanges.

8.3.2.2 Die temperature

High quality products, low production costs and high process reliability can not be achieved without temperature-controlled dies. The greatest primary source of error is a less-than-optimal die temperature. Regular heat flow in the melt, accurate die filling, controlled solidification as well as long die service life, require a professional temperature control system.

If die temperature goes out of boundaries, some issues can happen.

Defects due to *low die temperature*:

- Cold welding (material overlapping)
- Incomplete die filling
- Cold flow caused by early solidification

Poor removal capabilities (due to increased shrinkage forces) is an additional problem to consider.

Defects due to *high die temperature*:

- Insufficient spray film
- Insufficient strength due to too slow cooling
- Increased pore formation due to excessive spraying agent use
- No separating effect of spraying agent at too high die temperature

Here below, some examples of die temperatures range in relation to the molten alloy to be injected:

Pb/Sn	60-120°C
Zn	150-200°C
Al	180-300°C
Mg	150-250°C
Cu	300-350°C

Temperature control using *water* allows to reach a maximum temperature of 160°C; it is ideal for parts with thick walls and ensures better thermal transmission (approximately double compared to that of oil) and no environmental contamination due to escaping oil.

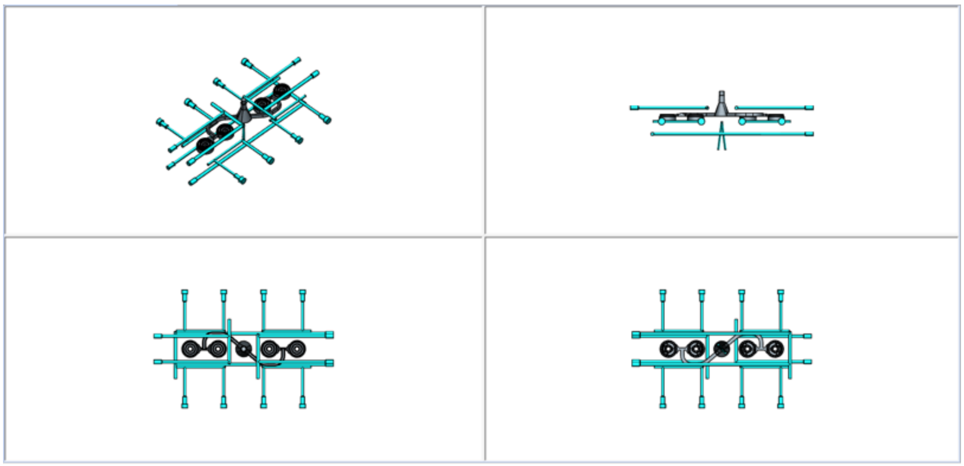
Moreover, this method is convenient because it employs an universally available temperature control medium, that guarantees saving costs with respect to the use of oil (that is more expensive).

Temperature control with *oil*, allows to reach maximum temperatures of 250°C, 320°C or 350°C (depending on the type) and is ideal for thin-walled parts [6].

<u>Controlled die cooling</u>

For having optimal die temperatures, it is necessary to keep under control flow volumes and pressure of the cooling system. Indeed, in case of issues, die casting process could be negatively affected, determining quality problems in the final pieces.

Here, an example of cooling system for a 4-cavities die.



Pressure losses in cooling channels

For the design of a cooling channel of 4 m length that deflects three times of 90°, pressure losses generated by different water flow rates and channel diameters have been recorded, in order to choose the best solution.

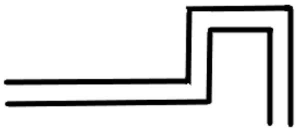


Figure 65: Schematic representation of the cooling channel

Diameter (mm)	Flow rate: 10 l/min	Flow rate: 15 l/min
8	2 bar	4 bar
10	1 bar	2 bar

Table 31: Pressure losses with different channel diameters and flow rate

Die surface temperatures

Comparison of different flow volumes during the die heating phase:

Flow	15 l/min	20 l/min	25 l/min	30 l/min
Temperature	149°C	165-170°C	170-175°C	175-180°C

Table 32: Effect of increasing flow rate on surface die temperature

Obviously, increasing flow rate it is possible to guarantee higher die temperature increase.

8.3.3 Basic casting parameters

Three basic parameters are essential to define the die casting process: casting volume, specific casting pressure (plunger diameter and hydraulic pressure on the casting unit), nitrogen pressure in bladder and plunger accumulator.

The casting profile can be adjusted through the setting of the following characteristics:

- Velocity of prefilling phase (1st phase)
- Start of die filling phase
- Velocity of die filling phase (2nd phase)
- Squeeze phase
- Cooling time

Here below, some of the possible die casting optimisation actions, depending on the configuration of the machine:

- Braking phase for Shot Stop and RC
- Profile velocity control RC
- Profile pressure regulation RC
- Prefilling
- Plunger stop in return stroke

8.3.3.1 Casting volume

According to DIN 24480 the theoretical casting volume can be expressed with the formula:

$V_{th} = A \cdot h - (V_1+V_2)$

A, h, V_1 and V_2 are indicated in figure.

