Design and manufacturing of complex moulds for powder injection moulding

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TABLE OF CONTENTS

1 PREFACE ............................................................................................................................ 1-8

2 OBJECTIVES ....................................................................................................................... 2-9

3 INTRODUCTION .................................................................................................................. 3-10
  3.1 POWDER INJECTION MOULDING .................................................................................... 3-10
  3.2 MOULDING PROCESS .......................................................................................................... 3-14
  3.3 MOULD DESIGN .................................................................................................................. 3-23

4 DESIGN .................................................................................................................................. 4-29
  4.1 TOROID MOULD .................................................................................................................. 4-29
  4.2 DOG-BONE SPECIMEN MOULD .......................................................................................... 4-38
  4.3 FLAT SPECIMEN MOULD .................................................................................................... 4-44
  4.4 DOUBLE CAVITY TENSILE TEST MOULD ......................................................................... 4-48
  4.5 MICROSTEP MOULD .......................................................................................................... 4-54

5 EXPERIMENTAL .................................................................................................................... 5-59
  5.1 EQUIPMENT AND MACHINES USED ................................................................................. 5-59
    1. POWDER AND BINDER MIXER ......................................................................................... 5-59
    2. INJECTION MOULDING MACHINE .................................................................................. 5-61
    3. FLOW REGULATOR AND HOT PLATE ............................................................................... 5-63
    4. HIGH TEMPERATURE FURNACE ...................................................................................... 5-63
    5. MACHINING EQUIPMENT .................................................................................................. 5-64
    6. MACHINING TOOLS .......................................................................................................... 5-66
  5.2 FEEDSTOCK ELABORATION ............................................................................................... 5-68
    1. HES-SO VALAIS Fe-Si FEEDSTOCK .................................................................................. 5-68
    2. ADVANCED METALWORKING PRACTICES Fe-Si FEEDSTOCK ....................................... 5-71
    3. INMATEC ALUMINIUM OXIDE FEEDSTOCK .................................................................. 5-71
  5.3 INJECTION MOULDING PROCESS ..................................................................................... 5-73
    1. TOROID MOULD ................................................................................................................ 5-73
    2. DOUBLE CAVITY TENSILE TEST MOULD ......................................................................... 5-76
  5.4 SOLVENT DEBINDING .......................................................................................................... 5-79
FIGURES INDEX

Figure 1 Key features of PIM ................................................................................................................... 3-11
Figure 2 PIM sequence............................................................................................................................. 3-11
Figure 3 PIM process .............................................................................................................................. 3-12
Figure 4 Injection moulding machine elements ................................................................................... 3-14
Figure 5 Hot runner ................................................................................................................................ 3-17
Figure 6 Injection moulding machine functional groups ............................................................... 3-17
Figure 7 Injection unit .......................................................................................................................... 3-18
Figure 8 Different close units ............................................................................................................ 3-18
Figure 9 Control Unit .......................................................................................................................... 3-18
Figure 10 Mould Close ......................................................................................................................... 3-19
Figure 11 Material injection ................................................................................................................. 3-20
Figure 12 Maintenance Pressure ........................................................................................................ 3-20
Figure 13 New plasticization cycle ..................................................................................................... 3-20
Figure 14 Part extraction ...................................................................................................................... 3-21
Figure 15 Power consumption during injection moulding cycle ....................................................... 3-21
Figure 16 Main runner ........................................................................................................................... 3-23
Figure 17 Sprue and cold trap .............................................................................................................. 3-23
Figure 18 Different gate designs ........................................................................................................ 3-25
Figure 19 Vents sketch ........................................................................................................................ 3-26
Figure 20 CAE flow simulation .......................................................................................................... 3-26
Figure 21 Injection pressure factor influence ..................................................................................... 3-27
Figure 22 Toroid Part ............................................................................................................................. 4-29
Figure 23 Steel Composition ................................................................................................................. 4-30
Figure 24 Nozzle .................................................................................................................................. 4-31
Figure 25 Internal multipoint injection .............................................................................................. 4-31
Figure 26 Diaphragm gate ................................................................................................................... 4-32
Figure 27 External gate ........................................................................................................................ 4-32
Figure 28 Runner section shape .......................................................................................................... 4-32
Figure 29 Mould plates disposition ................................................................................................... 4-33
Figure 30 Ejector disposition .............................................................................................................. 4-33
Figure 31 Ejectors cut ........................................................................................................................... 4-34
Final Project of Industrial Engineering
« Design and manufacturing of complex moulds for powder injection moulding »

Figure 32 Cold trap sketch ................................................................. 4-35
Figure 33 Vent dimensions ............................................................... 4-35
Figure 34 Heater (top view) and control devices ......................... 4-36
Figure 35 Full moulded specimen .................................................. 4-36
Figure 36 Volumes of different parts of an injection moulded component ... 4-37
Figure 37 Toroid mould result .......................................................... 4-37
Figure 38 Final toroid mould assembly .......................................... 4-37
Figure 39 Dog-Bone specimen .......................................................... 4-38
Figure 40 Dog-Bone specimen dimensions ..................................... 4-39
Figure 41 Vertical tangent injection .................................................. 4-40
Figure 42 Horizontal tangent injection ............................................ 4-40
Figure 43 Parallel injection .............................................................. 4-41
Figure 44 Tangent injection with short runner ............................... 4-41
Figure 45 Mould assembly ............................................................... 4-41
Figure 46 Ejector position .............................................................. 4-42
Figure 47 Cold trap sketch .............................................................. 4-43
Figure 48 Flat specimen ................................................................. 4-44
Figure 49 Flat specimen dimensions ............................................. 4-44
Figure 50 Direct filling ................................................................. 4-45
Figure 51 Perpendicular runner ...................................................... 4-46
Figure 52 Ejectors position ............................................................ 4-46
Figure 53 Cold trap sketch ............................................................ 4-47
Figure 54 Double cavity tensile test mould .................................. 4-48
Figure 55 Main runner flat specimen .............................................. 4-49
Figure 56 Ejectors cut ................................................................. 4-50
Figure 57 Valve sketch ................................................................. 4-51
Figure 58 Different valve positions ............................................... 4-51
Figure 59 Special tool ................................................................. 4-52
Figure 60 Specimens total volume .............................................. 4-52
Figure 61 Specimens total volume by steps ................................. 4-52
Figure 62 Final mould result .......................................................... 4-53
Figure 63 Microstep specimen ...................................................... 4-54
Figure 64 Microstep specimen dimensions .................................. 4-55
Figure 65 Different possibilities to inject the specimen ............................................................. 4-56
Figure 66 Microstep specimen injection possibilities............................................................... 4-56
Figure 67 Ejectors plaque position.......................................................................................... 4-57
Figure 68 Ejector diameter ..................................................................................................... 4-57
Figure 69 Cold trap sketch ..................................................................................................... 4-58
Figure 70 Full moulded specimen ......................................................................................... 4-58
Figure 71 Coperion sigma blade mixer ................................................................................ 5-59
Figure 72 Coperion mixer elements ...................................................................................... 5-60
Figure 73 Arburg 221 – K ..................................................................................................... 5-61
Figure 74 Hydraulic system to close mould ....................................................................... 5-62
Figure 75 Injection unit system Arburg ................................................................................ 5-62
Figure 76 Solvent debinding tools ........................................................................................ 5-63
Figure 77 Nabertherm VHT 8-16 MO .................................................................................. 5-63
Figure 78 Felhmann Picomax 54 .......................................................................................... 5-64
Figure 79 Weiler Praktikant GS ......................................................................................... 5-65
Figure 80 Schaublin 102N VM .......................................................................................... 5-66
Figure 81 Milling cutters ...................................................................................................... 5-67
Figure 82 Magnetic feedstock HES-SO Valais ................................................................. 5-69
Figure 83 HES-SO Valais magnetic feedstock components ............................................... 5-70
Figure 84 HES-SO Valais magnetic feedstock proportions ................................................ 5-70
Figure 85 HES-SO Valais magnetic feedstock elaboration process ..................................... 5-70
Figure 86 Advanced Metalworking magnetic feedstock .................................................... 5-71
Figure 87 Ceramic feedstock ............................................................................................... 5-71
Figure 88 Ceramic feedstock powder balance ..................................................................... 5-72
Figure 89 Ceramic feedstock properties ............................................................................. 5-72
Figure 90 Toroid part solidification process ...................................................................... 5-73
Figure 91 Part samples feedstock HES-SO Valais .............................................................. 5-74
Figure 92 Advamet feedstock injection parameters ............................................................ 5-75
Figure 93 Advanced Metalworking practice specimens ...................................................... 5-75
Figure 94 Dog-Bone specimen solidification ...................................................................... 5-76
Figure 95 Dog-Bone specimen injection parameters ......................................................... 5-76
Figure 96 Dog-Bone specimens .......................................................................................... 5-77
Figure 97 Flat specimen solidification process .................................................................. 5-77
Final Project of Industrial Engineering  
«Design and manufacturing  
of complex moulds for powder injection moulding»

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>98</td>
<td>Flat specimen injection mould parameters</td>
<td>5-78</td>
</tr>
<tr>
<td>99</td>
<td>Flat specimens</td>
<td>5-78</td>
</tr>
<tr>
<td>100</td>
<td>Solvent debinding process</td>
<td>5-79</td>
</tr>
<tr>
<td>101</td>
<td>Pre and post solvent debinding specimens</td>
<td>5-80</td>
</tr>
<tr>
<td>102</td>
<td>Debinding cycle</td>
<td>5-81</td>
</tr>
<tr>
<td>103</td>
<td>Sintering cycle</td>
<td>5-81</td>
</tr>
<tr>
<td>104</td>
<td>Post-sintering toroid specimens</td>
<td>5-82</td>
</tr>
<tr>
<td>105</td>
<td>Toroid shrinkage</td>
<td>5-82</td>
</tr>
<tr>
<td>106</td>
<td>Advamet feedstock debinding cycle</td>
<td>5-83</td>
</tr>
<tr>
<td>107</td>
<td>Industry cost analysis</td>
<td>6-86</td>
</tr>
<tr>
<td>108</td>
<td>PIM versus other net-shape technologies comparison</td>
<td>6-86</td>
</tr>
<tr>
<td>109</td>
<td>Toroid mould cost calculated by University of Rhode Island method</td>
<td>6-94</td>
</tr>
<tr>
<td>110</td>
<td>Toroid mould cost by University of Rhode Island method</td>
<td>6-95</td>
</tr>
<tr>
<td>111</td>
<td>Toroid mould cost % by University of Rhode Island method</td>
<td>6-95</td>
</tr>
<tr>
<td>112</td>
<td>Double Cavity mould cost by University of Rhode Island method</td>
<td>6-97</td>
</tr>
<tr>
<td>113</td>
<td>Double Cavity mould cost by University of Rhode Island method</td>
<td>6-97</td>
</tr>
<tr>
<td>114</td>
<td>Double Cavity mould cost % by University of Rhode Island method</td>
<td>6-97</td>
</tr>
<tr>
<td>115</td>
<td>Toroid mould cost by Boothroyd, Dewhurst and Knight method</td>
<td>6-101</td>
</tr>
<tr>
<td>116</td>
<td>Toroid mould cost by Boothroyd, Dewhurst and Knight method</td>
<td>6-101</td>
</tr>
<tr>
<td>117</td>
<td>Toroid mould cost % by Boothroyd, Dewhurst and Knight method</td>
<td>6-101</td>
</tr>
<tr>
<td>118</td>
<td>Double Cavity cost by Boothroyd, Dewhurst and Knight method</td>
<td>6-103</td>
</tr>
<tr>
<td>119</td>
<td>Double Cavity mould cost by Boothroyd, Dewhurst and Knight method</td>
<td>6-103</td>
</tr>
<tr>
<td>120</td>
<td>Double Cavity mould cost % by Boothroyd, Dewhurst and Knight method</td>
<td>6-103</td>
</tr>
<tr>
<td>121</td>
<td>Historical mould costs</td>
<td>6-106</td>
</tr>
<tr>
<td>122</td>
<td>Toroid mould cost by HES-SO method</td>
<td>6-108</td>
</tr>
<tr>
<td>123</td>
<td>Toroid mould cost by HES-SO method</td>
<td>6-109</td>
</tr>
<tr>
<td>124</td>
<td>Toroid mould cost % by HES-SO method</td>
<td>6-109</td>
</tr>
<tr>
<td>125</td>
<td>Double Cavity cost by HES-SO method</td>
<td>6-111</td>
</tr>
<tr>
<td>126</td>
<td>Double Cavity mould cost by HES-SO method</td>
<td>6-111</td>
</tr>
<tr>
<td>127</td>
<td>Double Cavity mould cost % by HES-SO method</td>
<td>6-111</td>
</tr>
<tr>
<td>128</td>
<td>(80-20) rule</td>
<td>6-112</td>
</tr>
</tbody>
</table>
1 PREFACE

Moulding is an ancient technique that has been used since ancient times, to manufacture weapons, armours and other tools through sand moulds where metal were poured directly.

Early demonstrations of Powder Injection Moulding (PIM) followed closely behind the first developments in plastic injection moulding in the 1920s. Injection moulded plastics were first produced in the 1930s (polyethylene was invented in 1933 by Eric Fawcett).

PIM technology was first used in the 1940s for injection moulding ceramic sheaths to mass produce spark plug insulators. The process was adopted by the investment casting industry in which it is still used for manufacturing ceramic cores. By late 1950s, carbide and ceramic components were being shaped using epoxy, wax or cellulose binders, but the production volumes were small.

However, PIM attracted little other interest until it was used for the moulding of metal powders in the mid 1970s. This novel application of what was considered a low tech process to a diverse range of particulate systems initiated considerable worldwide research in the following years. PIM knowledge is nowadays recognised as a sophisticated and interdisciplinary technology, which continues expanding along many sectors of the world industry.

Design of injection moulding machines has been influenced by the demand of products with complex geometry, different materials and specific properties. Furthermore they have conceived to reduce at maximum production costs.

Only intensive researching will allow getting future goals. The present project is only one step more to discover new production systems, which they will permit to obtain new goods for the society.
2 OBJECTIVES

The main goal of this work is the design, manufacturing and test of moulds for powder injection moulding (PIM technology).

A first mould is for manufacturing toroids, which are used for characterization of magnetic materials. Three moulds are for tensile test specimens to test mechanical properties. A last mould is a test microstep part to study the mouldability of PIM feedstocks.

Furthermore these moulds have been tested with soft ferromagnetic (Fe-2.7%Si) and ceramic (Al₂O₃) materials. The green parts have been debinded and sintered.

In addition, an economical analysis is performed for cost evaluation of moulds for PIM, comparing and analyzing different costing methods.

The main topics, which are treated in this project include:

- Knowledge about Powder Injection Moulding technology and its works
- Study of the different possibilities of injection to moulding parts.
- Full design of moulds for powder injection moulding.
- Feedstock and moulding parameters.
- Injection moulding of test parts
- Economics and viability study for PIM technology.
3 INTRODUCTION

3.1 POWDER INJECTION MOULDING

In the engineering world, the injection moulding is a process which consists to inject a polymer in liquid state to a closed mould with enough pressure. This mould became to be solid beginning to crystallize in polymers semi-crystallize. The final part is obtained opening the mould and extracting its content.

