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# Establishing Guidelines to Improve the High-Pressure Die Casting Process of Complex Aesthetics Parts

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**Abstract.** Zamak is a light-weight alloy presenting very good properties for parts not requiring high mechanical strength. Due to its low melting temperature, this alloy is perfectly suitable for complex shape parts because it is easily moulded by high-pressure die casting process. Industrial parts usually do not require perfect look but this alloy can be also suitable for aesthetic parts, requiring complex finishing processes.The challenge embraced by this work aims to optimize the injection parameters and mould configuration of a Zamak alloy aesthetic part, to be obtained through a single injected casting operation, minimizing finishing operations. In order to obtain healthy, defect-free Zamak parts with a good aesthetic appearance, it was necessary to study the problem and then try to find the best possible solution. Thus, a study was carried out about the high-pressure die casting process and corresponding parameters. Throughout the work, and in order to solve the problem, numerical simulations were carried out using the SolidCast™ software, studying the material flow into the mould and corresponding fusion lines, and empirical tests were carried out in order to correlate the results with the parameters. Changes in the mould were also performed. After the experiences, it was possible to draw some guidelines in order to achieve better results in the Zamak high-pressure die casting process of complex aesthetic parts, allowing for save time in next approaches.

**Keywords.** Die casting, Casting, Casting defects, Zamak, Aesthetic parts.

## Introduction

The use of complex parts in light-weight materials is very often. The need to obtain them in a quick manner in order to lower their cost uses frequently the high-pressure die casting process. Zamak is a light-weight alloy commonly used in mechanical parts subjected to polishing processes, smoothing the surface and becoming the products with a better look. The main goal of this work is to establish the main guidelines to use high-pressure die casting in aesthetic parts, avoiding or decreasing the finishing operations, reducing tasks and cutting in their final cost.The structure of this paper is divided into five sections: the first of these presents the introduction; section 1 consisted of a literature review, where the main topics regarding the subject of this paper are referred; section 2 deals with the methodology used in this study; section 3 describes the experiments taking into account the part used as case study and the practical work developed; section 4 presents the results and discussion, and section 5 deals with the conclusions and suggestions for future works.

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## 1. Literature review

Die casting is a manufacturing technique used to produce geometrically complex metal parts [1]. Automotive industry is one of the main markets for parts obtained by this process [2-4], but there are many other markets consuming in large amounts parts obtained through high-pressure die casting in light-weight alloys because the parts present good mechanical properties, low surface roughness and shape very close to the final shape desired, needing less machining time. For this process are used reusable moulds, called dies. For the process of die casting, there are a couple of things that are elementary. It is needed a furnace which melts the metal. This metal will be transferred by the die casting machine to the die. The die has the negative shape of the final product. authoritative systems. In our daily lives, everybody encounters products made by high-pressure die casting process, such as doorknobs, power tools, sports accessories, and so on. Even in sports, if the reader thinks about golf where metal golf clubs are used. All these parts undergo the die casting process, as well as several other industries. They use the process to produce parts for aerospace, automotive, computers and much more [5, 6]. The metals which are the most commonly used in this process are non-ferrous ones, such as aluminium and zinc alloys [7]. There are two main types of machines for die casting [8]: (a) hot chamber machines, which make use of metals with a low melting point, such as zinc alloys; (b) cold chamber machines for metals with a higher melting temperature, such as aluminium alloys. High-pressure die casting process consists of five main stages. After these steps, the product is finished and ready for usage. Depending on the part complexity, the cycle time will take between two seconds to one minute [9]. The five stages are the following ones [10]: Clamping, Injection, Cooling, Ejection and Trimming.