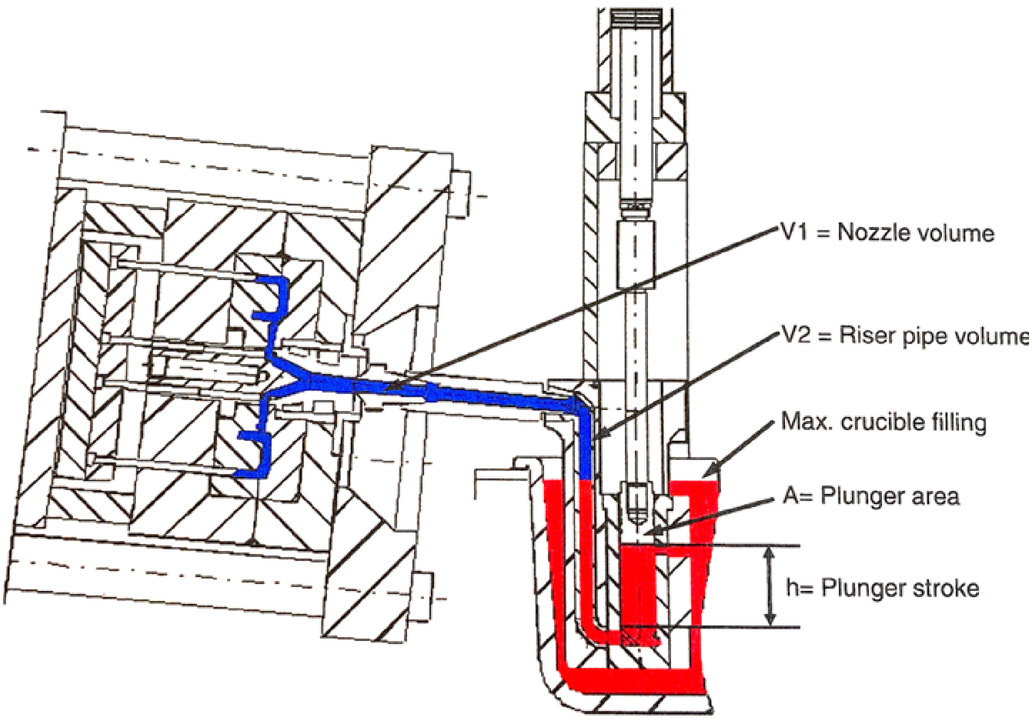


Figure 66: Casting unit schematic representation

Practical casting volume = 0,8 · theoretical casting volume

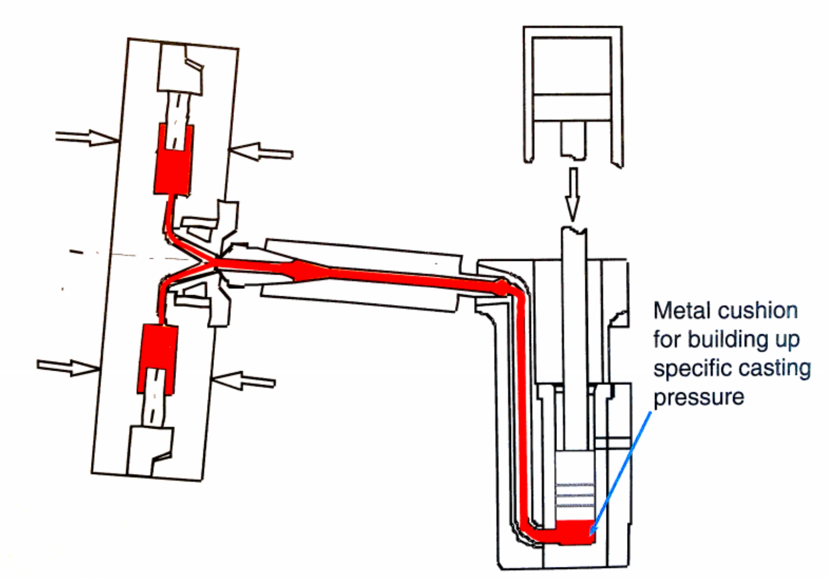


Figure 67: injected metal path in the casting unit

Possible plunger diameter and casting volume

Plunger diameter for DAW 80 F	Theoretical casting volume
50 mm	147 cm^3
55 mm	191 cm^3
60 mm	241 cm^3

Table 33: Theoretical casting volume with different plunger diameters

Practical tip: the maximum plunger stroke should never be reached

Plunger stroke	130 mm

8.3.3.2 Specific casting pressure

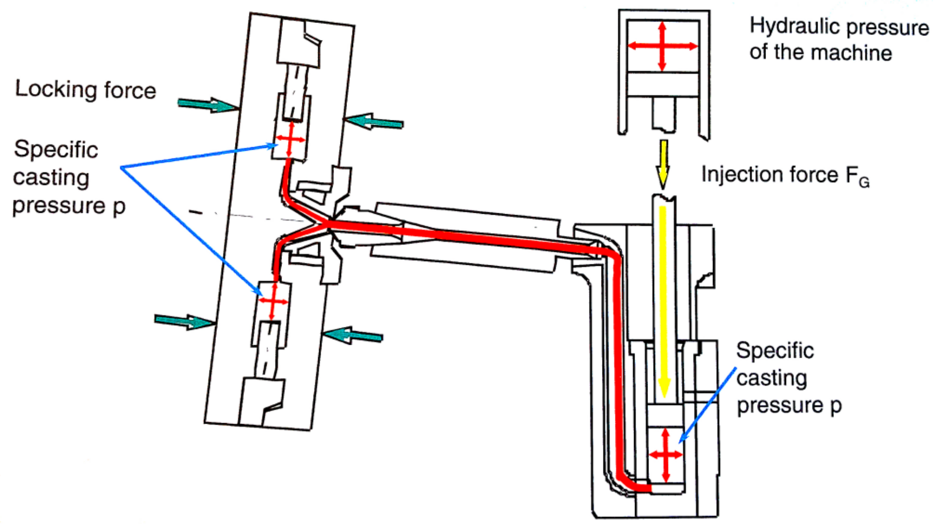


Figure 68: Casting unit representation with focus on pressures

Parts requirements	Recommended casting pressures for zinc alloys (bar)
Parts which have a low or no mechanical stress	130 – 200
Mechanically stressed parts	200 – 300
Pressure-proof or large-surface thin-walled parts	250 – 400
Galvanizable set parts	200 – 300

Table 34: Recommended casting pressures for die casting zinc alloys (bar) for different quality requirements

The maximum reachable specific casting pressure in a process depends on the plunger diameter.

An appropriate gooseneck have to be selected and installed according to the data sheet of the die-casting machine and considering the requirements for volume and quality of the cast parts.

Indeed, with a *too small gooseneck diameter*, the required casting volume could not be reached, determining a not complete die filling.

In this case, higher plunger velocities are required in order to totally fill the parts, always respecting set times. This modification can increase the probability of flash occurrence.

Consequence of a *too large gooseneck diameter* is pore formation.

Indeed, due to a too low specific casting pressure, the molten metal is not sufficiently compressed so as to eliminate residual air. As a resul of this fact, trapped air increases pore formation.

Small plunger strokes, instead, make precise adjustment difficult and reduce the control sensitivity.

Here below, two different die casting machines have been considered: the first (DAW 80) allows lower locking forces with the respect to the second (DAW 125).

Possible plunger diameter and specific casting pressures:

Plunger diameter for DAW 80 F	Reachable specific casting pressure
50 mm	396 bar
55 mm	327 bar
60 mm	275 bar

Table 35: Reachable specific casting pressures with different plunger diameters

Plunger stroke	130 mm
Max. casting force	78 kN

Possible plunger diameter and specific casting pressures:

Plunger diameter for DAW 125 F	Reachable specific casting pressure
60 mm	352 bar
70 mm	259 bar
80 mm	198 bar

Table 36: Reachable specific casting pressures with different plunger diameters

Plunger stroke	150 mm
Max. casting force	100 kN

Determine suitable casting pressure with the casting parameter calculation and adjust on the diecasting machine.

In practice, casting pressure very rarely has to be reduced.

Possible consequences of a *too low casting pressure* is pore occurrence.

Instead, *too high casting pressure* causes greater casting force and thereby favours flash development.

However, a reduced casting pressure only slightly reduces flash formation. Significantly more efficient is braking at the die filling end.

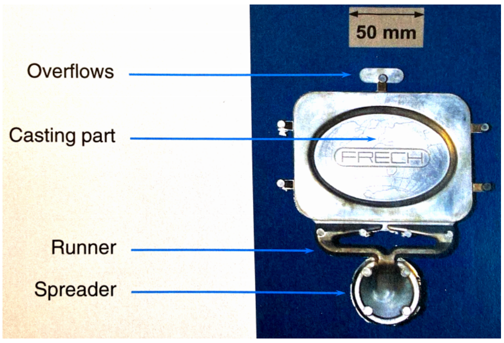
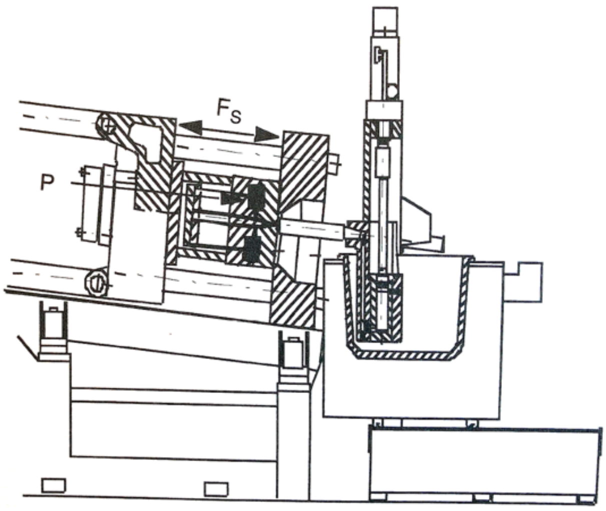