Moulding injection is a technique very common to manufacture very different articles. Only in United States, the plastic industry has grown to an annual range of 12% since the last 25 years. The principal process of transformation is the plastic injection followed by the extraction process. Examples of these techniques are components for automotive, aerospace ships and the popular games Lego and Playmobil.

Polymers have got replaced other materials like wood, metals, natural fibbers or ceramics. The popularity of this method is explained with the versatility and speed of parts it can be manufacturing. High levels of production allowed low cost per unit and it is also improved with automation of movements and transports of parts.

Moulding allows complex geometrics which it would be impossible with another technique. In addition de final parts requirements are despicable because final finish has enough precision, correct dimensional tolerance and texture.

At the same time, moulding injection is only a good choice for long series of parts because the cost of the machine injector, the study of the mould, the production tools… decrease the rateability of projects.

It is known that metal and ceramics have better properties than polymer, like higher strengths, higher stiffness or higher operating temperatures.

A new technology known as powder injection moulding (PIM) uses the shaping advantage of injection moulding but is applicable to metal and ceramics. This process combines a small quantity of a polymer with an inorganic powder to do form a feedstock that can be moulded. After shaping, the polymeric binder is extracted and the powder is sintered, often to theoretical densities.
Powder metallurgy injection is a manufacturing process where from fine powder and after its compacting to give them a determinate shape, they are warmed in control atmospheric (sintering) to obtain the part. Some examples of articles created of this shape are cutting tools or bearings.

Polymeric binders are used in shaping these small powders, holding the place until bonding in a sintering furnace. The process has similarities to other manufacturing concepts, such as tape casting, slip casting and extrusion. How it is seem at figure 1, PIM has five key features:

![Figure 1 Key features of PIM](image)

As a technology, PIM has been developed for some time, but really only saw widespread commercialization in the 1980s. For a limited time in the 1920s it was applied to the production of ceramic spark plug bodies. By the late 1950s, many carbide and ceramic component were being shaped using epoxy, wax or cellulose binder. In the 1980s major progress was made in forming ceramic heat engine components by PIM techniques. Today, the number of companies practicing PIM is large and it is regarded as a leading net-shaping technique.

We can divide the sequence in four steps, formation of the feedstock, moulding into the tooling, binder removal and sintering.

![Figure 2 PIM sequence](image)

Usually feedstock formulation involves mixing selected powders and binders to form pellets that easily flow into a moulding machine. Feedstock pellets are moulded into oversized tooling that contains the desired shape. The heated polymer allows viscous flow of the mixture to aid forming.
After moulding, the binder is removed and the remaining powder structure sintered; these last two steps can be combined into a single thermal cycle. Since significant shrinkage is associated with sintering densification, the final dimensions rely on uniform moulding to hold tight final tolerances. The sintered product may be further densified, heat treated, coined, plated or machined to complete the fabrication process.

Most important, the sintered component has the precision of plastic injection moulding in materials that deliver properties unattainable from polymers.

Figure 3 shows a schematic of individual steps involved in PIM. Everything begins by mixing selected powders and binder. The binder usually based on a common thermoplastic such a wax or polyethylene. It is allowed also, to use two or three components to form the binder. One example is a 65% of paraffin wax, 30% of polypropylene and 5% of stearic acid.

Feedstock is a term for the mixture of powder and binder. The formulation of a successful feedstock balance several considerations:

- Sufficient binder to fill all voids between particles
- Sufficient binder to lubricate particle sliding during moulding.
- Not binder excess to keep the component shape during debinding
- Form pellets that are easily transported to the moulding machine.

The pelletized feed stock is injection moulded into desired shape by heating in the moulding machine and hot ramming it under pressure into the tool cavity. By virtue of the binder, the feedstock becomes low enough in viscosity that it can flow into the die cavity under pressure. Cooling channel in the die extract heat and solidify the polymer to preserve the moulded shape.

Moulding pressure depends on several parameter, but might be 60 MPa or more. Pressure is maintained on the feedstock during cooling until the gate freezes to
reduce the formation of sink marks and shrinkage voids. After cooling in the die, the component is ejected and cycle repeated.

Usually the binder is removed from the component by debinding. One of these options is Thermal Debinding which consists in heating slowly the component to discompose the binder. Also it is possible to immerse it in a solvent that dissolves some binder, leaving some polymer behind to hold the particles in place for subsequent handling. The remaining binder is thermally extracted as part of the sintering cycle. Newer binders are water soluble, so the debinding solvent is water.

Another method consists in catalytic phase erosion of the binder. Most of the binder is attacked by vapour, with the residual binder being removed during heating to the sintering temperature.

The next step is sintering, which can be incorporated directly into a thermal debinding cycle. Sintering bonds the particles together, lending to densification. Often sintering serves the dual role of densification and chemical homogenization. In this process, mixed powder is moulded and sintering causes them to form homogeneous alloy by long-range atomic motion. Usually sintering shrinkage is uniform and isotropic, so the moulded component is oversized to deliver the desired final dimensions.

Sintering is often performed in a protective atmosphere which causes rapid elimination of the pores previously filled with binder. The oxide ceramics, such as silica, alumina, zirconia... can be sintered in air temperature between 1200 to 2000 °C. For steels and stainless steels, the range fluctuated between 1120 to 1350 °C for times of 30 to 120 minutes. The common shrinkage is about 12% to 18%.

After sintering the component has excellent strength, with properties often superior to those available from other processing routes. Final densification can be assisted by both hot and cold deformation, including hot isostatic pressing.

Other post-sintering steps include coining, drilling, reaming, machining, plating, passivation and heat treatment (hardening, nitriding, and carburization).
3.2 MOULDING PROCESS

Moulding consists, in simplest form, of heating the feedstock to a sufficiently high temperature such that it melts, then forcing this melt into a cavity where it cools and assumes the shape of the tool cavity.

The cycle starts by clamping the mould closed, injecting feedstock into the cavity, packing out the cavity until the gate solidifies and preparing the next charge while ejecting the cooled component.

It is recommendable to use a screw injection machine for moulding reinforced thermoplastics. A screw injection machine improves melt homogeneity, reduces variations in the moulded parts, and minimizes degradations and cold spots of the polymer melt.

The machine should be sized to use approximately 50-70% of machine barrel capacity per shot. This maintains a short barrel residence time and eliminates material degradation. The machine should have adequate clamp pressure to obtain 55-110 Newton per mm² of projected surface area. Generally, a reinforced material requires 50-70% higher clamping pressures than a non-reinforced polymer of the same type.

INJECTION MOULDING EQUIPMENT

The figure 4 describes a complete injection machine and their parts.

- Mould Clamping Cylinder: It allows regulate the movement of supports.
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« Design and manufacturing of complex moulds for powder injection moulding »

- Tie Bar: Guide for moving and fixed supports.
- Mobile and Fix Support: Between this plaques it is situated the mobile and fix plate of the mould tool.
- Mould Tool: It is composed of two different parts which they give the final shape to the part:
  - Fix Plate: Through it, the mixture of powder and binder are injected thought injection nozzle.
  - Mobile Plate: Thought it, the part is extracted using the ejector.
- Barrel: It contains the mixture and the screw.
- Screw: It push the mixture to the nozzle and also takes new charge of material.
- Granules: Pellets of metal or ceramic powder and polymer binder.
- Hopper: Keep the pellets.
- Drive Unit: Control the screw movement synchronizing the cycle
- Injection Cylinder: It is used to move the injection body in front or behind.
- Check Valve: Verifying parameters.
- Heater Bands: Electric resistance to melt the feedstock granules.

INJECTION MOULDING CONDITIONS

- **Injection Temperature**: Normally the rear zone is set 8 – 12 °C cooler than the front zone and nozzle. Some modifications may be needed depending on part size and configuration.
- **Mould Temperature**: Refer processing conditions; normally reinforced materials require higher mould temperatures than no reinforced materials. Higher mould temperatures will achieve a smoother, more blemish-free surface by providing a resin rich skin on reinforced materials.
- **Injection Pressure**: Injection pressure should be set low initially and increased to the point of filling the part just short of causing flash. Maximum pressure without flashes generates optimum physical properties.
- Injection Speed: Generally, the fastest possible cavity fill time is best. This minimizes glass orientation and maximizes weld line integrity.

- Screw RPM: The lowest possible rpm is recommended to minimize fiber breakage and screw recovery should be set accordingly. Slower rpm’s result to more uniform melt by minimizing shear heat builds up.

ADVICES TO IMPROVE MECHANICAL PROPERTIES

To improve slightly mechanical properties, it is possible to change some moulding injection parameter. However it is important to remark that these changes can cause other problems such as flashing, jetting or feedstock degradation.

Tensile Strength

- Use hotter mould temperatures
- Use high injection speed
- Avoid high melt temperature
- Injection pressure has little effect

Tensile Elongation

- Use hotter mould temperatures
- Avoid high melt temperature

Flexural Modulus

- Use higher melt temperatures
- Use high injection speed
- Injection pressure has only moderate effect

Flexural Strength

- Use hotter mould temperatures
- Avoid high melt temperature
- Injection pressure has only moderate effect

Notched IZOD Impact

- Use hotter mould temperatures (cold mould can cause 50% loss in impact strength)
- Avoid high melt temperature
Shrinkage

- Use cold mould to reduce shrinkage
- Use high injection pressure
- Avoid high screw rpm
- Avoid high melt temperatures

HOT RUNNER

To improve the mould filling, it is usually to use a hot runner, which heats the feedstock through electric resistances.

Figure 5 Hot runner

INJECTION MOULDING MACHINE FUNCTIONAL GROUPS

We also can divide the machine in four principal groups:

- **Injection Unit**: It is composed for the screw, the barrel, the nozzle and the heater bands around the barrel. Mixture it is introduced for the hopper to screw feed area where it becomes to liquid and the material is brought to the dosage area. During this process, the screw is turning continuously until injection moment when it starts to work like a piston.
- Close Unit: It is composed for mobile and fix plates and their support. Mobile support function is based in a hydraulic mechanism, by levers or an electric screw moving by a motor. The most important parameter is the force to keep close the mould. Other important parameters are also the distance between support, opening distance, plaque dimension and distance between columns. These dates are used to dimensioning the moulds.

- Control Unit: It is composed for a programmable logical control (PLC), PID controls for heater bands and the nozzle. The PLC allows program the cycle sequence of injection and the alarm signals. The PID controls are better to keep control the temperature owing to their speed answer.

- Power Unit: It is the system which it supplies need power to the injection unit function and the close unit. The principal types of power units can be classified such as:
  - Electric motor system and reduce unit of gears-
INJECTION MACHINE MAIN PARAMETERS

- Clamping force
- Injection capacity: material volume which it can be supplied by the injection machine (cm³/injection)
- Injection pressure: Maximum pressure which it can be flow by the injection unit to the mould. Usually it works at 60% if this pressure.
- Plasticization capacity: Maximum quantity of material it can be supplied by the screw per hour (Kg/h).
- Injection speed: Maximum speed it can be supplied by the injection unit of material to the mould. (cm³/s)

INJECTION MOULDING CYCLE

The injection cycle can be split in the following steps:

1. *Close of the mould*: empty mould is closed while the quantity of material inside the barrel is ready to inject. The mould is closed in three steps:
   a. First with high speed and low pressure
   b. Second with middle speed and low pressure until the two parts of the mould are in touch
   c. Finally, it is applied the enough pressure to get the close force necessary.

   ![Mould Close Diagram](image-url)
2. **Injection**: The screw injects the material, working like a piston without turning, pushing the material through the nozzle inside the mould cavities with injection pressure.

![Material injection](image)

3. **Maintenance pressure**: When injection material is over injecting, the screw is kept in front applying pressure before it is solidified, to minimize the part shrinkage during cooling. Maintenance pressure is usually smaller than injection pressure and it is support until the part starts to solidify.

![Maintenance Pressure](image)

4. **New Plasticization**: The screw turns passing the plastic grains since the hopper and it plasticized them. Fund material is supplied through the front part of the screw, where it is developed a pressure against close nozzle, forcing the screw to go back until it found require material for injection.

![New plasticization cycle](image)

5. **Extraction**: Material inside the mould continues cooling where the heat is dissipated for the cooling liquid. When cooling time is finished, the mould mobile part opens and the part is extracted.
6. **Close of the mould:** Mould is closed and the cycle restarts again.

**POWER CONSUMPTION DURING INJECTION MOULDING CYCLE**

- Mould closing does not require too much power to overcome the friction forces when mobile plate is moving.
- The injection step requires a maximum power during a short period.
- Injection unit approaching does not require too much power.
- The next figure represents the power consumption during the injection cycle.

**INJECTION CYCLE PERIODS**

- **Empty time**

- **Injection time:** Also it is denominated fill mould time. It is the necessary time to the material pass thought the barrel to the mould’s cavities. This time can be last around 5 – 30 % of the total cycle time.

- **Pressure application and maintenance time:** The objective of this step is to compensate material shrinkage during the solidified, to avoid fails or distortions on the part. There is no possible to establish a form to estimate this time, therefore it is calculated through testing.
It is not recommended to keep the maintenance pressure along the cycle because it increases cycle time and energy expense.

- **Plasticized time**: This is the time between the maintenance pressure final application and the beginning of the mould opening. This time must assure the material solidification and also when the part is extracted, it doesn’t be distorted. This is the largest time, around 50 – 85 % of the total cycle time.
3.3 MOULD DESIGN

Injection moulds must be properly designed to ensure quality components. Mould design impacts productivity and profitability of your moulding operation. This section offers guidelines for designing an efficient injection mould.

- **Main Runner**: Runner systems convey the melted plastic from the sprue to the gate or part. The most efficient profile for a runner is circular (full round). A less expensive, yet adequate profile is a trapezoid, with tapers as shown in the sketch to ensure a good volume to surface area ratio. Half rounds are not recommended because of their poor perimeter to area ratio.

![Main Runner](image)

- **Sprue and Cold Material Trap**: Sprues connect the nozzle of the injection moulding machine to the main runner or cavity. The sprue should be as short as possible to minimize material usage and cycle time. The bushing should have a smooth, tapered internal finish that has been polished in the direction of the draw to ensure clean separation of the sprue and the bushing.

![Sprue and Cold Trap](image)

- **Gate Design**: The gate serves as the entrance to the cavity and should be designed to permit the mould to fill easily. A cavity can have more than one gate. Gates should be small enough to ensure easy separation of the runner...
and the part but large enough to prevent early freeze-off of polymer flow, which can adversely affect the consistency of part dimensions.

<table>
<thead>
<tr>
<th>Submarine or Tunnel Gate</th>
<th>Pinpoint or Restricted Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>An edge gate located below the parting line or moulded surface</td>
<td>A restricted opening between the runner and moulded part. Normally used with thin wall parts.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fan or Edge Gate</th>
<th>Tab Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A common gate located in the sidewall of the part to prevent restriction of resin flow. Normally used with multi-cavity, two-plate moulds.</td>
<td>Used for melt orientation when a large volume is needed for mould fill. The tab helps avoid surface splotches due to high shear, direct gating, or jetting.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sprue Gate</th>
<th>Flash Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended for single cavity moulds requiring symmetrical filling. Usually used with circular parts.</td>
<td>A long, shallow, rectangular edge gate</td>
</tr>
</tbody>
</table>
External Ring Gate

A system used when concentricity and a smooth interior surface are important. Can be used in multi-cavity moulds.