The process is controlled by a series of important parameters such as the temperature of the molten material, the pressure exerted during the injection, the injection time, the over-pressure after injection and the solidification time [11-13]. However, there are other intrinsic parameters those need to be careful and that depends on the mould: sprue, gates, mould positioning, mould lubrication, thicknesses to be filled and cooling system [14]. Moreover, there are particular studies mainly devoted to the gates design and optimization [15]. The thermal flow between the molten metal and the mould walls and corresponding dissipation has also been studied for several authors, regarding the importance of the heat flow in this kind of process, with direct repercussions on the mould filling, solidification process and welding lines [16, 17]. Even the ejection process is important, regarding the integrity of the parts extracted and the surface quality desired, as can be observed in the work developed by Terek et al. [18], being extremely important the treatments applied to the mould surface, facilitating the part extraction in the ejection phase. Many studies have been carried out leading to the optimization of the injection conditions [19]. However, they will always depend on the mould configuration and remaining parameters. Indeed, one of the main parameters to be considered is the metal flow into the mould, which is conditioned by the mould design [20]. Due to these difficulties, many approaches have been done in order to overcome the problems related to defects on the parts obtained by high-pressure die casting. Regarding the number of parameters involved, Verran et al. [21] used the Design of Experiments (DOE) trying to establish the best set of parameters taking into account some assumptions. However, they just considered three main parameters: slow shot, fast shot and upset pressure. In the last two decades, software applications based on Finite Elements Methods (FEM) have been developed with increasing quality in the results accuracy, becoming this tools more reliable in its application [22-24]. Some authors have also been using simulation software for predicting the generation of some defects, through the analysis of the mould filling process [25]. Moreover, as casting processes are usually deeply affected by the generation of defects regarding the most diverse factors, there are several works carried out in this field [26-28], trying to correlate parameters, heat transfer and material flow into the mould looking for the best and most reliable results. The present study was developed in order to optimize the high-pressure die casting parameters and mould conditions in order to get aesthetic parts with low surface level of defects, minimizing the usual finishing operations.

## 2. Methodology

Regarding the challenging goal established for this work, a new methodology was designed incorporating experimental/empirical procedures (Empirical Approach) and advanced simulation (Advanced Approach), as can be seen in Figure 1. Moreover, an Ishikawa diagram was drawn in order to enumerate all possible factors influencing the lack of quality shown by the surface of the part (inner and outer faces). Preliminary assumptions were taken into account regarding all experiences needed to carry out further. Thus, the nozzle used in the high-pressure die casting process was selected and kept constant along all trials. The mould was properly studied in terms of geometry, sprue and runners dimensions and positioning, as well as vents. The Zamak alloy selected was Zamak 5 with the following chemical composition (wt%) assessed by mass spectroscopy properly calibrated for this kind of alloys: 3.8%Al, 0.95%Cu, 0.6%Mg, 0.04%Fe, balance Zn. The main mechanical properties of the Zamak 5 alloy were determined by tensile and hardness tests, providing the following values, respectively: 330 MPa and 94 HB. The melting temperature for this alloy is 390°C and its specific weight is 6.6 kg/m$^3$. The equipment used to carry out the high-pressure die casting experiences was a ZM3 equipment manufactured by PR METAL, Ltd. (Portugal). In order to carry out the work, an aesthetic part was selected, usually used in women wallet, showing the brand. The part needs to be obtained in Zamak alloy due to the light weight required, mechanical strength and easy further electroplated coating under different bright colours: gold and silver. The number of parameters was not restricted as in other studies [21], playing with all variables considered as with major influence in the process, as a function of the previous experiments. First of all, empirical experiences are carried out in order to find the best set of parameters able to improve the surface quality of the part under study. The combination of pressure, injection time and cooling time were explored in a 3! Trials (27), being carried out three trials for each set of conditions, totalising 81 trials. The sets of conditions selected are shown in the Experimental section. After the first approaches to optimize the parameters, a set of conditions is established as the ones able to produce the best results. The parameters considered are the following ones: pressure, injection time and solidification time. The mould position and geometry, gates positioning and dimensions, along with the venting channels are kept invariable. Thus, the simulation is used to understand the metal flow into the mould during the injection process, leading to realize that some changes in the mould were produced, based in a judicious analysis of the phenomena observed through simulation. New experiences are carried out, being possible to observe that the conditions established in the previous approach do not fulfil the current requirements under the new mould conditions. Thus, new empirical approach is carried out, leading to fix the problems and overcome the situation. After some fine-tuning experiences, the new set of parameters is found, but the results in terms of quality of the part produced cannot be satisfactory yet. In this case, new set of simulations is carried out in order to understand if the new set of parameters is in line with the material flow desired and final results required. Thus, this hybrid methodology was used in this work, as can be seen in Figure 1.