Figure 69: Casting area of a die casted part

Forces acting in a hot chamber die casting process

Casting force of a die $\mathbf{F_s}$ = Casting area $\mathbf{A_s}$ x specific casting pressure **p**



Locking force of a diecasting machine $\mathbf{F_{zu}}$ = casting force $\mathbf{F_S}$ x safety factor **f (1.3 – 1.6)**

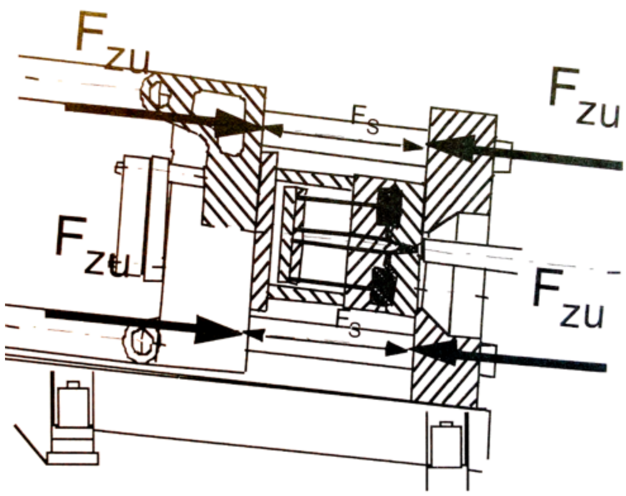


Figure 70: Schematic representations of forces acting in a casting unit

8.3.3.3 Nitrogen pressure in bladder accumulator

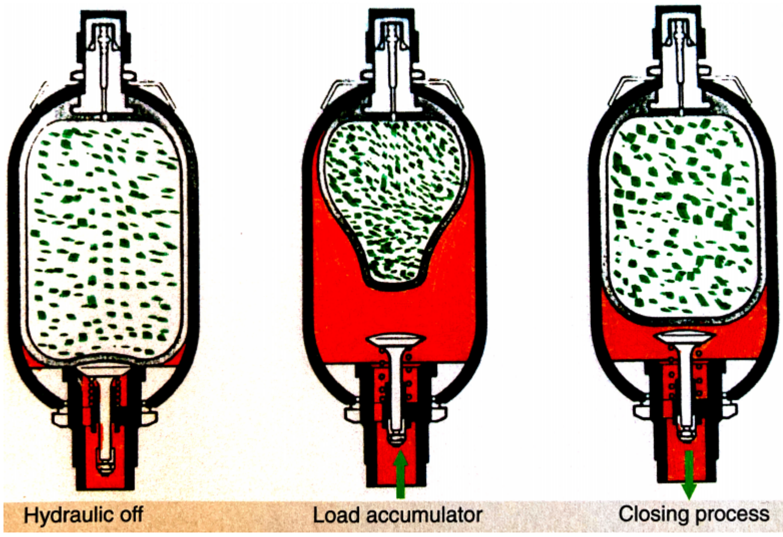


Figure 71: Representation of N_2 pressure in bladder accumulator

Filling pressure sealing accumulator

1. System pressure P = 140 bar
2. Nitrogen pressure $P(N_2)$ = P x 0,80

Consequently in case of a system pressure of 140 bar, Nitrogen pressure will be of 112 bar

Possible consequences in the case of *incorrect bladder accumulator pressure*:

- Extension of cycle time
- The die closes slower because there is too little compressed hydraulic fluid in the bladder accumulator. As a result, the die cools down.

Nitrogen pressure in plunger accumulator of *Standard casting units* is calculated as follows:

Nitrogen pressure = 0,8 x adjusted casting pressure

This implies that if the casting pressure is changed, the nitrogen pressure has to be adjusted.

Nitrogen pressure in plunger accumulator of *RC casting units,* instead, should never be set in RC machines, because the control automatically adjust it on the basis of the system pressure [6].

Note: The correct hydraulic temperature is 40 – 45°C, because the medium has the ideal viscosity in correspondence of this value.

8.3.4 Adjust casting profile

In order to correct deviations, improve part quality and have best-performing process, it is possible to modify some parameters that define a ‘’casting profile’’.

For working on these adjustments, it is necessary to know their effects on final part and relations between them.

For this reason, the following analysis regards:

- Velocity of prefilling phase (1st phase)
- Start of die filling phase
- Velocity of die filling phase (2nd phase)
- Squeeze phase
- Cooling time

8.3.4.1 Set velocity of the prefilling phase (1st phase)

In the first phase (prefilling phase) of the melt injection cycle, the feed channel is filled up to just before the gate (*Figure 72*).

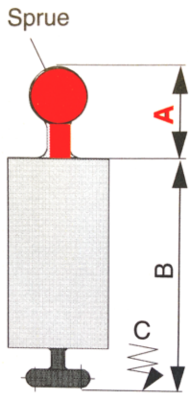


Figure 72: Representation of the filling level reached in the 1st phase, indicated with letter ''A''

After the die closing, air can still be found in the gooseneck, in the nozzle body and in the die (sprue bushing, sprue channel cavities and overflows).

First phase velocity should be as low as possible in order to allow air presence reduction. Indeed, air enclosed in the casting system requires time to escape and, at a too high speed, a turbulent flow favours air mixing with the melt.

In practice:

- 0,05 m/s is a suggested velocity value
- Minimum velocity of 0,03 m/s can be set for best ventilation
- Maximum velocity of 0,15 m/s for short cycle time and thin runners [6]

Possible consequences of *too low prefilling speed* are*:*

- Cold flow

- Extension of cycle time

In this case, indeed, the melt rapidly cools down due to the heat loss in the sprue bushing (water-cooled) and in the runner, determining cold flow in the final part.

Moreover, a slow plunger movement increases the casting process duration.

On the other side, a possible consequence of a *too high prefilling speed* is pore formation; the air, indeed, is swirled with the melt due to too high velocities in the sleeve and in the runner.