Internal Ring Gate

A System used with large circular parts when concentricity and smooth outer surface are required. Can only be used with single-cavity moulds.

Figure 18 Different gate designs

- **Injection Points**: The localization of the injection points must be found in the grossest part section to allow flow since gross sections to thin sections. Sometimes the final appearance of the part needs inject through the thin sections, but it is not recommendable.

- **Vents**: It allows gasses (air) found inside the mould to escape while the mixture is filling the cavities. Inadequate vents might do the gas compression and therefore the cavity is heated until make burns on the parts. High injection speed needs several vents.

Proper venting of cavities is very important. Inadequate venting can produce which the gas burns and also poor weld line strength and no filled parts. Too much venting can result in excessive flash and poor weld lines due to inadequate pressure build up. Venting should primarily be located at the last point of fill and where weld lines occur. Vent size depends on the viscosity of the polymer and can vary from 0.015 - 0.75 mm deep. Venting can also be used around knockout pins, moving cores and mould inserts.
The location of the vents can be calculated using flow simulation programs and also by testing. But in general, these holes should be situated in the opposite place from the injection points.

- **CAE Tools**: It is possible to use some CAE tools for plastic industry such as C-Mold, Mold Flow or Strim Flow. The generated results by CAE tools must be analyzed right.

- **Injection Pressure**: Injection pressure depends on many factors such as viscosity, flow length of the channel section. It should be minimum possible to reduce flushing effects and also to save power.

\[
P = \frac{\mu \cdot L \cdot Q}{r^{3n+1}}
\]

- \(P = \) Injection Pressure
- \(\mu = \) Viscosity
- \(L = \) Channel flow length
- \(Q = \) Caudal
- \(r = \) Channel radius
- \(n = \) Material constant \([0.15 - 0.36]\)
Mould Cooling: Cooling serves to dissipate the heat of the moulding quickly and uniformly. Fast cooling is necessary to obtain economical production and uniform cooling is required for product quality. Adequate mould temperature control is essential for consistent moulding. The layout of the cooling circuit warrants close attention especially if you consider cooling typically accounts for two thirds of a product's cycle time.

Optimal properties can be achieved only when the right mould temperature is set and maintained during processing. The mould temperature plays an important role on:

- Mechanical Properties
- Shrinkage
- Warpage
- Surface quality
- Cycle time
- Flow length in thin walled parts

Ejector Pins: Should be located on the heaviest sections of the part to minimize distortion when it leaves the core. They should be balanced as much as possible over the part's surface. Reinforced thermoplastics require more pins due to lower mould shrinkage and greater potential for drag during ejection.
Furthermore its dimension has to be adjusting to stringent tolerances to avoid possible part defects.

- **Nozzle:** It has to be with minimum possible length between the hot mixture and mould plates, to minimize temperature loss. An extended practice consists to use a hot runner (figure 5) which heats flow through electric resistance.
4 DESIGN

The next chapter describes the designs for the moulds. Fix, mobile and ejectors plates are detailed. Their plans are in the *annex II* and their assembly system is in the *annex III*. Injection moulding machine is specified in the chapter 5.1.2.

4.1 TOROID MOULD

First mould to design has been to obtain toroid shapes. The objective has been manufacture parts which allow studies about magnetic properties characterisation.

![Figure 22 Toroid Part](image)

**PART SECTION FORM**

One of the previous decisions has been set up the dimensions of the part and its shape. It was had two options: Circular o square section. Finally it has been chosen circular section because the extraction is easier than the other shape.

**PART DIMENSIONS**

On respect with the dimensions, it is established that measures have to be with following proportions:

\[ 1.25 \leq \frac{D_{\text{ext}}}{D_{\text{int}}} \leq 1.40 \]

One of the most important factors to be considered at the moment to choose the diameters, it is the green resistance of the part because it will be able to support the necessary efforts until sintering. We chose an exterior diameter of 50 mm and an interior diameter of 40 mm, therefore the thickness would be of 5 mm.

\[ 1.25 \leq \frac{50}{40} \leq 1.40 \]
MOULD MATERIAL

Our part will be built with soft ferromagnetic metal powders therefore it is important to take in account the requirements. We though in two different kinds of steel:

- **1.2316+ S**: Grade is a 16%Cr 1%Mo mould steel with improved corrosion resistance properties, thanks to the chromium and molybdenum additions. Furthermore specific sulphur additions are considered to increase the machinability properties. The grade in the quenched tempered condition has a fully bainite martensite microstructure and can be delivered in the prehardened condition (300HB or 340HB). The grade is not designed for highly finish polished surfaces or etched surfaces. The grade is commonly used for mould steel applications including cores, inserts, moulds... subjected to wet working conditions and / or storage conditions. The grade is also used for the manufacturing of corrosive materials like PVC

- **1.2085**: Plastic mould steel. Corrosion resistant, pre-hardened and magnetisable mould frame steel with good machinability and constant durability. 420FM can be substituted by 1.2099 due to similar applications. The significantly reduced share of C allows a reduction of Chromium while reaching the same grade of corrosion resistance working hardness: 280-325 HB (as delivered condition). Hardened and tempered maximal 280 - 325 HB. Due to the corrosion resistance, excellent in production environments with aggressive plastics or high levels of humidity.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C (wt.%)</th>
<th>Si (wt.%)</th>
<th>Mn (wt.%)</th>
<th>P (wt.%)</th>
<th>S (wt.%)</th>
<th>Cr (wt.%)</th>
<th>Mo (wt.%)</th>
<th>Ni (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2316</td>
<td>0.38</td>
<td>1.00</td>
<td>1.00</td>
<td>0.03</td>
<td>0.03</td>
<td>15.00 - 17.00</td>
<td>1.30</td>
<td>1.00</td>
</tr>
<tr>
<td>1.2085</td>
<td>0.35</td>
<td>1.00</td>
<td>1.40</td>
<td>0.03</td>
<td>0.10</td>
<td>15.00 - 17.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Finally it has been chosen **DIN 1.2316 + S** (M 314/5) because its cost is less than the other steel and both of them match the requirements.

NOZZLE

The nozzle is a mechanical device designed to control the direction or characteristics of the mixture fluid flow as it enters to the enclosed chamber of the mould. The university has many available normalize nozzle. It was consider choosing...
the short hot runner (35 mm length) to reduce the cooling across the channel. This nozzle has an exterior diameter of 20 mm and the flows form is conic with an exit of 3.8 mm, therefore the fix plate has to have one hole of 20 mm to introduce the entire nozzle.

**PART LOCATION INSIDE THE MOULD AND RUNNERS**

The most important step in mould design is to set the part cavity between the fix and mobile plaque, taking in account the ejectors plate and the injections channel, the nozzle and the possible vents.

The first step has been to decide if the location of the part is mobile and fix plates or only in the mobile. As this part is symmetric, it is possible to obtain each half in every plate.

It has been situated the part in the plaque. Therefore it is necessary to consider the nozzle hole and the ejector position do not generate distortions between the elements of the mould. University machine has the injection nozzle situated in the middle of the plaque.

To set the part in the middle of the plaque, being the nozzle inside the toroid. On this way we can inject the mixture by two or three channels which they join the nozzle and the interior diameter of the toroid. This form is called internal multipoint gate. The main problem of this method resides in the cooling of the mixture. How we inject from different points it will create many weld lines which they will decrease the part properties.

A very common way to inject a ring from inside is to set a diaphragm gate. It is often used for gating cylindrical or round parts that have an open inside diameter. It is
used for single cavity moulds which have a small to medium internal diameter. It is used when concentricity is important and the presence of a weld line is not acceptable. Typical gate thickness is 0.25 to 1.5 mm.

The main problem of this method resides on the considerable quantity of mixture which it is used to create the gate and the future problems to remove the gate from the part. With metallic parts, it is possible to be necessary machining to eliminate the burrs.

At that time it has been decided to use an external ring gate to inject the toroid. On this way it is formed only one weld line opposite to the channel and it saves material only with one thin way to inject. The main channel length is minimized to reduce the material and to keep it hot until it fills the mould.

At the moment to select the runner section, there are many options, but the most typical are circular, trapezoidal and semi-circular. The first is the best choice but in this kind of mould, the runner is located on the mobile plaque, therefore it is impossible to maching this surface. The trapezoid is also a correct choice but is more expensive and difficult to obtain than the semi-circular section, the final choice.
EJECTORS POSITION

Once it has decided the part situation in the fix and mobile plaques, the next step consist to design the mould extraction. To extract the part it is used the pin ejectors.

Normally the most of the pin ejectors are situated on the injection channel and the nozzle hole, but sometimes it is also necessary to situate some pin ejector along the part to improve the extraction and to avoid breaks and fissures in the part.

The first option had been to situate one pin ejector at the nozzle hole because part size is not much large. As well if it is used a minimum main channel from the nozzle to the part, it is got to minimize the bending moment in the joint section. How the main runner has 4 mm of diameter, we opted to choose an ejector of 3 mm of diameter.

But finally it has decided to add four little pin ejectors on the part to facilitate part extraction. The diameter of these new four ejectors has to be little with the aim of not to disturb the part form. It was opted for 1.5 mm of diameter situated at 45° of the main axis.
Concerning the ejectors length, they have been bought with enough length to get from ejector plate to mobile plate, considering the space between both plates (around 12 mm) and its thickness (12 mm ejectors plate and 45.10 main support and mobile plate).

![Ejectors cut](image)

Figure 31 Ejectors cut

It is necessary to cut them considering the deep requirements in each position. For the cold trap ejector it is needed 2 mm for the main runner diameter and 6 more for the trap. In the case of normal ejector in the part, it is only necessary 2.5 mm of cavity depth.

\[
L_{\#3COLDTRAP} = (12 + 12.10 + 45.10) - L_{RUNNER} - L_{COLDTRAP} = 69.20 - 2 - 6 = 61.20\, mm
\]

\[
L_{\#1.5TOROID} = (12 + 12.10 + 45.10) - L_{TOROID} = 69.20 - 2.5 = 66.70\, mm
\]

Annex VI includes the HASCO Pin ejector details.

**COLD TRAP**

At the beginning of the injection cycle, the first flow melt starts to solidify before than the melt rest so as to improve the homogeneous microstructure of the
part, it has used a cold trap to eliminate the beginning flow melt just in front of the nozzle hole. The standard dimensions are next to this rate:

\[ L_{\text{Cold Trap}} = 1.5 \ D_{\text{runner}} \]

VENTS

At first it was not considered to add vents to allow the air escaping and to avoid possible microfissures in the part. It is important to take in account that vents will increase the machining cost. Also they worsen final finished part (little defect in this joint place) and also the cycle time.

However the complete moulded part volume is no so much significant (about 3.18 cm\(^3\)), it has been considered to set a little vent in front of the main runner side (the last area to solidify). On this way the injection result would be improved.

John P. Beaumont describes the main measures for vents in his book [4]. This content has been the base to set new vent in the mould. The most significant measure is the deep of the beginning of the vent, with 0.2 mm. It has been selected 4 mm of wide, similar to main runner. The vent is situated in the fix plate.
HEATERS

To keep warm the mould at a controlled temperature and improve mould filling, an electrical heater has been situated on a hole inside the mould.

This heater can raise the temperature of a mould half to 50 °C. It is regulated through automatic power control. This is not the best way to keep warm a mould, but it represents a simple and rapid form.

It has been considered to design a system of heating by water circuit guided through the plaques by a closed circuit. This substantially improves the injection moulding operation.

A recommendable temperature for mould plates is between 40ºC and 70ºC depending on the feedstock. If the fix and mobile plates have similar temperature, it could be easier the part ejection and therefore it can be possible to work in continuous mode during the injection moulding. This can be caused by mould dilatation that retains the parts.

FINAL PART MOULDED VOLUME
Complete mould assembly

Figure 37 Toroid mould result

Figure 38 Final toroid mould assembly
4.2 DOG-BONE SPECIMEN MOULD

Due to the specific rules for shape design in MIM it is obvious which tensile test samples which can be manufactured without additional machining operations have distinct advantages both in terms of cost savings and technically..

The HES – SO Valais University had dog-bone specimen mould to obtain test parts which it allows experiments about properties of the different mixtures of MIM. One serious inconvenient are the dimensions of this parts were not normalized.

To make normalize experiments, the University decides to standardize the measures of the tensile test part as ISO norms sets.

SPECIMEN SHAPE AND DIMENSIONS

As MIM is usually a net-shape or near-net-shape manufacturing process, the technical advantage is which the surface condition of the test samples is the same as which of the MIM component

This is the reason because MIM industry, at an early stage already, has developed its own tensile test sample geometries. These so-called MIMA samples, designated after the American Metal Injection Moulding Association by which they have first been proposed, were adopted by the ISO 2740 [5] standard defining tensile test samples in powder metallurgy.

European MIM manufacturers found that these test samples which have been designed with holes in their clamping heads to facilitate clamping tend to fracture outside the gauge length if weld lines or cracks are formed due to irregular mould filling. To avoid this problem, an additional shape was proposed which is almost identical to the MIMA shape, but where the hole at the clamping heads is missing (Fig. 40).
The mould dimensions (diameter at the gauge length: 5.0 mm) are between the large MIMA sample (diameter at the gauge length: 5.82 mm) and the small MIMA sample (diameter at the gauge length: 3.8 mm). All three sample geometries have been admitted and integrated in ISO 2740.

**MOULD MATERIAL**

The requirements for this mould are similar than the toroid mould. The most important is the corrosion resistance to avoid possible problems caused by hot mixture injection of materials like PVC. In addition it is also important to have a good machinability.

Finally we chose the same steel which the toroid mould, DIN 1.2316 + S (M314/5) because its cost is less than the order steel and both of them keep the requirements.

**NOZZLE**

The university has many available normalize nozzle. It was consider choosing the short hot runner (35.5 mm length) to reduce the cooling across the channel.

**CAVITY LOCATION INSIDE THE MOULD AND RUNNERS**

The tensile test will be used in strength traction tests where probably the part will broke around the middle of it. With the purpose of not create any distortions around this area, the injection must be for one of the ends.
Also it is important to consider the flow recover filling the mould. It is necessary to improve this recover to decrease the filler time. The first idea had been to set a tangent channel to take the circular form of the part to cover all the mould. It was considered the necessity of moulding two parts in each cycle or only one. How it exist enough space in the mould plaques, it was chosen two parts.

In addition it had been considered the gravity factor when the mould is filling. If the position of the both parts was the same respect perpendicular axis, the result would be more homogenous. On this point a “Y” channel was designed with the parts in vertical position respect the mould but finally was rejected because it forces to set a large injection channel.

The tangent channel was rule out because the length of the main runner was too large, it would cause a mixture cooling during the filling process creating many weld fronts and consequently a non homogenous solidification. Also it wasted a considerable quantity of mixture in every cycle to filling the runners.