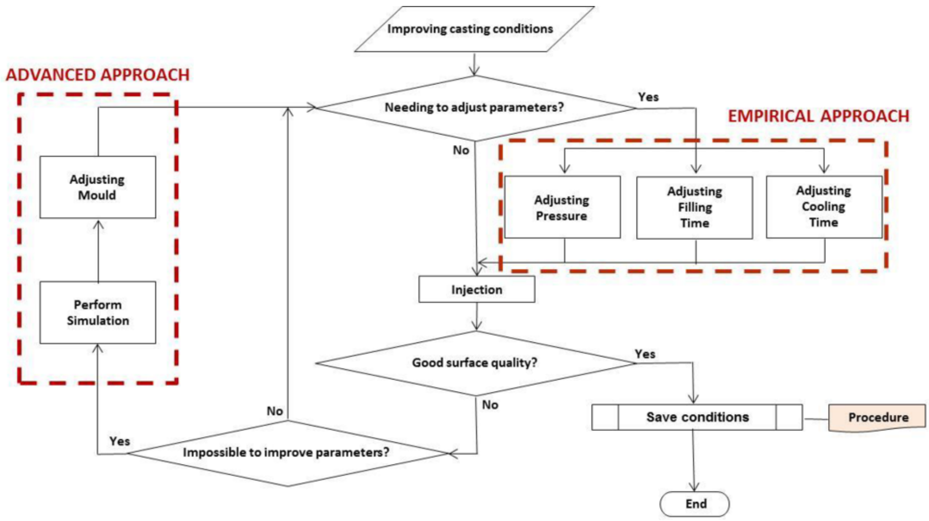



**Figure 1.** Flow diagram of the hybrid methodology used in this work.

## 3. Experimental

In order to carry out this work, an aesthetic part was selected as case study, as represented in Figure 2 in a 3D model and contextualized in one of the final products where these parts are used.


**Figure 2.** (a) Part used as case study in this work. (b) Contextualization of the part in the fnal product.

First of all, literature was revisited and, regarding the faced problem, an Ishikawa diagram was drawn considering all possible factors influencing the casting final results. The Ishikawa diagram can be seen in Figure 3. The variables were analysed and weighted in order to discard all thought as less or not influent in the faced problem. Thus, the influencing parameters were divided into two categories: (a) the ones related with the process itself (pressure, injection time and cooling time) and the parameters mainly mould-related, such as mould positioning, runners and vents. Pressure, injection time and cooling time were studied through an empirical approach and the mould-related parameters were investigated by simulation. It must be referred that the mould used in these trials has just one cavity, does not having an extracting system because it was manufactured just focused in these trials. Thus, the extraction was made manually in all cases.

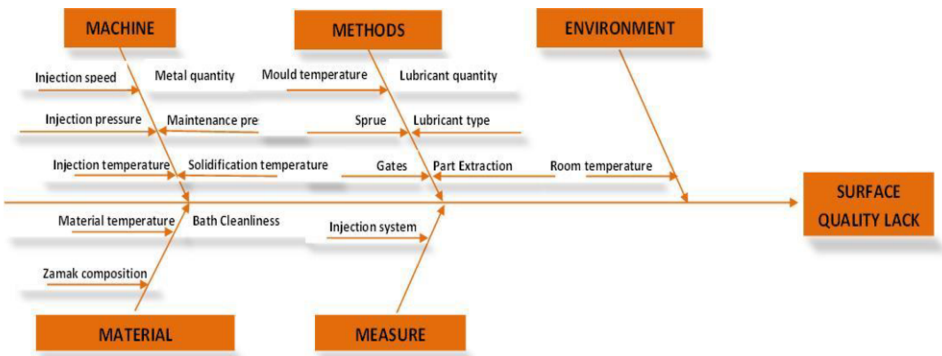



**Figure 3.** Ishikawa diagram corresponding to problem root-causes analysis.

The practical work was divided into different stages as described in table 1. The Zamak alloy was kept 10ºC to 20ºC above 430ºC into the machine crucible, temperature below which the machine automaticaly prevents the injection. Due to the light weight and low wall thickness of the part, the cooling system usually linked to the mouls was kept switched off.

**Table 1.** Parameters established for the first round of injection trials.

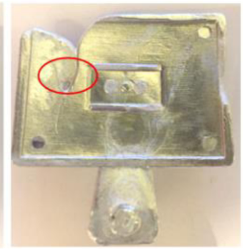
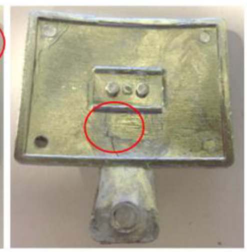
| Parameter | Unit | Low level | Medium level | High level |
|---|---|---|---|---|
| Pressure | bar | 0.3 | 1.5 | 4 |
| Injection time | ºC | 0.2 | 3 | 6 |
| Cooling time | ºC | 0.02 | 0.5 | 1 |

Thus, the first empiral round of tests was carried out, following these conditions. Regarding that the combination of these parameters. Further evolutions were conducted as a function of the previous results and/or simulation approach. The evaluation of the results was made by visual observation of the complete mould filling (part complete witl all the details filled).