Plunger input profile

Phase number	1	2	3
Piston displacement (mm)	0	80	120
Velocity (m/s)	0,2	1,2	0,35

Table 37: Casting profile – Piston displacement and speed

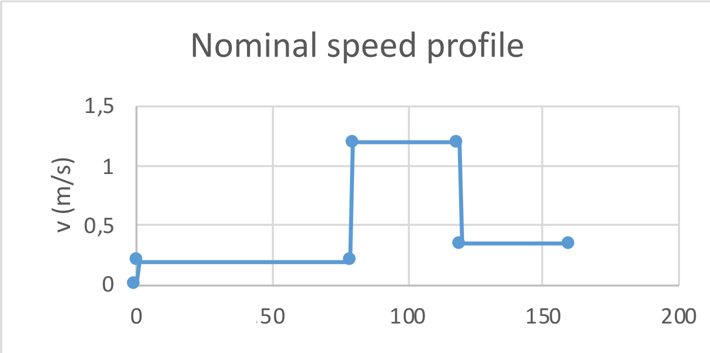


Figure 73: Example of casting speed in function of plunger displacement

Plunger input profile

	[mm]	[m/s]
	0	0,00
1st phase	1	0,05
	55	0,05
2nd phase	56	0,40

[ms]	[bar]
0	160
2000	160

Table 38: Piston speed with focus on prefilling (on the left) and constant pressure value (on the right)

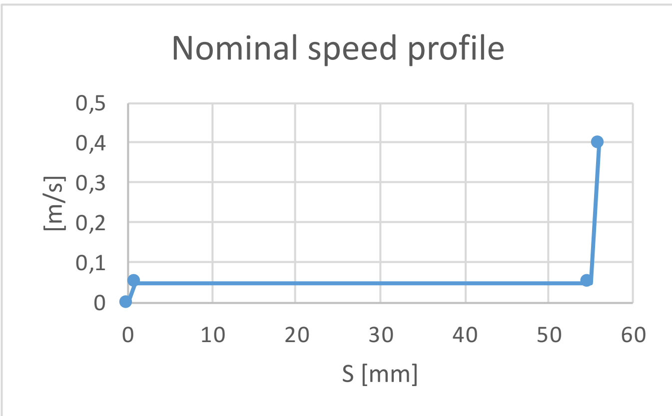


Figure 74: Casting speed in function of plunger displacement with focus on prefilling velocity

8.3.4.2 Starting point of die filling phase

The changeover point from the prefilling phase (1st phase) to the die filling phase (2nd phase) must be carefully determined.

Possible consequences of *too early changeover* are:

- Pore formation
- Cold flow

In this condition, the air is swirled with the melt due to too high velocities in the sleeve and the runner, determining pores occurrence.

Moreover, too slow die filling after the gate causes severe cooling of the melt and increases cold flow occurrence probability.

Plunger input profile

Phase	1	2	3
Piston displacement (mm)	0	80	120
Velocity (m/s)	0,2	1,2	0,35

Table 39: Casting profile – Piston displacement and speed

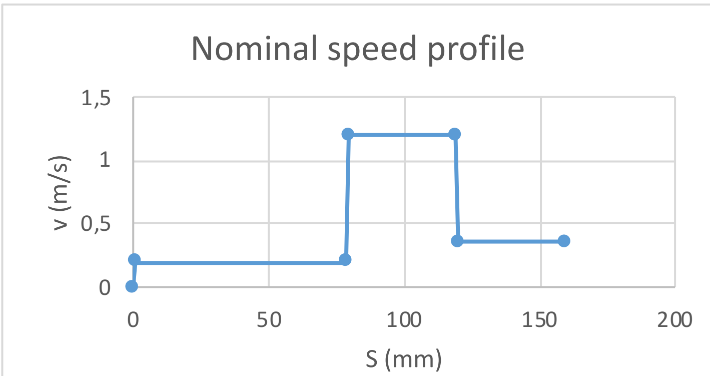


Figure 75: Representation of casting speed in function of plunger displacement

Plunger input profile

Velocity

	[mm]	[m/s]
	0	0,00
1st phase	1	0,05
	55	0,05
2nd phase	56	0,40

Pressure

[ms]	[bar]
0	160
2000	160

Switching point

For maximum acceleration, a practical trick is to set the second value 1 mm larger than the first value (as showed in the above table, 55 mm at the end of the first phase and 56 mm at second phase start) [5].

8.3.4.3 Velocity of die filling phase (2nd phase)

In the die filling phase, mould cavities and overflows are filled.

Die filling speed depends on:

- Wall thickness of the die cast part (the thinner they are, the shorter the die filling phase)
- Die surface temperature
- Quality requirements of part to be manufactured

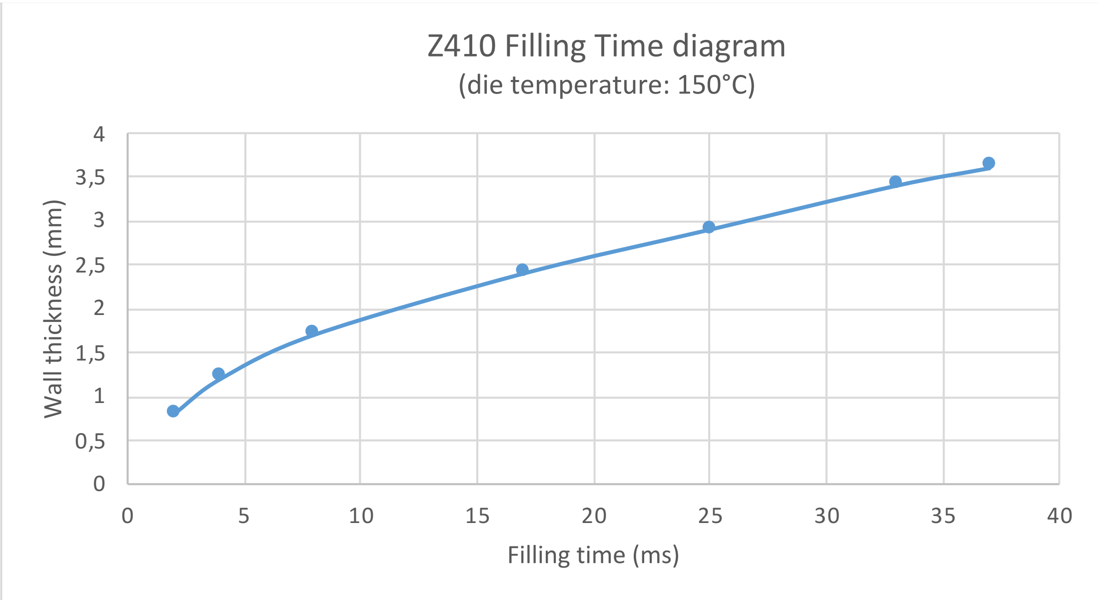


Figure 76: Die filling time of a Zama alloy in function of component wall thickness

Initial adjustment of the velocity of the 2nd phase (from 0,3 to 0,5 m/s) can determine complete die filling without flash development.

In practice, 2nd phase speed is generally increased in steps of 0,2 m/s until the calculated value or good parts quality is reached.

A possible consequence of a *too low speed* is cold flow; too slow die filling causes metal cooling, determining melt solidification before the die is filled.

Possible consequences due to *too high velocity*:

- Cavitation
- Flash development

Cavitation, indeed, can be generated by too high molten metal speed at the gate.

At the same time, too high plunger speeds can cause a hard impact at die filling end; in this case, pressure peaks promote flash occurrence.

8.3.4.4 Squeeze phase

The squeeze phase begins just after the die filling is completed and finishes after the secondary compression end, lasting at least 0,5 seconds with a standard gate thickness of approximately 0,5 mm.

During this phase the metal is compacted inside the mould; pressure values and related increase rate depend on quality requirements of the cast part.

In practice, setting a secondary compression time of about 2 seconds, the casting graph displays the resulting squeeze time. Squeeze time deducted from the secondary compression duration have to be added to the cooling time.