To decrease the injection channel length, it was opted to change the tangent injection for a direct system from the middle of the part’s end. In theory, it is a good solution but the only problem which one of the end is near to plaque border, in other words if the two parts were situated in parallel join by one of the ends with the main channel, only 7 mm in each side separate the part from the border because of which the cooling is not homogenous.
Finally it has decided to use some advantages of each design and avoid the gravity factor because in these small parts, it does not play an important role. Obviously the mould would design for two parts in parallel, with its entrances situated in angle so which the length of the main channel is minimum. Also it is important to consider the necessary space for the ejectors. At last the attack angle had fixed in 20°.

One important factor to be considered is the fix hole of each plaque and the semi-part situation. The injection machine requires fixing every plaque (fix and mobile) for two points, forming a cross.

On respect with the joint between the channel and the part, it had not considered because there is not an important problem to obtain some small defects.
on the end border. It is more important to obtain a fast homogenous filling to save internal structure faults.

How it was decided with the toroid mould runner section, it has selected a semi – circular shape with 20° of attack angle respect plaque borders and a diameter of 4 mm, the same than the cold trap.

**EJECTORS POSITION**

Once it has decided the part situation in the fix and mobile plaques, the next step consist to design the mould extraction which it will be like toroid mould help by pin ejectors.

Like last time, it has set the first pin ejector in front of the nozzle mould, with a diameter of 3 mm. In this section there is no problem with the ejector impact because the defects will be caused on the channel.

In this time, the parts disposition requires at least two additional pin ejectors in each part. It was opted to situated them on every end centre with a diameter of 8 mm, which it was enough help to remove the part and to avoid breaks and possible fissures.

Annex VI includes the HASCO Pin ejector details.

**COLD TRAP**

As explained in the mould theory, at the beginning of the injection cycle, the first flow meld starts to solidified before than the meld rest so as to improve the homogeneous microstructure of the part, it is used a cold trap to eliminate the beginning flow meld just in front of the nozzle hole.
Figure 47 Cold trap sketch
4.3 FLAT SPECIMEN MOULD

To open some new experiments, the HES – SO Valais University needed to find new forms of test tubes to allow new possibilities to compare experiment results.

At the beginning the specimen dimensions were not available. Only there were some part examples. Measures were taken of the part shape. After that, it was considered the feedstock’s shrinkage.

![Figure 48 Flat specimen](image)

SPECIMEN SHAPE AND DIMENSIONS

With the help of a calibre, the part dimensions were measured concluding the following sketch:

![Figure 49 Flat specimen dimensions](image)

It has supposed which the part will be shrinkage about a 10 %, therefore final dimensions have been oversized on this percentage.

MOULD MATERIAL

The requirements for this mould are similar than other moulds. The most important is the corrosion resistance to avoid possible problems caused by hot mixture injection. In addiction it is also important to have a good machinability.
Finally we chose the same steel which the toroid mould, *DIN 1.2316 + S* (M 314/5) because its cost is less than the order steel and both of them keep the requirements

**NOZZLE**

The university has many available normalize nozzle. It was consider choosing the short hot runner (35.5 mm length) to reduce the cooling across the channel.

**CAVITY LOCATION INSIDE THE MOULD AND RUNNERS**

As the other tensile test, this part will be used in strength traction tests where probably the part will broke around the middle of it. With the purpose of not create any distortions around this area, the injection must be for one of the ends.

Also it is important to consider the flow recover filling the mould. It is necessary to improve this recover to decrease the filler time. The first idea had been to set the channel in front of one of the ends of part, to create a direct flew which fill direct the part.

![Figure 50 Direct filling](image)

With this idea the gravity factor is taken in account and both parts are situated parallel to part border and joined by a straight main runner. But this first design had been rejected because this kind of injection usually creates the flash effect produced by excess material in the thin entrance exceeding normal part geometry. Mould is over packed or parting line on the tool is damaged, too much injection speed/material injected, clamping force too low. It could also be caused by dirty and contaminants near tooling surfaces.
This channel has been dimensioned to set minimum length runner to maintain the cooling process more homogeneous and also to save mixture which would be lost in a large channel. Also it would increase a considerable quantity of mixture in every cycle to filling the runners.

On respect with the joint between the channel and the part, it had not been considered because there is not an important problem to obtain some little defects in the end border. It is more important to obtain a fast homogenous filling to save internal structure faults.

As it was decided with the other tensile test and its main runner section, it was selected a semi – circular shape with diameter of 2 mm, the same than the cold trap.

**EJECTORS POSITION**

Once it has decided the part situation in the fix and mobile plaques, the next step consist to design the mould extraction which it will be like toroid mould help by pin ejectors.

As the same than the other moulds, the main ejector will be set in front of the nozzle, with a diameter of 3 mm. In this time, the parts disposition requires at least two additional pin ejectors in each part. It was opted to situated them on every end centre with a diameter of 5 mm, which it was enough help to remove the part and to avoid breaks and possible fissures.

Annex VI includes the HASCO Pin ejector details.
COLD TRAP

For the same reason than the other moulds, it is necessary to establish a Cold Trap to avoid the initial mixture flowed and improve the homogenous solidification. It is used a cold trap to eliminate the beginning flow meld just in front of the nozzle hole.

![Cold Trap Sketch](image)

Figure 53 Cold trap sketch
4.4 DOUBLE CAVITY TENSILE TEST MOULD

At the last two chapters they have been described two different tensile test specimens and their complete development to mould two cavities per cycle.

The university does not need more than short number of moulded units. On this way it has been decided to create a new mould design with both types of tensile test specimens. It allows saving manufacturing cost, space and set up time.

However these kinds of moulds require a system to ability the control of the flow, feeding only one of the parts. This system could be a kind of valve in "or" which it can be situated it two different positions. Therefore it has been possible to use the previous single part designs and mixing them with the valve.

CAVITY LOCATION INSIDE THE MOULD AND RUNNERS

The dog-bone specimen length requires situating the main runner in diagonal direction to keep the flow heat while it is filling. Therefore the flat specimen should be located in function of this runner.

The easiest way to create a multi-position valve is to set each location with a fixed angle. It has been chosen 45 grads between x / y angles and runner position. On conclusion the mobile plate is composed by two different tools: The plaque and the valve.

To leave more space available for parts and runner, the dog-bone specimen has been located with 22 mm from the x axis. On this way it is possible to increase the diameter of the valve and also to increase the runner attack angle until 45°. The flat specimen will be injected since one of the ends. As this part has square section, it allows moulding the full part only in one of the parts because it reduces the manufacturing cost doing only necessary to machining the mobile plate.
Respect runner dimensions and section, it has been decided to continue with semi-circular shape with a diameter of 4 mm (similar to nozzle hole 3.8 mm). But for the flat specimen it is necessary to reduce this section because the full deep of the part is only of 2 mm. Therefore it is possible to reduce the main channel of 4 mm to 2 mm of diameter with a curvature of 2 mm to improve the flow.

![Diagram of final runner design](image)

Figure 55 Main runner flat specimen

The holes in the plaque to keep the valve will be made in function of the valve dimensions and requirements. It is important to take special attention with the tolerances between both parts.

**EJECTORS POSITION**

Once it was setting both of the parts and the main runners, the following step consist in to situate the ejector. As it has been decide with the single moulds, it has been selected 2 pin ejector in each part, with 8 mm of diameter for dog-bone specimen and 4 mm for flat specimen.

As the same than the other moulds, the main ejector will be set in front of the nozzle, but in this case it is necessary to take in account the dual valve and its dimensions. It is required a diameter of 3 mm.

Respect ejectors length, they have been bought with enough length to get from ejector plate to mobile plate, considering the space between both plates (around 12 mm) and its thickness (12 mm ejectors plate and 45.10 main support and mobile plate).
It is necessary to cut them considering the deep requirements in each position. For the cold trap ejector it is needed 2 mm for the main runner diameter and 6 more for the trap. In the case of normal ejector in the part, it is only necessary 2.5 mm of part deep (dog-bone specimen) or 2 mm of deep (flat tensile specimen).

\[ L_{\phi 3COLDTRAP} = (12 + 12.10 + 45.10) - L_{RUNNER} - L_{COLDTRAP} = 69.20 - 2 - 6 = 61.20 \text{mm} \]

\[ L_{\phi 4FLATSPEIMEN} = (12 + 12.10 + 45.10) - L_{SPECIMEN} = 69.20 - 2 = 67.20 \text{mm} \]

\[ L_{\phi 8DOG–BONE} = (12 + 12.10 + 45.10) - L_{DOG–BONE} = 69.20 - 2.5 = 66.70 \text{mm} \]

Annex VI includes the HASCO Pin ejector details.

**SWITCH VALVE DESIGN**

It is necessary to design the valve and its possibilities. Consequently the holes to keep the valve inside the plaque the must be according to its dimensions. It was decide to situate a mobile cylinder with two different weights 25 mm and 9.5 mm. The first is the same than the hole in the mobile hole (with a little tolerance) and the second is 0.5 mm less than the plaque. Only it is necessary to adjust exactly one of
them. It improves the mobility of the plaque when it will be turned in different positions.

![Figure 57 Valve sketch](image)

The valve has to be mobile and at least with two positions changing with a 90° angle. So it is possible to set this valve and fixing it to the mobile plaque with two screws, whose head will be inside the valve to allow a perfect plane superficies.

Therefore it is necessary four holes in the plaque, two per position, and it allows four different orientations (Figure 58) for the main runner. Two first positions for each part, the third is available for future parts (right up) and the last one is not possible because the dog-bone specimen is too long eliminates the space.

It has been chosen two screws of metric M4 x 0.7 and its holes for the head of 8 mm of diameter with a deep of 5 mm, both measures oversized.

![Figure 58 Different valve positions](image)

To enable the change of position, it was designed a special key which has two cylinders to introduce in each hole (for the screws) and turn it. Other possibility estimated has been making the head of the valve hexagonal, to allows turn it with an Allen key. This last option was discarded because it could create some problems with the flow.
**FINAL PART MOULDED VOLUME**

<table>
<thead>
<tr>
<th>Part</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part</td>
<td>0.457</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.277</td>
</tr>
<tr>
<td>Main Runner</td>
<td>0.088</td>
</tr>
<tr>
<td>Secondary Runner</td>
<td>0.004</td>
</tr>
<tr>
<td>Connector Runner Curvature</td>
<td>0.008</td>
</tr>
<tr>
<td>Cold Trap</td>
<td>0.075</td>
</tr>
<tr>
<td>Adjust Nozzle - Fix Plaque</td>
<td>0.057</td>
</tr>
<tr>
<td>Adjust Nozzle - Cold Trap</td>
<td>0.008</td>
</tr>
<tr>
<td><strong>INVENTOR VOLUME</strong></td>
<td><strong>0.950</strong></td>
</tr>
</tbody>
</table>

**TOTAL VOLUME FLAT SPECIMEN**

<table>
<thead>
<tr>
<th>Part</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part</td>
<td>2.972</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.277</td>
</tr>
<tr>
<td>Main Runner</td>
<td>0.141</td>
</tr>
<tr>
<td>Cold Trap</td>
<td>0.075</td>
</tr>
<tr>
<td>Adjust Nozzle - Fix Plaque</td>
<td>0.057</td>
</tr>
<tr>
<td>Adjust Nozzle - Cold Trap</td>
<td>0.008</td>
</tr>
<tr>
<td><strong>INVENTOR VOLUME (REAL)</strong></td>
<td><strong>3.499</strong></td>
</tr>
</tbody>
</table>

**TOTAL VOLUME DOG-BONE SPECIMEN**

<table>
<thead>
<tr>
<th>Part</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part</td>
<td>0.457</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.277</td>
</tr>
<tr>
<td>Main Runner</td>
<td>0.088</td>
</tr>
<tr>
<td>Secondary Runner</td>
<td>0.004</td>
</tr>
<tr>
<td>Connector Runner Curvature</td>
<td>0.008</td>
</tr>
<tr>
<td>Cold Trap</td>
<td>0.075</td>
</tr>
<tr>
<td>Adjust Nozzle - Fix Plaque</td>
<td>0.057</td>
</tr>
<tr>
<td>Adjust Nozzle - Cold Trap</td>
<td>0.008</td>
</tr>
<tr>
<td><strong>INVENTOR VOLUME</strong></td>
<td><strong>0.950</strong></td>
</tr>
</tbody>
</table>

Figure 59 Special tool

Figure 60 Specimens total volume

Figure 61 Specimens total volume by steps
COMPLETE MOULD RESULT

Switch valve does not cause any problem during the injection moulding despite of the adjust tolerances between the mould and this component. This system has allowed a cost and storage space reduction, including a reduction of the set up time.

Figure 62 Final mould result
4.5 MICROSTEP MOULD

Finally the last and one of the most important parts to obtain has been the microstep tensile test. These idea rise from a common project of HES – SO Valais and Carlos III Universities, to develop mouldability test in powder injection moulding parts.

The project consisted to obtain a useful part to observe the weld lines and his influence in the part properties with different height and width. There is not any norm about this topic therefore it had to create an own design.

PART SECTION FORM

The first idea had been obtained from micro MIM, which defined the measures of a similar part to a pyramid with square base of 25 mm of side and each step height of 8 mm in 5 levels, giving a total height of 50 mm. Also it has been defined the height factor reduction on 1:3.

![Figure 63 Microstep specimen](image)

This factor reduction provides part thicknesses to can test micro MIM properties but this range of measures (since 0.3 mm to 25 mm) are not common for normal powder injection moulding.

PART DIMENSIONS

According to the micro MIM indications, the base part would be square of 25 mm, each step a height of 8 mm and finally a reduction thickness factor of 1:3. On this way the part measure has been the following:
One of the most important factors to be considered at the moment to choose the dimensions, it is the green resistance of the part because it will be able to support the necessary efforts until sintering.

**MOULD MATERIAL**

The requirements for this mould are similar than other moulds. The most important is the corrosion resistance to avoid possible problems caused by hot mixture injection. In addiction it is also important to have a good machinability.

It has to be considering that this mould requires electroerosion process to obtain part square edges, impossible to obtain for machining due tool curvature.

**NOZZLE**

The University has many available normalize nozzles. It was consider choosing the short hot runner (35.5 mm length) to reduce the cooling across the channel.

**PART DISPOSITION INSIDE THE MOULD AND RUNNERS**

As the same than the other parts, the most important step in the mould design is to set the part situation between the fix and mobile plaque, keeping in account the ejectors plate and the injections channel, the nozzle and the possible vents.

This Kind of part can be divided in two symmetric in two ways, one per each axis. In function of this cut, the part is situated into the mould in a different position.
To create an easy part to remove from the mould during the extraction, it has been selected the transversal semi part which permits to keep constant the thickness in the contact plane (right figure 65).

The next step was design the main runner for which with this little part volume would be enough only with one channel of injection but the objective of the experiments is to analyze the weld line in different thickness. To create a clear weld line, it has been situated two injection channel in the part in “U” form, with 2 mm of diameter, joined to the sprue by a common way with 3 mm of diameter. The section shape used is a semi-circular area, as other moulds.

Obviously the part has to be injected since the wide side to the thin side therefore this location parallel to the border with the gross side near to the nozzle hole.