## 4. Results and discussion

The first round of trials allows for fine-tunning the injection conditions, among the ones previously selected and presented in Table 1, regarding the quality surface required. The most characteristic results can be seen in Table 2.

**Table 2.** The most characteristic results from the first round of trials.

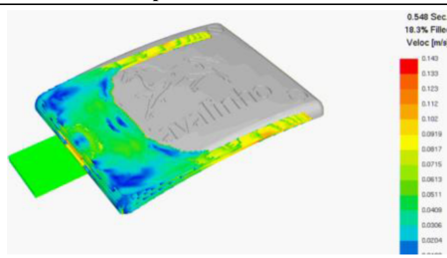
| Set of Parameters | Defects | Pictures |
|---|---|---|
| **Pressure:** 0.3 bar<br>**Injection time:** 6 s<br>**Cooling time:** 0.02 s | Lack of filling |    |
| **Pressure:** 0.3 bar<br>**Injection time:** 6 s<br>**Cooling time:** 1 s | Small surface depression and crack |    |
| **Pressure:** 1.5 bar<br>**Injection time:** 0.2 s<br>**Cooling time:** 0.02 s | Really bad surface quality |   |
| **Pressure:** 1.5 bar<br>**Injection time:** 0.2 s<br>**Cooling time:** 0.5 s | Really bad surface quality and filling slight lacks |   |
| **Pressure:** 4.0 bar<br>**Injection time:** 0.2 s<br>**Cooling time:** 0.5 s | Poor surface quality |    |

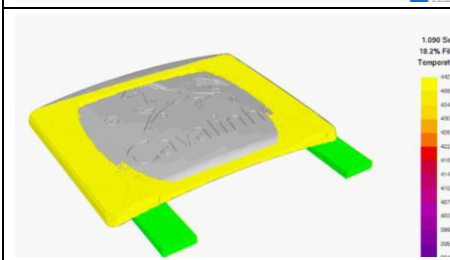
Regarding the results of Table 2 and comparing the two first lines, one can conclude that cooling time needs to be medium/high. All parts with low cooling time presented bad quality surface. However, there are samples with medium cooling time which also present filling lacks and poor surface quality. Thus, it is impossible to take conclusions about the cooling time. The injection time seems also does not present a conclusive trend. Effectively, the first two lines were produced following the same injection time and present contrasting situations. However, when the injection time is reduced, which means that the metal speed entering the mould is greater, conducting to higher turbulence during the filling process, conducts invariably to poor surface quality. The conjugation of the other parameters is impossible to improve given the dispersive trend shown by the results. Thus, the only conclusion able to extract from the empirical set of the trial is that the pressure should be lower in order to avoid turbulence in the mould filling process. Being this phase concluded, it was time to improve the mould, changing the other conditions around the parameters.

In order to start the advanced approach, SolidCast™ V8.4 software was used in order to evaluate the filling conditions and other runners positioning, allowing for better results. The modelled part was upload to the software and the adequate parameters characterizing the materials and process were programmed. Different runners dimensions and positioning were tested in order to realise how the filling process occurs in each situation. Some tests can be observed in Figure 4.

| **Example of list of parameters** | |
|---|---|
| Mold Materials | Steel |
| Material type | |
| External Heat Transfer Coefficient | 1,50% |
| Casting material/Riser material | 100% |
| Ambient/Casting material | 10% |
| Steel/Casting material | 50% |
| Graphite/Casting material | 0% |
| Riser material/Ambient | 10% |
| Riser material/Steel | 50% |
| Riser material/Graphite | 0% |
| Ambient/Steel | 10% |
| Ambient/Graphite | 0% |
| Steel/Graphite | 0% |
| Ambient temperature | 30Cº |
| Pour time | 3sec |

**Example of simulations done**



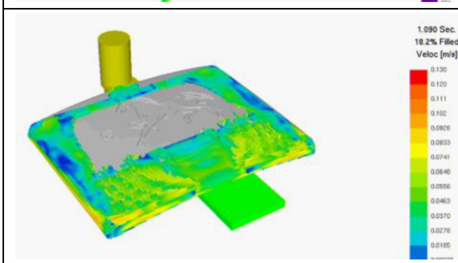



**Figure 4.** Parameters used in the simulations process and some tests carried out with different runner positioning.

As can be seen in Figure 4, the runners position, number and section were tested in different situations, trying to understand the material flow and solidification process, leading to perceive on how to change the parameters and achieve better results: mould completely filled and surface quality does not need further care before electroplating process. Moreover, as can be seen in the last picture of Figure 4, the inclusion of Raisers was also tested. Observing carefully the filling process, it was possible to perceive that mould positioning in the machine seemed does not be favourable. Thus, the position was inverted in the modelation and new simulations were performed in order to realise if this change seems viable to lead to better results. The observations allowed for concluding that turbulence is lower in this new position and, due to the concavity of the part (formerly, convexity), the filling process occurs with a better material distribution over time (Figure 5 – right hand). Moreover, Risers were again considered, as depicted in Figure 5 (left hand).