Possible consequences of a *too short secondary compression time* are:

- Pore formation
- Shrink porosities

Because of a lack of pressure during solidification, the metal is not sufficiently pressed, so as to eliminate residual air; as a result, trapped air determines pores occurrence. Moreover, considering that at the end of die filling a volume reduction of the melt is registered due to solidification, in this case a too short secondary compression can not compensate this shrinkage.

A *too long secondary compression time* instead, means more extended cycle time.

Indeed, a long lasting pressing phase extends the casting process; moreover, unnecessary extended pressure application on the melt causes strong wear of the piston rings.

The last important thing about this topic is to make it clear that secondary compression time is different from squeeze time.

Here below, some sample datasets in castings taken from real production:

Compression time				**0,6 s**
Cooling time				**2,0 s**
Velocity				**0,10 m/s**
Cold shot monitoring	Start	**5,0 mm**	End	**42 mm**
Cold shot monitoring max. pressure		**140 bar**		
Plunger stroke	Current	**0,7 mm**	Shot	**0,0 mm**
Start secondary compression time at				**Start 2nd phase**

Table 40: Sample datasets in casting

In conclusion, solidification time depends on compression time and cooling time, as expressed in the following important formula:

<u>Solidification time = compression time + cooling time</u>

8.3.4.5 Cooling time

Cooling starts after the end of the secondary compression; its duration depends on the configuration of the die cooling channels and on the wall thickness of cast part and sprue.

The die remains closed during this phase; cooling time must be long enough so that the component reaches sufficient mechanical strength, in order to avoid cast part deformation after die opening and subsequent ejection.

If the sprue breaks at the thickest point, this indicates that the cooling phase has a not sufficient capacity or that is too short.

The possible consequence of *too long cooling time* is shrinkage.

In this case, the cast part at the end of the process can not be easily removed.

Instead, the possible consequence of *too short cooling time* is component deformation.

Indeed, in this situation, the cast part is still too hot and does not have sufficient mechanical strength.

However, although the previous analysis is important to better understand process dynamics, in practice, the required cooling time can only be determined by trial, using lesson-learned from past projects to simplify this process.

8.3.5 Definition of the casting profile through limit lines

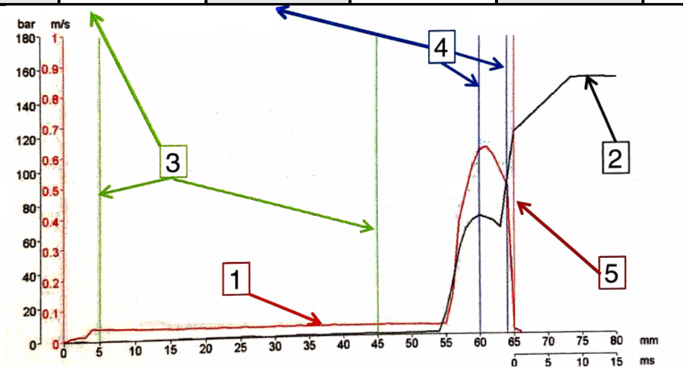
When the basic profile setting doesn't provide a completely filled die it is necessary a 2nd phase speed increase.

The casting curve is necessary to monitor casting parameters and to correctly adjust them.

In *Figure 77* it is possible to find a graphical representation of:

1. Plunger velocity (red curve)
2. Casting pressure (black curve)
3. Limit lines 1 and 2 (green), display of measured values between lines 1 and 2
4. Limit lines 3 and 4 (blue), display of measured values between lines 3 and 4
5. Limit line 5 (red), start of scale in milliseconds

T_1 act.	1169 ms	T_2 act.	7 ms	T3 act.	92 ms	P0 act.	1 bar
V_1 act.	0,03 m/s	V_2 act.	0,57 m/s	Pmax	155 bar	P3 act.	154 bar



	1	2	3	4	5	
Limit lines	5	45	60	64	65	[mm]

Figure 77: Representation of casting limit lines

Recommended positions of limit lines

Limit line 1 should be fixed at 5 mm from graph origin in case of hot chamber die casting machines, or after the initial speed ramp (to reach first phase velocity), at piston displacement start, in case of cold chamber. The second limit line, instead, should be placed 2 mm (for hot chamber machines) or 10 mm (for cold chamber machines) before second phase start. For what concerns the third limit, it must be positioned at the piston stroke, where the melt reaches the gate. At the end of die filling, limit line 4 defines a speed drop down. The last limit to be set is line 5, that is placed 1 mm after line 4.

These limits allow the automatic computation of:

- V_1 -> Measurement of the velocity of the 1st phase
- V_2 -> Measurement of die filling velocity
- T_2 -> Measurement of filling time

Limit lines setting

Limit lines have to be set from the right to left: so starting from limit line 5 and finishing with the set of limit line 1 [10].

The die filling end is recognizable by the severely dropping velocity curve. Limit line 4 have to be positioned at this location. Limit 5 is set immediately after that.

Subtracting the calculated filling stroke from the die filling end (limit line 4), it is computed the location of limit line 3.

T_1 ist.	462 ms	T_2 ist.	18 ms	T3 ist.	25 ms	P0 ist.	2 bar
V_1 ist.	0,12 m/s	V_2 ist.	0,80 m/s	Pmax	160 bar	P3 ist.	141 bar

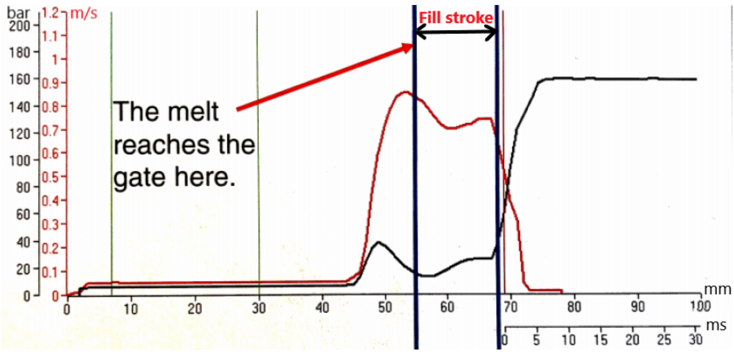


Figure 78: Graphical filling stroke representation

Second phase speed must be reached before the gate. The starting point of the 2nd phase must be set in relation to the acceleration rate before the gate.

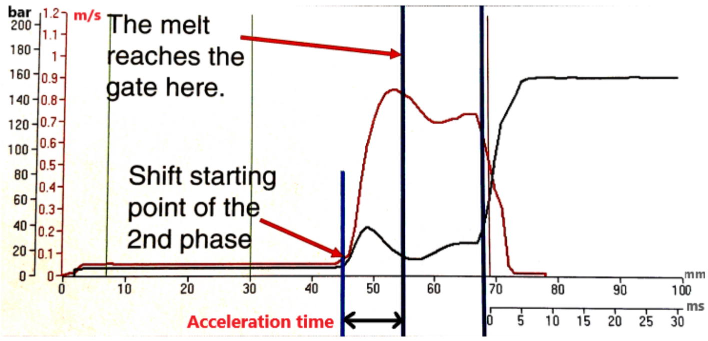


Figure 79: Second phase shift starting point

If the limit lines are shifted during the casting process, measurements in the quality table change, but the quality of the castings remains the same.

Figure 80 reports an example of casting curve, the relative fill stroke and limit lines position.