In these case it is not a problem the considerable quantity of mixture which it is used to create the gate (it is possible to reuse it again after a recycle process) because it is necessary to create the weld line in the middle.

Also it is not so much important the future problems to remove the gates from the part because they are located on the base and they don’t disturb the main purpose of the part.
EJECTORS POSITION

The next step consists to design the part extraction.

As in other moulds, the main ejector has been situated in front of the nozzle hole, in the main runner. In this position there is no problem with the ejectors impact which can be caused part breaks or fissures.

![Ejectors plaque position](image)

Figure 67 shows both ejector plaques with the holes distribution. On the left there is the first design which shows two ejectors on the first step of 4 mm, three more holes for pin ejector of 2 mm and the last one with only 1.2 mm of diameter. This design has obviously a very complicate remove and an extra difficult machining. Located more useful pin ejector is near to be impossible because the location left no enough space.

On the right side there is the other design, with many ejector holes, situated in the middle of each step, with a diameter of 3 mm, a part of the main ejector in the main runner. This position allows having more ejector and many ways to eject but it also requires synchronization of each pairs of ejectors.

![Ejector diameter](image)

Annex VI includes the HASCO Pin ejector details.

COLD TRAP

At the beginning of the injection cycle, the first flow meld starts to solidified before than the meld rest so as to improve the homogeneous microstructure of the
part, we use a cold trap to eliminate the beginning flow melt just in front of the nozzle hole. The standard dimensions are next to this rate:

![Cold trap sketch](image)

**FINAL PART MOULDED VOLUME**

![Full moulded specimen](image)

**INVENTOR VOLUME (REAL)** 8.041 cm³
5 EXPERIMENTAL

5.1 EQUIPMENT AND MACHINES USED

For this master thesis has been necessary to use several equipments and machines. Also it has been advisable to learn knowledge about their operation and capacities. In the following part, the tools will be described with technique characteristics.

1. POWDER AND BINDER MIXER

The Coperion LUK 1.0 K2 mixer allows homogenizing the feedstock mixture of metallic powders and binders through sigma blades that cut the mix.

![Coperion sigma blade mixer](image)

**TECHNIQUE CHARACTERISTICS**

- **Machine Type:**
  - COPERION LUK 1.0 K2
- **Total capacity:** 1.5 l
- **Useful capacity:** 1 l
- **Front paddle speed:** 10 – 100 t/min
MACHINE DESCRIPTION

Rotation speed regulation is controlled by electrical control and it corresponds with the rear paddle. There is a temperature regulator which allows verify temperature increases of mixture. These parameters are set by an hydraulic thermoregulator HB-THERM, connected to mixer.

The magnetic feedstock, with Fe-Si powder do not require special environment to be mixed. But it is available to manufacture the powder in control atmosphere of argon. On this way, it is possible to avoid the powder contamination by the oxygen.

MIXTURE PROCESS

1. Filling the chamber with argon
2. Establishment of the powder and the binder
3. Heating of the mixing chamber
4. Interlocking blades
5. Mixture
6. Cooling
7. Storage in the chamber of the mixer
2. INJECTION MOULDING MACHINE

HES-SO Valais University has an ARBURG 221K machine for injection moulding of plastics and PIM technology. The length of the injection screw is 25 mm.

![Arburg 221 – K](image)

Figure 73 Arburg 221 – K

TECHNICAL CHARACTERISTICS

- **Machine Type**
  - ARBURG 350 – 100
  - ALLROUNDER 221 K
- **Close Unit**
  - Close force 350 kN
  - Mould security force 2 kN
  - Maximum aperture course 200 kN
  - Minimum mould thickness 150 mm
  - Maximum plates distance 500 mm
  - Distance between columns: 221 mm
  - Maximum ejection force 24 KN
  - Maximum ejection course 60 mm
- **Injection Unit**
  - Screw diameter 25 mm
  - Maximum screw course 100 mm
  - Maximum dosage volume 49 cm³
  - Injection volume 54 cm³/s
  - Maximum injection pressure 2000 bar
  - Maximum circular speed 300 Nm
  - Maximum base force 50 KN
- **Hydraulic System**
  - Motor Power 7.5 kW
MACHINE DESCRIPTION

- Close Unit: This unit is composed for two columns system with hydraulic levers and hydraulic ejector.

- Injection Unit:
  - Injection cylinder with and screw with 25 mm of diameter.
  - Hoper: To keep the plastic pellets
  - Hydraulic system composed for a motor to turn the screw and a piston for the injection.

- Control Unit: To introduce the parameter and to follow the machine activities and process, it is used the SELOGICA command. With this tool, it is possible to control most of the parameters such as close force, maintenance pressure, mixture pressure, times, speeds…In addiction it is also possible to keep this dates in an extern disc.
3. FLOW REGULATOR AND HOT PLATE

Solvent debinding can be done with the hot plate IKAMAG FCT. The temperature has been measured by a thermometer and it is regulated through CS LAUDA heater regulator, which controls the water flow to heat the solvent (heptane).

![Figure 76 Solvent debinding tools](image)

4. HIGH TEMPERATURE FURNACE

Debinding and sintering are made in a special high temperature furnace. HES-SO Valais has a NABERTHERM VHT 8-16MO furnace, which allows to work under vacuum or controlled atmosphere of N2, H2 or Ar.

![Figure 77 Nabertherm VHT 8-16 MO](image)
TECHNICAL CHARACTERISTICS

- Producer and model: NABERTHERM VHT 8-16MO
- Vacuum high temperature furnace
- Max. temperature: 1600°C
- Max. heating temperature: 30 – 1300°C: 600 °C/h, 1300°C -1600°C: 300°C/h

5. MACHINING EQUIPMENT

To elaborate the complex moulds at the university, it has been used several machining machines of the atelier unit. This team includes milling, drilling and turning machines with numerical control.

MILLING MACHINE

To machine the mould surface, the main tool used has been the FEHLMANN PICOMAX 54. This compact machine allows milling and drilling and it combines manual operation and automatic operation controlled by CNC. It's possible to work with this machine conventionally as well as two axes CNC.

TECHNICAL CHARACTERISTICS

- Producer and model: FELHMANN PICOMAX 54
- Travelling distances
  - X: 500 mm
  - Y: 260 mm
  - W machine head: 490 mm
  - Z quill stroke: 160 mm
- Machining area
  - Clamping surface L x W: 880 x 320 mm
  - Table to spindle nose distance: 0 – 610 mm
Final Project of Industrial Engineering
"Design and manufacturing of complex moulds for powder injection moulding"

- Work spindle
  - Drive power: 7.6 KW
  - Speed: 100 – 7100 rpm
- Other data
  - Control unit: Heidenhain TNC 320
  - Installation space (W/D/H): 1.8 / 1.5 / 2.5 m
  - Weight: 2400 Kg

TOURNING MACHINES

To parts with a revolution symmetry such as the valve in “OR”, has been made in a WEILER PRAKTIKANT GS machine. It combines good quality and versatility with straight-forward operation.

![Figure 79 Weiler Praktikant GS](image)

TECHNICAL CHARACTERISTICS:

- Producer and model: WEILER PRAKTIKANT GS
- Distance between centres: 650 mm
- Swing over
  - Bed: 320 mm
  - Cross slide: 190 mm
- Spindle bore: 40 mm
- Drive Power: 2.6 / 3.1 KW
- Number of spindle speeds: 16 mm
- Speed Range: 48 – 2500 rpm
To cut ejectors and adjust them to required measure, it has been used a SCHAUBLIN 102N VM. This machine is ideal for machining threads and other special work features.

![Figure 80 Schaublin 102N VM](image)

**TECHNICAL CHARACTERISTICS:**

- **Producer and model**: SCHAUBLIN 102N VM
- **Maximum swing over bed**: 200 mm
- **Maximum swing over carriage**: 120 mm
- **Maximum distance between centres**: 470 mm
- **Length of the bed**: 1000 mm
- **Height of the bed**: 168 mm
- **Power continuous**: 1.5 KW
- **Spindle speed**: 100 - 5'000 / min
- **Maximum throughbore**: 14.5 mm
- **Manual moving of carriage on bed**: 442 mm
- **Maximum transverse stroke, X-axis**: 100 mm
- **External diameter of the spindle**: 40 mm
- **Weight**: 350 Kg
- **Dimension of machine in mm (length x depth x height)**: 2 / 0.8 / 1.55 m

**6. MACHINING TOOLS**

To create moulds with real parts shape, it is necessary to use different machining tools for each piece. Milling cutters come in several shapes and many sizes. There is also a choice of coatings, as well as rake angle and number of cutting surfaces. In a milling operation, the workpiece is moved around the stationary cutting tool, the tool is moved across the stationary material, or some combination of the two. The average machining speed is not so high caused by the material strength (about 80 m/min).
The principal milling cutters used have been:

- Cylindrical handle (diameter 6 mm) with ball nose cutter of 5 mm to machining the curve surfaces.
- Cylindrical handle (diameter 6 mm) with slot drill of 2 mm and 4 mm to machining flat surfaces.
5.2 FEEDSTOCK ELABORATION

Every mould has been conceived for specific reasons such as to allow strength and flexion testing or to create parts with controlled weld line to study its influence in the post-sintering properties.

As it was explained in the introduction, the feedstock composition depends on many factors such as particle diameter of main component or viscosity. In case of double cavity tensile test mould, feedstock is not fixed due to several possibilities of PIM mixtures and its correspondent tests. The first feedstock used with this mould was ceramic, aluminium oxide (alumina) Al$_2$O$_3$-96%purity.

The toroid mould was conceived to study soft ferromagnetic materials. This project was developed in collaboration with HES-SO Vaud à Yverdon.

To obtain different materials, different feedstocks were moulded in the toroid mould. Two feedstocks were manufactured by HES-SO Valais and Carlos III University. A third one was bought to the company Advanced Metalworking.

1. HES-SO VALAIS Fe-Si FEEDSTOCK

**Powder components:**

- **Iron (Fe):** Iron-based alloys are the most common metals and the most common ferromagnetic materials in everyday use.

- **Silicon (Si):** It is used on the steel industry as a component of silicon-steel alloys. For making steel, molten steel is deoxidizes adding small amounts of silicon, the common steel contains less than 0.03% silicon. The silicon steel containing 2.5 to 4% silicon, used to make the cores of electrical transformers, since the alloy has low hysteresis.

**Binder components:**

- **Low Density Polyethylene (LDPE):** Is a thermoplastic made from petroleum. It was the first grade of polyethylene. LDPE is defined by a density range of 0.910 - 0.940 g/cm$^3$. It is unreactive at ambient temperature, except by strong oxidizing agents, and some solvents cause swelling. It can withstand
temperatures of 80°C continuously and 95°C for a short time. Made in translucent or opaque variations, it is quite flexible, and tough but breakable. In addition the LDPE presents a good processability; it means it can be conformed by thermoplastics methods, such as injection.

- **Stearic Acid (SA):** is a saturated fatty acid with the formal IUPAC name octadecanoic acid. It is a wax solid and its chemical formula is \( \text{C}_{18}\text{H}_{36}\text{O}_2 \). Stearic acid is also used as a parting compound when making plaster castings from a plaster piece mould or waste mould and when making the mould from shellacked clay original. In this use, powdered stearic acid is dissolved in water and the solution is brushed onto the surface to be parted after casting. Stearic acid is one of most commonly used lubricants during injection moulding and pressing of ceramic powders.

- **Paraffin Wax (PW):** Paraffin wax is mostly found as a white, odorless, tasteless, waxy solid, with a typical melting point between about 47 °C to 64 °C, and having a density of around 0.9 g/cm³. It is insoluble in water, but soluble in ether, benzene, and certain esters. Paraffin is unaffected by most common chemical reagents. Also it burns easily.

![Figure 82 Magnetic feedstock HES-SO Valais](image)

<table>
<thead>
<tr>
<th>POWDER-BINDER BALANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWDER-BINDER</strong></td>
</tr>
<tr>
<td><strong>Number</strong></td>
</tr>
<tr>
<td><strong>Component</strong></td>
</tr>
<tr>
<td><strong>Density (g/cm³)</strong></td>
</tr>
<tr>
<td><strong>D50 (microns)</strong></td>
</tr>
<tr>
<td><strong>wt.%</strong></td>
</tr>
<tr>
<td><strong>P/B vol.%</strong></td>
</tr>
<tr>
<td><strong>Vol.%</strong></td>
</tr>
<tr>
<td><strong>P/B wt.%</strong></td>
</tr>
<tr>
<td><strong>wt.%</strong></td>
</tr>
</tbody>
</table>
Approx feedstock relative density (g/cm³) | 4.80
---|---
Figure 83 HES-SO Valais magnetic feedstock components

### Sigma Blade Mixer Standard batch

<table>
<thead>
<tr>
<th>Component</th>
<th>Fe</th>
<th>Si</th>
<th>LDPE</th>
<th>SA</th>
<th>PW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>4317.34</td>
<td>119.80</td>
<td>127.24</td>
<td>33.98</td>
<td>200.26</td>
</tr>
</tbody>
</table>

1kg Feedstock Formula

<table>
<thead>
<tr>
<th>Component</th>
<th>Fe</th>
<th>Si</th>
<th>LDPE</th>
<th>SA</th>
<th>PW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>899.71</td>
<td>24.97</td>
<td>26.52</td>
<td>7.08</td>
<td>41.73</td>
</tr>
</tbody>
</table>

1kg Powder Formula

<table>
<thead>
<tr>
<th>Component</th>
<th>Fe</th>
<th>Si</th>
<th>LDPE</th>
<th>SA</th>
<th>PW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>973.00</td>
<td>27.00</td>
<td>28.68</td>
<td>7.66</td>
<td>45.13</td>
</tr>
</tbody>
</table>

Figure 84 HES-SO Valais magnetic feedstock proportions

**Elaboration process:**

**Powder and Binder Mixer Machine: Coperion Luk 1.0 K2**

<table>
<thead>
<tr>
<th>Step</th>
<th>Component / Process</th>
<th>Quantity (g)</th>
<th>T(°C)</th>
<th>Time</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Powders premixing</td>
<td>Fe 3108, Si 86</td>
<td>Room temperature</td>
<td>15’</td>
<td>In Turbula mixer</td>
</tr>
<tr>
<td>2</td>
<td>Binder premixing</td>
<td>LDPE 32.6, SA 24.5, PW 144.2</td>
<td>Room temperature</td>
<td>15’</td>
<td>In Sigma Blade mixer</td>
</tr>
<tr>
<td>3</td>
<td>Powders preheating</td>
<td>-</td>
<td>R.T. - 90</td>
<td>60’</td>
<td>In Sigma Blade mixer (Manual Agitation 10 rpm/min)</td>
</tr>
<tr>
<td>4</td>
<td>Binder addition</td>
<td>-</td>
<td>90</td>
<td>To the preheated powders</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Temperature increase</td>
<td>-</td>
<td>90 - 140</td>
<td>60’</td>
<td>Time needed to achieve homogeneous temperature in the mixture (Manual Agitation 10 rpm/min)</td>
</tr>
<tr>
<td>6</td>
<td>Keep Constant Temperature</td>
<td>-</td>
<td>140</td>
<td>300’</td>
<td>Mixing speed: 30 rpm/min</td>
</tr>
</tbody>
</table>

Figure 85 HES-SO Valais magnetic feedstock elaboration process
2. ADVANCED METALWORKING PRACTICES Fe-Si FEEDSTOCK

_Powder and binder components:_

A Fe-2.7%Si based feedstock has been acquired from Advanced Metalworking Practices (Carmel, United States). The nominal purity was of about 99.9%. Main impurities are manganese and boron. The binder composition is proprietary.