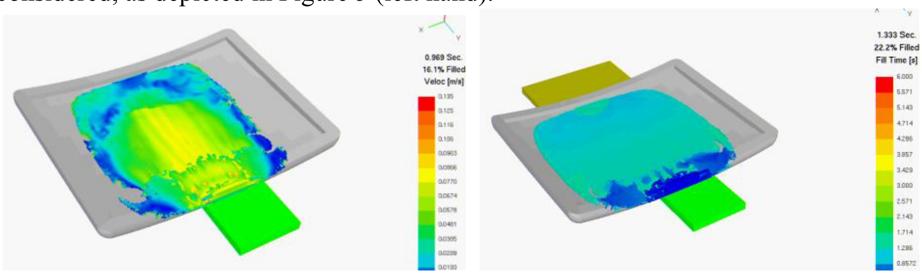



**Figure 5.** (Right hand) Simulation after the mould has been inverted and using a central runner; (Left hand) Simulation after the mould has been inverted and using a central runner and a posterior riser.

The use of a thin central runner and a posterior riser conducted to the best results in the simulation process. Thus, concluded the advanced approach, it is time to adjust once again the parameters. So that, a new set of trials was carried out, now without a previously defined grid of experiences to follow, but following an iterative process, whick took into account the previous trial in order to define the next set of conditions. After several trials, the best conditions were finally found, as can be seen in the Table 3. Moreover, the parts obtained with the best quality can be observed in Figure 6.

**Table 3.** Most characteristic results from the first round of trials.

| Pressure | Injection time | Cooling time |
|---|---|---|
| 2 bar | 0.5 s | 1 s |

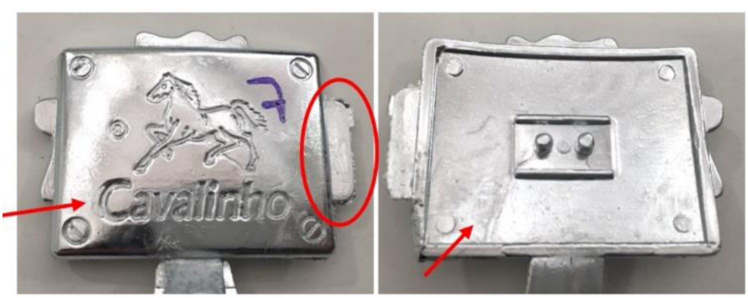



**Figure 6.** Parts obtained with the inverse positioning of the mould, central runner and three risers in the other sides of the part. The part is not perfect, but the quality is enough to avoid intermediate steps before coating.

Thus, the parameters optimization taking into account the best results attained by simulation previously, allowed for achieving conditions interesting enough to produce the part by high-pressure die casting, sending it directly to the electroplating, do not needing intermediate finishing operations, such as blasting and manual polishing operations.

## 6. Conclusion and future work

The main challenge of this work was developing and validating a hybrid approach to solve high-pressure die casting problems regarding parameters optimization. The model was designed, implemented and tested through a case study, which allowed for establishing the main guidelines to be able to shorten the time and steps needed to improve the parameters capable of leading to a required surface quality of aesthetic parts. Thus, the approach allowed for establish the following guidelines:

- The correct definition of the material is a very important step because the fluidity of the material presents a direct influence on the material distribution during the filling process.
- The pressure should be low in order to avoid turbulance. This rule is so most applicable, the more complex is the part shape.
- The filling time should be low, depending on the part weight. Parts with about 25 grams like the used as case study, only needs about 0.5 seconds.
- The cooling time should be medium, allowing for the part consolidation.
- If the part comprises curvature, the central part should be the lower part, receiving the first material flow and distributing it to the upper areas of the mould. In this case, simulation is absolutelly needed in order to explain how the material flows into the mould.
- A central runner is usually preferable than two or more runner, due to turbulence at the confluence of streams, as well as in the definition of the welding lines.
- In parts subjected to turbulence (high ratio between area and thickness), the use of risers should be considered.

Future works should be done in the sequence of this research, allowing for explore the influence of different vents positioning, as well as surface treatments of the mould cavity, in order to help improve the surface quality of the part, facilitating the material flow during the filling process.

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