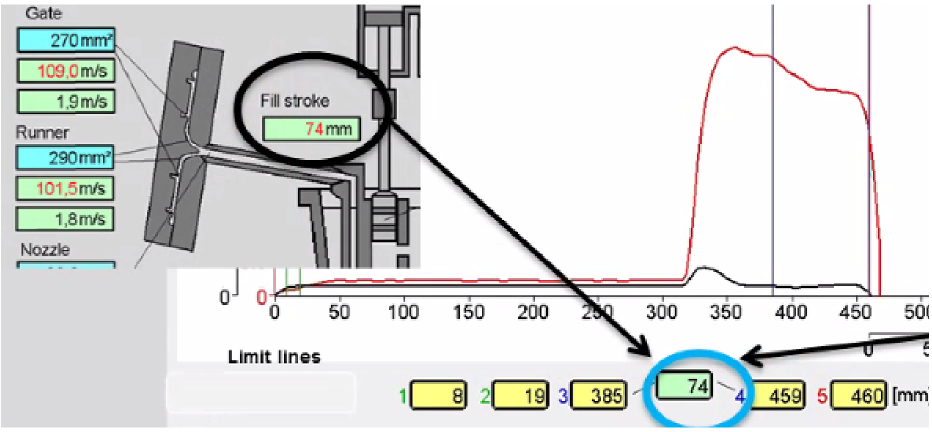


Figure 80: Casting curve, fill stroke and limit lines

After the 5th line, it is necessary to continue shot parameters recording (in particular pressure) and these values have to be included in the displayed casting curve [10].

If limit line 5 is set after the injection piston stop (like in *Figure 81*) and the pressure measurement ends, the last measured pressure value is taken for P3.

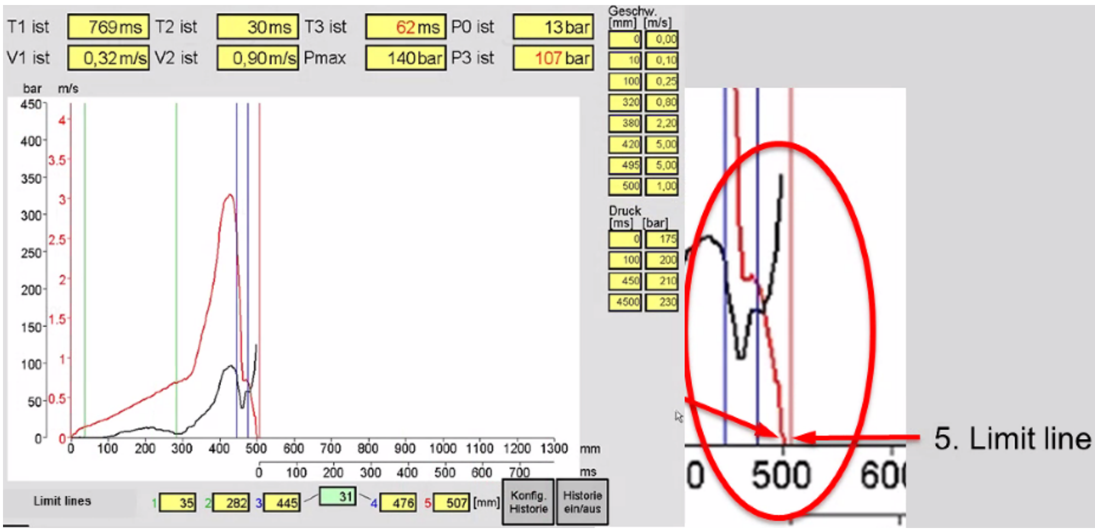


Figure 81: Focus on limit line 5 position

If P3 value has a tolerance to respect, it could happen that limit is exceeded. In this case, the casting would be classified as scrap and therefore ejected, although it is actually good; this because the value considered as P3 was not the real final pressure.

8.3.6 Additional optimization options depending on machine configuration

Following final part requirements, it is possible to consider the optimisation of other elements.

8.3.6.1 Braking phase for shot stop and RC casting units

Since in the braking phase there is a die filling speed reduction, it's important to gradually approach the braking point and to have a progressive deceleration rate.

Deceleration velocity should be equal to half die filling speed (2nd phase); if needed, it can also be lower.

The braking point, to be effective, must always be set shortly before die filling process end, but at the same time, it should not be set too early, otherwise the filling time would require too much time.

Starting point of this phase is usually placed 1 mm before the reaching of mould filling end, considering that setting it too early could lead to have cold flow in the final part.

The proper functioning of this phase can be verified through the pressure curve: with a correctly set braking phase (*Figure 82*), pressure at filling end drops only briefly and then it rises.

The consequence of a *correct braking,* in addition to achieve successively a faster pressure increase, is the reaching of a minimum speed loss at filling end.

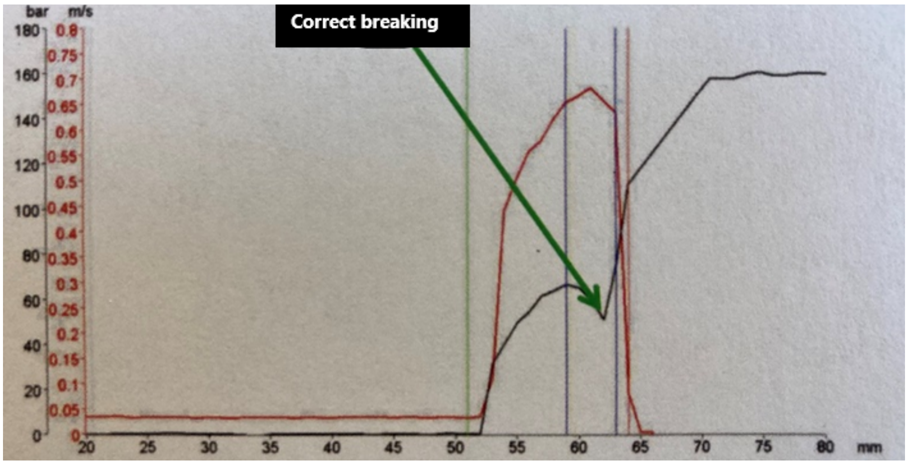


Figure 82: Correct braking (the black curve indicates the pressure)

Too strong or too early breaking, instead, causes lower pressure values (near 0 bar) that can successively too slowly increase and, in addition, high velocity losses at filling end (*Figure 83*)

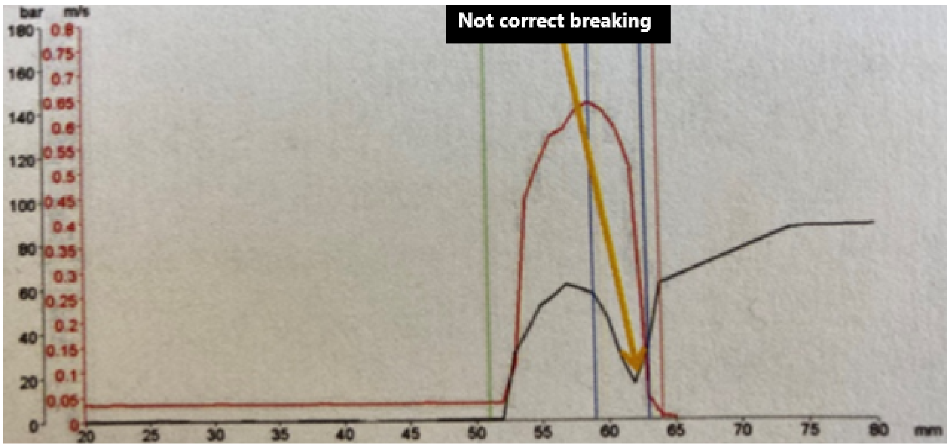


Figure 83: Incorrect breaking (the black curve indicates the pressure)

8.3.6.2 Prefilling

With standard filling, when the injection starts, the melt in the casting system is at the metal bath level (*Figure 84*).