![Advanced Metalworking magnetic feedstock](image)

3. INMATEC ALUMINIUM OXIDE FEEDSTOCK

_Powder components_

- **Aluminium Oxide**(Al₂O₃-96.5%): Also commonly referred to as alumina. It is produced by the Bayer process from bauxite. Its most significant use is in the production of aluminium metal, although it is also used as an abrasive due to its hardness and as a refractory material due to its high melting point.

![Ceramic feedstock](image)
Feedstock Properties

<table>
<thead>
<tr>
<th>Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Al₂O₃</td>
<td>Na₂O</td>
<td>Fe₂O₃</td>
<td>B₂O₃</td>
<td>SiO₂</td>
<td>MgO</td>
<td>CaO</td>
<td>Humid</td>
<td>LOI</td>
</tr>
<tr>
<td>Relative density (g/cm³)</td>
<td>99.500%</td>
<td>0.070%</td>
<td>0.013%</td>
<td>1.080%</td>
<td>0.062%</td>
<td>0.064%</td>
<td>0.022%</td>
<td>0.160%</td>
<td>0.190%</td>
</tr>
<tr>
<td>Spec.Surf. Area at 1100°C (m²/g)</td>
<td>3.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Density (g/cm³)</td>
<td>2.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fired Density (g/cm³)</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shrinkage</td>
<td>15.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 88 Ceramic feedstock powder balance

<table>
<thead>
<tr>
<th>FEEDSTOCK PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Component</td>
</tr>
<tr>
<td>Theoretical Density</td>
</tr>
<tr>
<td>Moulding Temperature</td>
</tr>
<tr>
<td>Mould Temperature</td>
</tr>
<tr>
<td>Debinding</td>
</tr>
<tr>
<td>Sintering Temperature</td>
</tr>
<tr>
<td>P&amp;B wt% detail</td>
</tr>
</tbody>
</table>

Figure 89 Ceramic feedstock properties
5.3 INJECTION MOULDING PROCESS

During the project it has been possible to perform moulding tests with both the toroid mould and double cavity tensile test mould. The first feedstocks have been the magnetic (Fe-Si) of HES-SO Valais and Advanced Metalworking Practices. In addition it has been used the ceramic (Al₂O₃) feedstock of INMATEC.

1. TOROID MOULD

MOULD FILLING

![Toroid part solidification process](image)

5.2.1 MAGNETIC HES-SO VALAIS FEEDSTOCK

SPECIMENS

HES-SO Valais feedstock has been difficult to inject because the opposite section to the toroid entrance has presented filling problems. This trouble can be avoided changing binder composition. Analyzing every moulding factor, it was considered that one of the most important parameters in the injection process is the plates mould temperature. Room temperature do not allow an homogenous solidification, causing problems in the last filled areas.

Therefore it is important to consider a future system of plates heating, such as water circuit inside the supports.
Complete solidified part, including nozzle, runner and trap cold.

Complete part, apparently without microfissures.

Defect by feedstock lack.

Defect by solidification fail.

Figure 91 Part samples feedstock HES-SO Valais

5.1.2 MAGNETIC ADVANCED METALWORKING FEEDSTOCK

SUGGESTED MOULDING CONDITIONS

Based in Advamet tests, the following conditions can be used as starting point for moulding their feedstock. It is important to remark that these parameters must be regulated and optimized for the specific geometry, mould design, material type and moulding machine.
### Injection Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel Temperature</td>
<td>175 °C</td>
</tr>
<tr>
<td>Nozzle Temperature</td>
<td>190°C</td>
</tr>
<tr>
<td>Mould Temperature</td>
<td>43°C</td>
</tr>
<tr>
<td>Mould Clamping Pressure</td>
<td>19 MPa</td>
</tr>
<tr>
<td>Injection Pressure</td>
<td>12 MPa</td>
</tr>
<tr>
<td>Holding Pressure</td>
<td>8 MPa</td>
</tr>
<tr>
<td>Holding Pressure duration</td>
<td>6 sec</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>20 sec</td>
</tr>
</tbody>
</table>

Figure 92: Advamet feedstock injection parameters

### SPECIMENS

<table>
<thead>
<tr>
<th>Description</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete solidified part, including nozzle, runner and trap cold.</td>
<td><img src="image1.png" alt="Specimen Image" /></td>
</tr>
<tr>
<td>Damaged part by solidification fail.</td>
<td><img src="image2.png" alt="Specimen Image" /></td>
</tr>
<tr>
<td>Damaged part by feedstock lack.</td>
<td><img src="image3.png" alt="Specimen Image" /></td>
</tr>
<tr>
<td>Damaged part by injection fail.</td>
<td><img src="image4.png" alt="Specimen Image" /></td>
</tr>
</tbody>
</table>

Figure 93: Advanced Metalworking practice specimens
2. DOUBLE CAVITY TENSILE TEST MOULD

5.2.1 DOG-BONE SPECIMEN

MOULD FILLING

![Dog-Bone specimen solidification](image)

Figure 94 Dog-Bone specimen solidification

INJECTION PARAMETERS

<table>
<thead>
<tr>
<th>Specimen N°</th>
<th>Temp. Before opening</th>
<th>Test Volume (cm³)</th>
<th>Commutation Point</th>
<th>Injection Speed (cm³/s)</th>
<th>Injection Pressure (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 8</td>
<td>0</td>
<td>7</td>
<td>2.6</td>
<td>2</td>
<td>700</td>
</tr>
<tr>
<td>T821</td>
<td>T801</td>
<td>T802</td>
<td>T803</td>
<td>T804</td>
<td>T805</td>
</tr>
<tr>
<td>40</td>
<td>159</td>
<td>160</td>
<td>162</td>
<td>165</td>
<td>168</td>
</tr>
</tbody>
</table>

Heating Temperatures (°C)

<table>
<thead>
<tr>
<th>Specimen N°</th>
<th>P311</th>
<th>P312</th>
<th>P313</th>
<th>P314</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen N°</td>
<td>t (s)</td>
<td>P (Bar)</td>
<td>t (s)</td>
<td>P (Bar)</td>
<td>t (s)</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>700</td>
<td>3</td>
<td>700</td>
<td>2</td>
</tr>
<tr>
<td>2 - 3</td>
<td>3</td>
<td>300</td>
<td>0.5</td>
<td>300</td>
<td>0.3</td>
</tr>
<tr>
<td>4 - 5</td>
<td>3</td>
<td>300</td>
<td>0.3</td>
<td>200</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 95 Dog-Bone specimen injection parameters
SPECIMENS

Complete filled part, including nozzle, runner and trap cold.  
Parts with different injection conditions. (Figure 95)

Figure 96 Dog-Bone specimens

5.2.2 FLAT SPECIMEN

PART SOLIDIFICATION

Switch over point = 2.9 cm³
Volume = 0.95 cm³

Figure 97 Flat specimen solidification process

INJECTION MOULDING PARAMETERS

<table>
<thead>
<tr>
<th>Specimen N°</th>
<th>Temp. Before opening</th>
<th>Test Volume (cm³)</th>
<th>Commutation Point</th>
<th>Injection Speed (cm³/s)</th>
<th>Injection Pressure (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>0</td>
<td>5</td>
<td>2.9</td>
<td>3</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating Temperatures (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T821</td>
<td>T801</td>
<td>T802</td>
<td>T803</td>
<td>T804</td>
<td>T805</td>
</tr>
<tr>
<td>40</td>
<td>159</td>
<td>160</td>
<td>162</td>
<td>165</td>
<td>168</td>
</tr>
<tr>
<td>Maintenance Pressure Cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen</td>
<td>P311</td>
<td>P312</td>
<td>P313</td>
<td>P314</td>
<td>Q</td>
</tr>
</tbody>
</table>
SPECIMENS

<table>
<thead>
<tr>
<th>N°</th>
<th>t (s)</th>
<th>P (Bar)</th>
<th>t (s)</th>
<th>P (Bar)</th>
<th>t (s)</th>
<th>P (Bar)</th>
<th>t (s)</th>
<th>P (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 4</td>
<td>0.5</td>
<td>700</td>
<td>0.5</td>
<td>300</td>
<td>0.3</td>
<td>200</td>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>5 - 8</td>
<td>2</td>
<td>700</td>
<td>1</td>
<td>500</td>
<td>1</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 98 Flat specimen injection parameters

Complete filled part

Parts with different injection moulding conditions

Figure 99 Flat specimens
5.4 SOLVENT DEBINDING

One of the most widely used debinding processes consists of two steps: solvent debinding followed by thermal debinding. The moulded part is immersed in a solvent bath to remove the soluble binders first. Then, the solvent-debinded parts are heated to decompose the remaining binder and subsequently sintered.

ELABORATION PROCESS

1) Take weight measures of several parts (green weight)
2) Immerse the moulded parts into the solvent. In our case it is heptane H₃C(CH₂)₅CH₃ or C₇H₁₆ because it is widely applied in laboratories as a totally non-polar solvent. A liquid, it is ideal for transport and storage.
3) Heat the solvent to 50°C using the flow regulator CS LAUDA (view 5.1.3).
4) Agitate the solvent with a magnetic stirrer using the IKAMAG FCT (view 5.1.3).
5) Keep agitation during 5 hours approximately.
6) Extract the parts and take weight measures to compare with the green weight.

It is possible to remove 95% content of stearic acid, paraffin wax and other soluble binders, making easier in this way the further thermal debinding,

The toroids from HES-SO Valais feedstock have been subjected to this treatment. In the figure 100, it is shown the difference between the pre and post solvent sintering. Removing the most of the binder, the part green-strength has been reducing severally because the microfissures have grown a cause of the binder lost.
These microfissures must be avoided by improving both binder composition and injection moulding parameters.

Figure 101 Pre and post solvent debinding specimens
5.5 THERMAL DEBINDING AND SINTERING

FEEDSTOCK: ADVANCED METALWORKING

PART: TOROID

THERMAL CYCLE DESCRIPTION

The following cycle has been provided by Advamet MIM Feedstocks. It describes the dewaxing and debinding temperatures and heating times. It has to be done in nitrogen atmosphere during the dewaxing and debinding to improve the heat transmission. During the sintering it has to be in hydrogen atmosphere to avoid ferrite oxides.

<table>
<thead>
<tr>
<th>Approximate Part Temperature</th>
<th>Heating Rate or Hold Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>R.T</td>
<td>80 °C</td>
</tr>
<tr>
<td>80 °C</td>
<td>200 °C</td>
</tr>
<tr>
<td>200 °C</td>
<td>Hold 30 minutes</td>
</tr>
<tr>
<td>200 °C</td>
<td>240 °C</td>
</tr>
<tr>
<td>240 °C</td>
<td>Hold 30 minutes</td>
</tr>
<tr>
<td>240 °C</td>
<td>310 °C</td>
</tr>
<tr>
<td>310 °C</td>
<td>Hold 30 minutes</td>
</tr>
<tr>
<td>310 °C</td>
<td>360 °C</td>
</tr>
<tr>
<td>310 °C</td>
<td>510 °C</td>
</tr>
<tr>
<td>510 °C</td>
<td>Hold 120 minutes</td>
</tr>
</tbody>
</table>

De-waxing complete
Debinding Complete

<table>
<thead>
<tr>
<th>Approximate Part Temperature</th>
<th>Heating Rate or Hold Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>510 °C</td>
<td>1300 °C</td>
</tr>
<tr>
<td>1300 °C</td>
<td>Hold 120 min</td>
</tr>
<tr>
<td>1300 °C</td>
<td>R.T.</td>
</tr>
</tbody>
</table>

Sintering Complete

Annex V includes cycle graphic and program data. It is important to remark after the debinding step had finished, the furnace detected to alarms caused by...
atmosphere change from nitrogen to hydrogen. The thermal cycle was re-started to times.

POST-SINTERING TOROID SPECIMENS

Figure 104 Post-sintering toroid specimens

POST – SINTERING TOROID PROPERTIES

<table>
<thead>
<tr>
<th>Measure</th>
<th>Green</th>
<th>Post - Sintering</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Diameter (mm)</td>
<td>50.00</td>
<td>41.18</td>
<td>17.64%</td>
</tr>
<tr>
<td>Internal Diameter (mm)</td>
<td>40.00</td>
<td>33.02</td>
<td>17.45%</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>5.00</td>
<td>4.13</td>
<td>17.40%</td>
</tr>
<tr>
<td>Height</td>
<td>5.00</td>
<td>3.90</td>
<td>22.00%</td>
</tr>
<tr>
<td>Density (g/cm3)</td>
<td>4.80</td>
<td>7.65</td>
<td>37.25%</td>
</tr>
<tr>
<td>Volume (cm3)</td>
<td>2.776</td>
<td>1.547</td>
<td>44.27%</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>13.325</td>
<td>11.878</td>
<td>10.86%</td>
</tr>
</tbody>
</table>

Figure 105 Toroid shrinkage

FEEDSTOCK PARAMETERS:

\[ \rho_{\text{Theoretical Fe-\%Si}} = 7.70 \text{g/cm}^3 \]
\[ \rho_{\text{Post-Sintering}} = 7.65 \text{g/cm}^3 \]
\[ \text{Porosity} = 1 - \frac{7.65}{7.7} = 0.65\% \]

Average Lineal Shrinkage = 17.55%
Average Volumetric Shrinkage = 44.27%
SUGGESTED DEBINDING CYCLE FOR COMPLEX PARTS

<table>
<thead>
<tr>
<th>Approximate Part Temperature</th>
<th>Heating Rate or Hold Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>R.T</td>
<td>140 °C</td>
</tr>
<tr>
<td>140 °C</td>
<td>Hold 6 hours</td>
</tr>
<tr>
<td>140 °C</td>
<td>165 °C</td>
</tr>
<tr>
<td>165 °C</td>
<td>Hold 1 Hour</td>
</tr>
<tr>
<td>165 °C</td>
<td>205 °C</td>
</tr>
<tr>
<td>205 °C</td>
<td>Hold 5 Hour</td>
</tr>
</tbody>
</table>

Figure 106: Advamet feedstock debinding cycle
# 6 VIABILITY AND ECONOMIC ANALYSIS

## 6.1 PIM TECHNOLOGY COSTS

### 1. PRODUCTION ECONOMICS AND KEY COST FACTOR

To understand PIM production cost, here it is showed minimal guidelines. As generalization, powder cost ranges from 15 to 50% of manufacturing cost, processing steps (including tool amortization) account for about 50% of product cost, and finishing, inspection and heat treatment steps might add 10 to 50% into the cost. In some cases post − sintering steps can be the most expensive. These values are highly variable with factors that include differences in geography, technology and components.