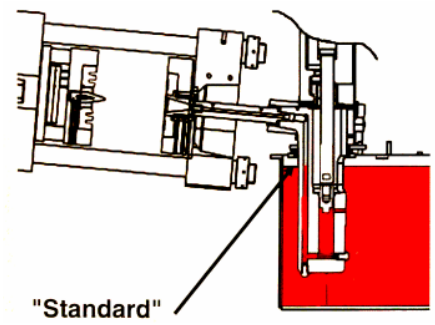


Figure 84: Standard filling system, in which molten metal is represented in red

In casting processes with prefilling, instead, since the melt in this phase fills the casting system up to shortly before the nozzle tip, the die filling phase starts with the melt already in close proximity to the mould cavities (as shown in *Figure 85*).

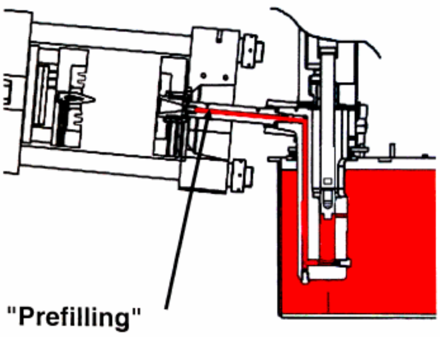


Figure 85: Molten metal (represented in red) at prefilling end, before die filling start.

Prefilling	
Start delay, prefilling	1,0 s
Plunger stroke, prefilling	20,0 mm
Plunger diameter	60mm

Table 41: Prefilling adjustment

The advantages of this system are a reduced quantity of entrapped air in the casting unit (around 20%) that results in a remarkable part quality improvement and a shortened cycle time (0,3 ÷ 0,5 seconds) which increases productivity.

Prefilling phase must end before the starting point of the second phase. The important prerequisite for working with ‘’prefilling’’ is that the sprue could be uniformly and constantly remelted in the nozzle.

During this phase, the plunger moves the melt through the nozzle body up to the nozzle tip (at a previously set velocity) and since the die is open, the air can escape.

Only a brief stop at the prefilling position (approximately 0,5 seconds) is allowed, before the casting process continues, because waiting too long at the prefilling position, the melt flows back into the crucible.

8.4 Processes optimization: improvement actions practical examples

8.4.1 Case 1: Defects in critical areas

A case of damaged production has been object of study during the internship in Dynacast: the analysis has been conducted on 1000 Zama die-casted parts, many of which with damages localized in critical areas.

Figure 86 shows defects found (dents) and explain how the piece should be assembled once delivered to the final customer. It is possible to see that dents appear in areas in contact with other components of the assembly; for this reason, functional problems can be generated.

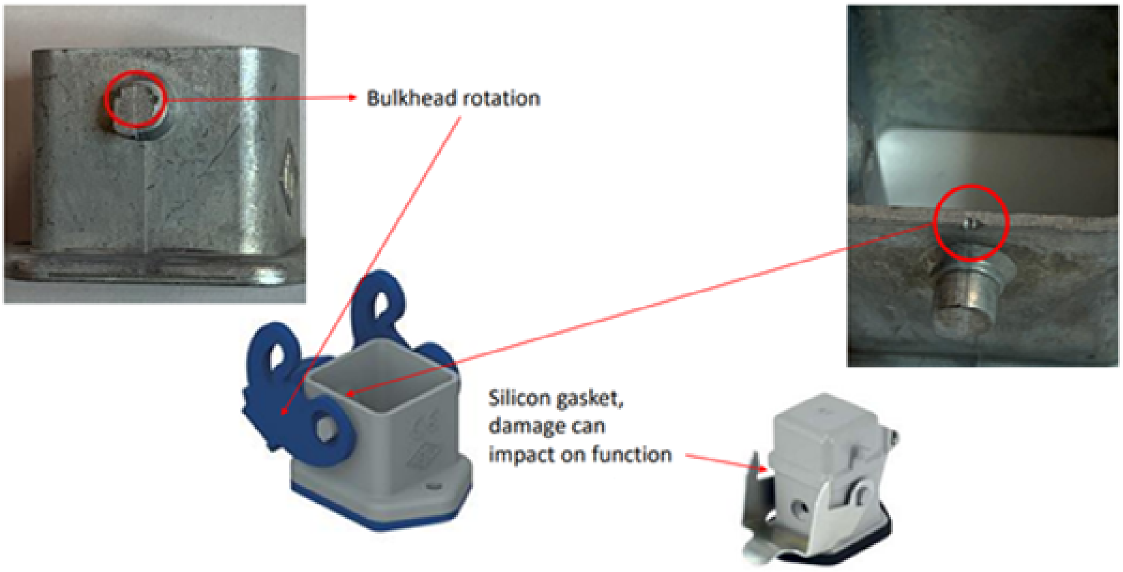


Figure 86: Dents on the part

In the first step of the investigation phase, the visual analysis of 500 cast components belonging to damaged batches has been carried out, in order to determine the entity of the problem.

Output of the analysis was:

- 20 pieces presented damage in correspondence of the upper edge
- 93 parts reported damages on the pin

So, around 20% of identified critical pieces.

After a defects analysis, considering all the possible root causes and potential negative effects on the final product (functional problems), some corrective actions to the die casting process have been implemented in order to perform quality defect prevention. To avoid dents, an important consideration is that they are mostly caused by hits of parts with other harder surfaces.

Here below the list of actions taken:

1. Addition of ventilation at the end of the die casting process, in order to rapidly cool pieces
2. Use of robots for automatic pieces separation (pieces are casted in multi cavity dies)
3. Covering the lateral surfaces of the conveyor belt with soft material to avoid impacts
4. Use of slides to reduce the height of drop from the conveyor belt to the box containing die-cast products

Analysis of modifications

1. By adding ventilation, temperature of the part at the exit of the die casting machine decreases. Assuming that lower temperature means lower material deformability, it becomes more difficult to damage parts during contacts with other surfaces (for example, sliders, bottom of containers).
2. The addition of robots for automatic separation of pieces produced with multi-cavity dies increases the accuracy of this operation, avoiding probability of damaging pieces during manual separation.
   Moreover, it allows parts to be gently placed on the conveyor belt, decreasing the risk of hits generated by the free falling of pieces from the die.
   Furthermore, it is important to handle parts with high care since, when components are separated, ventilation hasn't been applied yet, so parts are still hot and easily deformable.
3. To avoid parts to hit other surfaces, the conveyor belt lateral sides have been covered with softer material (ex. Teflon) that avoid Zama damage.
4. Adding slides, the height of drop from a surface to another (in this case from the conveyor belt to the box containing die-cast products) is reduced and parts reach more delicately the box with the other parts.