For parts below about 10 g in mass, powder cost is less of a factor in the piece price, plus there must be profit add 15 to 20% to the price, plus there be profit and tax charges. Combined, these typically add 20 to 35% onto the sale price. Unit cost tends to level out when the production quantity becomes large, but the point of asymptotic cost depends on the component size.

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Percentage Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder Cost</td>
<td>10 – 50%</td>
</tr>
<tr>
<td>Processing</td>
<td>10 – 50%</td>
</tr>
<tr>
<td>Finishing</td>
<td>10 – 50%</td>
</tr>
</tbody>
</table>

\[
C_{\text{MANUFACTURING}} = C_{\text{POWDER}} + C_{\text{PROCESING}} + C_{\text{FINISHING}}
\]

\[
\text{PREVIOUS SALE PRICE} = C_{\text{MANUFACTURING}} + C_{\text{ADMINISTRATION}} + C_{\text{AMORTIZATION}} + C_{\text{SEVERAL}}
\]

\[
C_{\text{ADMINISTRATION}} + C_{\text{AMORTIZATION}} + C_{\text{SEVERAL}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 10 – 15\%
\]

\[
\text{FINAL SALE PRICE} = C_{\text{PREVIOUS}} + C_{\text{PROFIT}} + C_{\text{TAXES}}
\]

\[
C_{\text{ADMINISTRATION}} + C_{\text{AMORTIZATION}} + C_{\text{SEVERAL}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 10 – 15\%\]

\[
\text{PROFIT} + \text{TAXES} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 5 – 15\%
\]

As the component mass increases the cost of PIM powder becomes a problem. Indeed, the barrier to large component production by PIM is economic, not technical. Cost reduction efforts should target components with a high ratio of cost to value, not just large or high cost components.

Normally there are three approaches to cost estimation:
**Ballpark number:** For PIM components, the historical ratio of powder cost to total component fabrication works out to be 32% with a standard deviation of 17%. For smaller components this ratio tends to have lower fraction on powder cost and the opposite for lager components.

Example: Part of 10 g if mass whose powder cost is 14.60€/kg

<table>
<thead>
<tr>
<th>1 Kg</th>
<th>14.60€</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 g</td>
<td>0.15€ / part</td>
</tr>
</tbody>
</table>

Powder Cost Range (smaller parts) 15 – 50 % → 32 % ± 17% → 0.29€/part - 0.97€/part

Adding taxes and profit 35% (roughly) → **Total cost** (0.41€/part – 1.31 €/part)

This indicates is very crude and fails to look at the detail, but it gives a first cost estimate.

**Complex manufacturing estimation:** Usually an 80-90% of the fabrication cost derives from a few difficult aspect or secondary treatment. Taking the Ballpark cost from above, the critical items would be identified and additional cost added to account for greater complexity or deducted for less complexity.

For example thicker sections slow all processing steps and add cost in moulding, debinding and sintering. Roughly, these additional cost scales with the section thickness squared. Of the average PIM component is 10 mm thick, the same mass with 20 mm thickness component would be more costly, since cycle times would be longer, while a 5mm thick component would be less costly. These tend to be 10 to 20% cost corrections.

**Pro-forma accounting:** This cost method report for the production process, detailing all purchases, labour rates, machine use factors and items involved in production. These are site-specific and sensitive to differences in cost allocation.

- In analyzing OIM, a few factors dominate cost:
  - Component mass and powder cost
  - Tooling cost and number of cavities
  - Process yield
  - Component maximum and minimum dimensions
  - Production quantities
  - Post-sintering finishing steps
Since labour is not dominant factor, PIM operations in expensive labour region (Switzerland) versus low labour cost regions (China) are not dramatically different in final cost.

Figure 108 compares the advantages and limitations of various net shape technologies against which PIM routinely competes. The decision of use PIM technologies usually comes from cost, shape, capabilities, productivities and precision. As it is normal, each kind of operation (machining, gridding, drilling, finishing…) increases the PIM advantages and improves its competing. Also the quantity is another key factor to fix the technologies. High production quantities make PIM better alternative respect machining.
2. COST COMPONENTS

- Powder Cost

Powder or feedstock cost involves accounts for up to 50% of the manufacturing cost. Compositions that are popular tend to have lower powder prices. Also the product quantity plays an important role, for example 15 micrometer of stainless steel powder by water atomization goes from 27€/kg at 100 Kg to 11€/kg to 10000Kg. The powder quality or form is another important fact. For example 30 Kg of titanium angular powder have price of 69€/kg however for spherical powder, the cost will increase until 93€/Kg.

It is important also to note that the raw materials cost involves only a minimum part of the final cost. For example for stainless steel, the raw ingredients (iron, nickel, chromium) cost less than 2€/Kg and atomization cost about 1.5€/kg, so the difference reflects a combination of atomization yield (sometimes only 20% of the powder is size range desired for PIM), overhead and profit.

- Tooling Cost

Moulds are obtained from wrought steel or tool steel. Last technologies advances have allowed a decreasing of tool construction to an average of 4 – 6 weeks. It is used the traditional machining, with numerical control, and also the electrical discharge. After machining, it is necessary a heat treatment to achieve the desire hardness.

There are two significant factors impacting in mould cost. The first is about tool complexity. Higher mould cost is associated to holes, bumps, protrusions and more part with close tolerance. The time and cost for tool construction can be estimated based on the following factors:

- Die plate area and thickness
- Number of lifters, threaded parts, slides and side pulls.
- Part area, perimeter and complexity
- Number of holes, bumps, ejector pins and machined depressions.
- Surface finish and tolerances
- Parting line complexity
- Number of cavities
Normally to set an estimation or cost construction, it is used a standard shop factor of 45€/h. Finally, raw material costs are added along with a safety margin, overhead and profit to arrive at the final quotation.

Generally the cost increases with the complexity $(\Psi)$ in a power manner. Complexity $(\Psi)$ depends on tolerances, holes, perimeter to width ratio, perimeter to length ratio, and as well other special features.

\[ C = a \cdot \Psi^{1.27} \]

Tolerances on tooling have a significant impact on cost an empirical index has been isolated bases on the collection of dimensions $d_i$ and their associated tolerances $t_i$ as:

\[ B = \sum \log(d_i / t_i) \]

If multiple cavities are required, then the cost of multiple tools set $C_N$ increases in proportion to the number of cavities $N$ as follows:

\[ C_N = C \cdot N^{0.74} \]

### Moulding Cost

Main necessary parameters to set the moulding costs per part are the cycle time and the number of cavities. Also there is an initial set up cost but once installed the internal operating cost per hour for moulder is a standard rate about 25€/h. This is a combination of machine depreciation, floor space rental, electricity, labour, overhead and profit. To distribute these costs over more components it is desirable to use multiple cavities, producing multiple parts in one single shot.

As the number of cavities increases, the moulding cost decreases but the tool cost increases. Normally the economic transition from single cavity tooling if often in the 100,000 to 300,000 parts per year. Four cavities usually are producing 1 million parts per year.

To decrease moulding costs, it is useful to improve the cooling allowing reduction of the cycle time or obtaining more parts per hour (less moulding cost per part).

Another way to lower moulding costs is to use a hot runner system, where the flow channel in the tool is maintained hot between cycles.
**Debinding Cost**

Debinding cost depends on the system used. For example, thermal debinding cost in function of the atmosphere, but thermal extraction of the binder is most productive. In contrast, catalytic debinding relies on expensive equipment with high operating costs from the following protective atmosphere and environmental controls.

The capital costs of the equipment vary by a factor of ten between **debinding technologies**. If it is necessary to set an environmental approbation, the low emissions system increases the cost. On the other hand, if the debinding occurs with water soluble binder, then the cost is dramatically lower.

**Sintering Cost**

Sintering is the final phase of PIM production and they are around 30€ - 85€ per hour range. The load in the furnace, the cycle time and other factors, set the cost per part. Normally cost are typically in the 6€/Kg which can vary with a factor of five (1€/Kg – 30€/Kg).

To set the furnace design, it must be considered production quantity (from less than 1Kg to 300Kg), material to be sintered, operating cost type of atmosphere and post-sintering cooling rate.

Furnaces are normally around 2-3 m of diameter and typically operate on cycles of 6 – 24 h. Finally the part shape and size another main parameter which can increase cost factor by five.

**Secondary cost**

Often it consider only the direct process costs to set the total cost, but some operations as shipping, secondary treatments (machining, electroplating, heat treatments...), packaging or inspection. It is usually to check each part dimensions and it is an accumulated cost.
6.2 TOOL COST CALCULATIONS

One of the costs more difficult to estimate is tooling cost because it depends on several factors such as shape, complexity, material, work time, labour cost… In the following lines it is explained two different tool costing models developed by two different sources. Also it is developed a third model adapted to HES-SO Valais needs.

1. UNIVERSITY OF RHODE ISLAND TOOL COSTING METHOD

Considerations:

- Standard mould base
- Model is based on toolmaker’s tome at equal weighting for all tasks
- Final cost is calculated from total time and hourly rate
- Number of cavities is determined by bath size, machine rate and cycle time
- No rework or design interactions are included

Mould Base Cost:

\[ C_B = 2 \cdot (40 + 0.45 \cdot A_d \cdot D_d^{0.4}) \]

\( C_B \) [€]: Cost of manufactured mould base including cooling and ejection parts
\( A_d \) [cm²]: Die plate which depends on part and machine.
\( D_d \) [cm]: Combined thickness of die plates which depends on part and machine

Modification: In the original method, the fixed cost is 1000€. However this factor is not valid for HES-SO moulds.

Time to Form Mould Actions:

\( t_s \) [h]: Estimated hours to form each side pull.
\( t_l \) [h]: Estimated hours to form each internal lifter.
\( t_u \) [h]: Estimated hours to form each unscrewing device.

Time to Form Cavity and Core:

Projected area time:

\[ t_{\text{COMPLEXITY}} = 5 + 2.5 \cdot A_P^{0.5} + 0.0085 \cdot A_P^{1.2} \]
$t_A$ [h]: Machining time associated with cutting the projected area.
$A_p$ [cm²]: Projected area of part perpendicular to the direction of mould opening

**Geometric Complexity Time:**

$$t_G = (C_I + C_O)^{1.27}$$

$t_G$ [h]: Manufacturing time associated with the geometric features of the part.

$$C_I = 0.01 \cdot N_S + 0.04 \cdot N_H$$

$$C_O = 0.01 \cdot N_S + 0.04 \cdot N_H$$

$C_I$ [dimensionless]: Inner complexity of the part.
$C_O$ [dimensionless]: Outer complexity of the part.
$N_S$ [integer]: Number of surface protrusions, bumps or patches.
$N_H$ [integer]: Number of holes or depressions.

**Parting Plane Time:**

$$t_p = F_p \cdot A_p^{0.5}$$

$t_p$ [h]: Time to manufacture the parting plane.
$A_p$ [cm²]: Projected area of part perpendicular to the direction of mould opening.
$F_p$ [dimensionless]: Factor depending on the type of curvature:

<table>
<thead>
<tr>
<th>Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat parting plane</td>
<td>0.0</td>
</tr>
<tr>
<td>Single step or angle</td>
<td>1.3</td>
</tr>
<tr>
<td>2 to 4 steps</td>
<td>2.0</td>
</tr>
<tr>
<td>over 4 steps</td>
<td>2.5</td>
</tr>
<tr>
<td>Complex Curve</td>
<td>3.0</td>
</tr>
<tr>
<td>Steps and Curve</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Tolerance Time:**

$$t_T = F_T \cdot t_p$$

$t_T$ [h]: Manufacturing time associated with the required tolerances.
$t_p$ [h]: Time to manufacture the parting plane.
$F_T$ [dimensionless]: Tolerance Factor

$$F_T = 0.0167 / T_R$$

where

$$T_R = (\pi T_i)^{1/m}$$

$T_R$ [mm]: Root-mean of the +/- tolerances.
ΠTI [integer]: Indicate the product of the +/- tolerances (multiply all m tolerances times each other)
m [integer]: Number of tolerances

Surface finish time:

\[ t_F = F_F \cdot (t_A + t_G) \]

\( t_F \) [h]: Time associated with surface finishing
\( t_A \) [h]: Time associated with the projected area as calculated above
\( t_G \) [h]\( T_R \) [mm]: Manufacturing time associated with the geometric features of the part
\( F_F \) [dimensionless]: Surface finish factor

\[ F_F = 0.125 + \frac{0.06}{R_s} \]

\( R_s \) [μm]: Surface roughness specified on the tooling

Cumulative Mould Cost:

\[ C_T = C_I \cdot N_c^{0.74} \]

\( C_T \) [€]: Cumulative mould cost for a multiple cavity mould
\( C_I \) [€]: Single cavity mould cost
\( N_c \) [Integer]: Cavities number

\[ C_T = C_B + R \cdot (t_S + t_L + t_U + t_A + t_T + t_G + t_F + t_P) \]

\( R \) [€/h]: Toolmaker's hourly rate for mould fabrication

Mould Price

\[ C_P = C_T \cdot \frac{1+C_A}{1-P} \]

\( C_P \) [€]: Price of the mould to the customer
\( C_T \) [€]: Cumulative mould cost for a multiple cavity mould
\( C_A \) [dimensionless]: Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2
\( P \) [dimensionless]: Target profit per job (0.05 - 0.4) usually 0.07
### TOROID MOULD COST

#### UNIVERSITY OF RHODE ISLAND METHOD

<table>
<thead>
<tr>
<th>Mould Base Cost</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB [€]</td>
<td>336.51</td>
<td>CHF 502.26</td>
</tr>
<tr>
<td>Ad [cm²]</td>
<td></td>
<td>216.00</td>
</tr>
<tr>
<td>Dd [cm]</td>
<td></td>
<td>2.00</td>
</tr>
</tbody>
</table>

#### Time to Form Mould Actions

| ts [h] | Estimated time to form each side pull | 0 |
| tl [h] | Estimated time to form each internal lifter | 0 |
| tu [h] | Estimated time to form each unscrewing device | 0 |

#### Time to Form Cavity and Core

**Projected Area Time**

| tA [h] | Machining time associated with cutting the projected area | 12.38 |
| Ap [cm²] | Projected area of part perpendicular to the direction of mould opening | 8.47 |

**Geometric Complexity Time**

| tG [h] | Manufacturing time associated with the geometric features of the part | 4.39 |
| CI [dimensionless] | Inner complexity of the part | 0 |
| Ns [integer] | Number of surface protrusions, bumps or patches | 0 |
| Nh [integer] | Number of holes or depressions | 0 |
| Co [dimensionless] | The outer complexity of the part | 0.16 |
| Ns [integer] | Number of surface protrusions, bumps or patches | 0 |
| Nh [integer] | Number of holes or depressions | 4 |

#### Parting Plane time

| tp [h] | Time to manufacture the parting plane | 0.00 |
| Ap [cm²] | Projected area of part perpendicular to the direction of mould opening | 8.47 |

| Fp [dimensionless] | Factor depending on the type of curvature | 0 |
|                   | Flat parting plane | 0.0 |
|                   | Single step or angle | 1.3 |
|                   | 2 to 4 steps | 2.0 |
|                   | over 4 steps | 2.5 |
|                   | Complex Curve | 3.0 |
### Tolerance Time