After these implementations, a final production check demonstrated a consistent quality improvement.

To do this, two different cases have been considered and studied:

- Die-casted components transported on the conveyor belt picked before falling in the box
- Die-casted components transported on the conveyor belt and then let dropping in the box

As expected, the analysis demonstrated, by checking 500 die-casted pieces in both cases, that these adjustments positively affect the production quality, reaching 100% of good pieces in both checks.

As next step, the investigation phase has been oriented on thermal treatments, with the aim of verifying if they could represent one of the damaging causes.

For this purpose, thermal deburring has been performed on pieces previously checked that didn't present defects; as result of quality control, a small percentage of components has resulted damaged.

Defect appearance could be associated to side effects of the air-gas explosion in the thermal deburring machine, that are:

- High temperature
- High internal energy that makes parts hit themselves

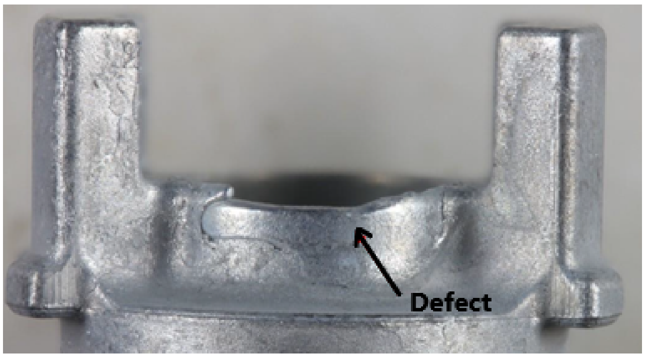
Combination of high speed contacts and elevated temperature has been, in this case, the main cause of dents generation.

To solve this problem, thermal deburring phase has been replaced with a sandblasting phase, eliminating high speed and high temperature contacts between parts, enhancing quality of final production and reducing scraps.

8.4.2 Case 2: Cold shots

A second analysis has been carried out in order to study potential causes that could have determined 16 defective die casted components over the total production (33000 pieces).

These components, as possible to see in *figure 87*, show a not perfectly defined contour due to the lack of material in certain areas that, during die casting process, have not been entirely filled.



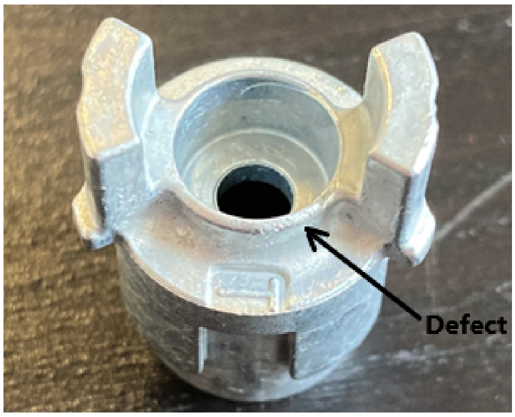


Figure 87: Visible defect on the part

To start the investigation, in order to understand the root causes of the non-conformity, it is necessary to know the cavities of pieces deemed not within the limits of acceptability. In fact, the cavity position in a multi cavity mould could affect die filling phase and may help detecting the origin of the quality defect.

After the identification of the die casting machine in which parts were produced and of robots used for pieces separation (ABB robotics), some hypothesises about defects occurrence have been done:

1. Not effective automatic scrap separation system at machine start-up
2. Cold shot
3. Too low die temperature
4. Excess of lubricant oil

At this point, the investigation phase began. Considering that after every machine start-up the robot discards the first five pieces to prevent defective components (due to not stabilized casting parameters) from being delivered to the customer, in order to verify the efficiency of automatic scrap separation at system start-up, these initial scrapped parts have been analysed. While the first three picked pieces were not conform to customer standards, both the fourth and the fifth component were acceptable for production requirements; in this way the effectiveness of robot parts separation has been demonstrated. For this reason, the possibility that the elimination of the first five shots wasn't sufficient to avoid not compliant pieces has been discarded.

Focusing now on other factors, since a lower nozzle temperature could have caused cold shot, its temperature chart has been checked in machine database; standard nozzle working temperature was 460°C and temperature controls verified that values have never exceeded the range of +/- 5% of the nominal one.

In an attempt to reproduce the defect, the worst reachable situation has been set, decreasing melting furnace temperature from 430 to 410°C and reducing nozzle temperature from 460°C to 400°C; immediately second phase velocity diminished (due to the higher density of the molten metal) passing from 0,61 m/s to 0,4 m/s.

In this case a not perfectly complete die filling has been reached. However, thanks to the standard setting of an inferior velocity limit value, the machine noticed an excessive speed reduction and stopped. So, the idea that a decrease in temperatures caused the defect has been dismissed.

In addition, a too cold die surface has been evaluated as possible root cause. To verify this hypothesis, die temperature has been lowered at 20°C; after this setting, produced cast pieces reported on the overall external area a not homogeneous surface, highlighting the effect of a too fast solidification of Zama in contact with cavity walls; differences of defects configuration compared to studied defective parts allowed us to dismiss also this possibility.

At this point, further researches have been oriented on lube: production recordings database showed that the machines used a traditional electric lubricant system.

Since the mould was vertically oriented, its cavities were localised at different heights, and the molten metal filled the die in a different way in comparison with horizontally mounted dies. Since the gravity influences the lubricant oil distribution, in case of excessive lube, oil would accumulate in the lowest zones of the cavity, impeding a correct filling and solidification in that positions. However, the examined defects were not in the lowest zones.

Moreover, trying to reproduce the defect, spraying higher quantity of lubricant on the die, the resultant casted pieces showed on the overall surface a not homogeneous quality, so a different defect configuration with respect to that reached in the case under examination, in which the damage was in a single point.

From the moment that none of the considered hypothesis helped us to detect defect origin, the analysis continued and records of extraordinary maintenance operations showed a nozzle replacement after a machine notification about a twisted nozzle.

Even though the difficulty of demonstrating that a crooked nozzle caused an irregular melt injection, due to the impossibility of reproducing the defect in the same conditions, this was the most likely potential cause.

So, standard casting parameters like nozzle temperatures and the use of lubricant oil have not been modified, but an additional control about nozzle proper functioning has been set on the machine.

9 Conclusions

The aim of the Thesis, was to introduce efficient improvement actions to the current hot chamber die casting process of zinc components.

Researches, performed during my five months internship in Dynacast, have been useful to demonstrate the importance of ever-increasing process improvements, in order to allow Zinc alloys die casting industry to have a competitive advantage in the market, especially in the automotive field, exploiting the benefits that casting components produced with this technology can offer.

In particular, the introduction of automated technology in the production process and simulation software in the Research and Development activity, allowed to reach higher productivity within advantageous times and costs; at the same time, the analysis of functioning principles of the hot chamber die casting technology and consequent adjustments implemented on the basic casting parameters (optimization of nozzle temperature, specific casting pressure and die temperature) have resulted in an improved melt injection phase, determining a consistent enhancement of the production final quality.

Analysis like the practical examples described in this Thesis are carried out every day in high tech industries like Dynacast, with the purpose of a safer, faster, cheaper and more environmental-sustainable production, always satisfying market ever-increasing high standards in terms of quality, durability and safety.

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