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tT [h]</td>
<td>Manufacturing time associated with the required tolerances</td>
<td>0.00</td>
</tr>
<tr>
<td>tp [h]</td>
<td>Time to manufacture the parting plane</td>
<td>0.00</td>
</tr>
<tr>
<td>FT [dimension less]</td>
<td>Tolerance Factor</td>
<td>0.02</td>
</tr>
<tr>
<td>TR [mm]</td>
<td>Root-mean of the +/- tolerances</td>
<td>0.822</td>
</tr>
<tr>
<td>ΠT₁ [integer]:</td>
<td>indicate the product of the +/- tolerances (multiply all m tolerances times each other)</td>
<td>0.020</td>
</tr>
<tr>
<td>m [integer]</td>
<td>Number of tolerances</td>
<td>20</td>
</tr>
</tbody>
</table>

### Surface finish time

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tF [h]</td>
<td>Associated with surface finishing</td>
<td>2.15</td>
</tr>
<tr>
<td>tA [h]</td>
<td>Associated with the projected area as calculated above</td>
<td>12.4</td>
</tr>
<tr>
<td>tG [h]</td>
<td>Manufacturing time associated with the geometric features of the part</td>
<td>4.39</td>
</tr>
<tr>
<td>FF [dimensionless]</td>
<td>Surface finish factor</td>
<td>0.13</td>
</tr>
<tr>
<td>Rs [μm]</td>
<td>Surface roughness specified on the tooling</td>
<td>20</td>
</tr>
</tbody>
</table>

### Cumulative Mould Cost

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT [€]</td>
<td>Cumulative mould cost for a multiple cavity mould</td>
<td>1'226 €</td>
</tr>
<tr>
<td>CI [€]</td>
<td>Cost of a single cavity Mould</td>
<td>1'226 €</td>
</tr>
<tr>
<td>Nc [Integer]</td>
<td>Number of cavities</td>
<td>1</td>
</tr>
<tr>
<td>R [€/h]</td>
<td>Toolmaker's hourly rate for mould fabrication</td>
<td>€ 47.00</td>
</tr>
<tr>
<td>Total Time [h]</td>
<td>Total Time cost manufacturing</td>
<td>18.92</td>
</tr>
</tbody>
</table>

### Mould Price

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP [€]</td>
<td>Price of the mould to the customer</td>
<td>1'226 €</td>
</tr>
<tr>
<td>CT [€]</td>
<td>Cumulative mould cost for a multiple cavity mould</td>
<td>1'226 €</td>
</tr>
<tr>
<td>CA [dimensionless]</td>
<td>Fixed administrative cost, interest rates, amortized (0,2 to 0,4) usually 0,2</td>
<td>0</td>
</tr>
<tr>
<td>P [dimensionless]</td>
<td>Target profit per job (0,05 - 0,4) usually 0,07</td>
<td>0</td>
</tr>
</tbody>
</table>

### COST %

<table>
<thead>
<tr>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td>336.51 %</td>
</tr>
<tr>
<td>Labour cost</td>
<td>889.29 %</td>
</tr>
<tr>
<td>TOTAL MOULD COST</td>
<td>1'225.80 €</td>
</tr>
<tr>
<td>Material %</td>
<td>27.45%</td>
</tr>
<tr>
<td>Labour %</td>
<td>72.55%</td>
</tr>
<tr>
<td>TOTAL MOULD COST</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Figure 109 Toroid mould cost calculated by University of Rhode Island method.
DOUBLE CAVITY MOULD COST

UNIVERSITY OF RHODE ISLAND METHOD

<table>
<thead>
<tr>
<th>Description</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mould Base Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB [€] Cost of manufactured mould base including cooling and ejection parts</td>
<td>336.51</td>
<td>CHF 502.26</td>
</tr>
<tr>
<td>Ad [cm²] Die plate which depends on part and machine.</td>
<td>216.00</td>
<td></td>
</tr>
<tr>
<td>Dd [cm] Combined thickness of die plates which depends on part and machine</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td><strong>Time to Form Mould Actions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ts [h] Estimated hours to form each side pull</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>tl [h] Estimated hours to form each internal lifter</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>tu [h] Estimated hours to form each unscrewing device</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Time to Form Cavity and Core</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projected Area Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tA [h] Machining time associated with cutting the projected area</td>
<td>13.63</td>
<td></td>
</tr>
<tr>
<td>Ap [cm²] Projected area of part perpendicular to the direction of mould opening</td>
<td>11.48</td>
<td></td>
</tr>
</tbody>
</table>

Miguel A. Enríquez Baranda
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tG [h]</td>
<td>Manufacturing time associated with the geometric features of the part</td>
<td>10.59</td>
</tr>
<tr>
<td>CI [dimensionless]</td>
<td>Inner complexity of the part</td>
<td>0</td>
</tr>
<tr>
<td>Ns [integer]</td>
<td>Number of surface protrusions, bumps or patches</td>
<td>0</td>
</tr>
<tr>
<td>Nh [integer]</td>
<td>Number of holes or depressions</td>
<td>0</td>
</tr>
<tr>
<td>Co [dimensionless]</td>
<td>The outer complexity of the part</td>
<td>0.32</td>
</tr>
<tr>
<td>Ns [integer]</td>
<td>Number of surface protrusions, bumps or patches</td>
<td>0</td>
</tr>
<tr>
<td>Nh [integer]</td>
<td>Number of holes or depressions</td>
<td>8</td>
</tr>
<tr>
<td>Parting Plane time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tp [h]</td>
<td>Time to manufacture the parting plane</td>
<td>0.00</td>
</tr>
<tr>
<td>Ap [cm²]</td>
<td>Projected area of part perpendicular to the direction of mould opening</td>
<td>11.48</td>
</tr>
<tr>
<td>Fp [dimensionless]</td>
<td>Factor depending on the type of curvature</td>
<td>0</td>
</tr>
<tr>
<td>Flat parting plane</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Single step or angle</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>2 to 4 steps</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>over 4 steps</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Complex Curve</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Steps and Curve</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>Tolerance Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tT [h]</td>
<td>Manufacturing time associated with the required tolerances</td>
<td>0.00</td>
</tr>
<tr>
<td>tp [h]</td>
<td>Time to manufacture the parting plane</td>
<td>0.00</td>
</tr>
<tr>
<td>FT [dimensionless]</td>
<td>Tolerance Factor</td>
<td>0.02</td>
</tr>
<tr>
<td>TR [mm]</td>
<td>Root-mean of the +/- tolerances</td>
<td>0.822</td>
</tr>
<tr>
<td>(\prod T_i) [integer]:</td>
<td>indicate the product of the +/- tolerances (multiply all m tolerances times each other)</td>
<td>0.020</td>
</tr>
<tr>
<td>m [integer]</td>
<td>Number of tolerances</td>
<td>20</td>
</tr>
<tr>
<td>Surface finish time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tF [h]</td>
<td>Associated with surface finishing</td>
<td>3.10</td>
</tr>
<tr>
<td>tA [h]</td>
<td>Associated with the projected area as calculated above</td>
<td>13.6</td>
</tr>
<tr>
<td>tG [h]</td>
<td>Manufacturing time associated with the geometric features of the part</td>
<td>10.59</td>
</tr>
<tr>
<td>FF [dimensionless]</td>
<td>Surface finish factor</td>
<td>0.13</td>
</tr>
<tr>
<td>Rs [μm]</td>
<td>Surface roughness specified on the tooling</td>
<td>20</td>
</tr>
<tr>
<td>Cumulative Mould Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT [€]</td>
<td>Cumulative mould cost for a multiple cavity mould</td>
<td>1'620 €</td>
</tr>
<tr>
<td>CHF</td>
<td></td>
<td>2'418</td>
</tr>
</tbody>
</table>
Final Project of Industrial Engineering
«Design and manufacturing of complex moulds for powder injection moulding»

| CI [€] | Cost of a single cavity Mould | 1'620 € | CHF 2'418 |
| Nc [Integer] | Number of cavities | 1 |
| R [€/h] | Toolmaker’s hourly rate for mould fabrication | € 47.00 | CHF 70 |
| Total Time [h] | Total Time cost manufacturing | 27.31 |

**Mould Price**

| CP [€] | Price of the mould to the customer | 1'620 € | CHF 2'418 |
| CT [€] | Cumulative mould cost for a multiple cavity mould | 1'620 € | CHF 2'418 |
| CA [dimensionless] | Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2 | 0 |
| P [dimensionless] | Target profit per job (0.05 - 0.4) usually 0.07 | 0 |

**CUSTOMER PRICE**

| COST % |
| Material Cost | 336.51 € |
| Labour cost | 1'283.77 € |
| **TOTAL MOULD COST** | 1'620.28 € |
| Material % | 20.77% |
| Labour % | 79.23% |
| **TOTAL MOULD COST** | 100.00% |

Figure 112 Double Cavity mould cost by University of Rhode Island method

Figure 113 Double Cavity mould cost by University of Rhode Island method

Figure 114 Double Cavity mould cost % by University of Rhode Island method
2. **BOOTHROYD, DEWHURST AND KNIGHT TOOL COSTING METHOD**

This tooling cost model was developed for less complicated shapes without slides, moving pieces, inserts, or unscrewing portions and single cavity moulds. It is especially useful for tools used in die stamping of sheet metal, but provides a lower-bound cost estimate for simple PIM tools.

**Basic Die Cost Estimate:**

\[ C_D = 255 + 0.36 \cdot A_D \]

*C_D [€]: Die Cost
*A_D [cm²]: Die Area

*Modification: In the original method, the fixed cost is 120€. However this factor is not valid for HES-SO moulds.*

**Time to Form Mould Actions:**

\[ t_C = 30 + 0.56 \cdot X_p^{2/3} \]

*t_c [h]: Time to manufacture the profile based on the complexity
*X_p [dimensionless]: Complexity of the part

\[ X_p = (P / L) \cdot (P / W) \]

*P [cm]: Profile perimeter
*L [cm]: Length of the object
*W [cm]: Width of the object

*Note: Width parameter modifications cause several differences of final cost, therefore it can be considered as a not reliable factor.*

**Frontal Area Size Correction Factor:**

\[ F_S = 1 + 0.0276 \cdot L \cdot W \cdot X_p^{0.093} \]

*F_S [dimensionless]: Correction Factor for the size
*X_p [dimensionless]: Complexity of the part
*L [cm]: Length of the object
*W [cm]: Width of the object

**Thickness Correction Factor:**

\[ F_D = 0.25 + 0.02 \cdot F_T \]
FD [dimensionless]: Correction Factor for the tool thickness  
FT [dimension less]: Correction Factor to account for die life

\[ F_T = 0.5 + 0.025 \cdot V \cdot h^2 \cdot \ln \frac{\sigma}{\sigma_u} \]

V [integer]: Required production volume in number of shots  
h [cm]: Thickness of the body being formed  
\( \sigma/\sigma_u \) [dimensionless]: Ratio of peak stress as a ratio to the tool strength

Note: \( \sigma/\sigma_u \) parameter modifications cause several differences of final cost, therefore it can be considered as a not reliable factor.

Total Mould Fabrication Hours:

\[ t_T = t_c \cdot F_D \cdot F_S \]

t_T [h]: Total time to fabricate the mould  
t_c [h]: Time to manufacture the profile based on the complexity  
FD [dimensionless]: Correction Factor for the tool thickness  
FS [dimensionless]: Correction Factor to account for die life

Cumulative Mould Cost:

\[ C_T = C_D + t_T \cdot R \]

CT [€]: Is cumulative mould cost for a multiple cavity mould  
CD [€]: Die Cost  
t_T [h]: Total time to fabricate the mould  
R [€/h]: Toolmaker's hourly rate for mould fabrication

Mould Price

\[ C_P = C_T \cdot \frac{1 + C_A}{1 - P} \]

CP [€]: Price of the mould to the customer  
CT [€]: Cumulative mould cost for a multiple cavity mould  
CA [dimensionless]: Fixed administrative cost, interest rates, amortized (0,2 to 0,4) usually 0,2  
P [dimensionless]: Is target profit per job (0,05 - 0,4) usually 0,07

<table>
<thead>
<tr>
<th>TOROID MOULD COST</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BOOTHROYD, DEWHURST and KNIGHT MODEL</strong></td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td><strong>Basic Die Cost Estimate</strong></td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>
### Final Project of Industrial Engineering

« Design and manufacturing of complex moulds for powder injection moulding »

<table>
<thead>
<tr>
<th>CD [€]</th>
<th>Die Cost</th>
<th>332.76 €</th>
<th>CHF 496.66</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD [cm²]</td>
<td>Die Area</td>
<td>216.00</td>
<td></td>
</tr>
</tbody>
</table>

#### Time to Form Cavity and Core

| tc [h] | Time to manufacture the profile based on the complexity | 41.35 |
| Xp [dimensionless]| Complexity of the part | 91.20 |
| P [cm] | Profile perimeter | 25.39 |
| L [cm] | Length of the object | 14.14 |
| W [cm] | Width of the object | 0.50 |

#### Frontal Area Size Correction Factor

| FS [dimensionless]| Correction Factor for the size | 1.30 |
| L [cm] | Length of the object | 14.14 |
| W [cm] | Width of the object | 0.5 |
| Xp [dimensionless]| Complexity of the part | 91.20 |

#### Thickness Correction Factor

| FD [dimensionless]| Correction Factor for the tool thickness | -0.64 |
| FT [dimension less]| Correction Factor to account for die life | -56.77 |
| V [integer] | Required production volume in number of shots | 10000 |
| h [cm] | Thickness of the body being formed | 0.50 |
| σ/σu [dimensionless]| Ratio of peak stress as a ratio to the tool strength | 0.40 |

#### Total Mould Fabrication Hours

| tT [h] | Total time to fabricate the mould | 34.07 |
| tc [h] | Time to manufacture the profile based on the complexity | 41.35 |
| FD [dimensionless]| Correction Factor for the tool thickness | 0.64 |
| FS [dimensionless]| Correction Factor to account for die life | 1.30 |

#### Cumulative Mould Cost

| CT [€] | Cumulative mould cost for a multiple cavity mould | 1'934 € | CHF 2'886 |
| CD [€] | Die Cost | 333 € | CHF 497 |
| R [€/h]| Toolmaker’s hourly rate for mould fabrication | € 47.00 | CHF 70 |
| tT [h] | Total time to fabricate the mould | 34.07 |

#### Mould Price

| CP [€] | Price of the mould to the customer | 1'934 € | CHF 2'886 |
| CT [€] | Cumulative mould cost for a multiple cavity mould | 1'934 € | CHF 2'886 |
| CA [dimensionless]| Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2 | 0 |
| P [dimensionless]| Target profit per job (0.05 - 0.4) usually 0.07 | 0 |

**CUSTOMER PRICE** | 1'934 € | CHF 2'886 |
COST %

<table>
<thead>
<tr>
<th></th>
<th>Material Cost</th>
<th>Labour Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>332.76 €</td>
<td>0 €</td>
<td></td>
</tr>
<tr>
<td>1'601.19 €</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL MOULD COST</td>
<td>1'933.95 €</td>
<td></td>
</tr>
</tbody>
</table>

Material % 17.21%
Labour % 82.79%
TOTAL MOULD COST 100.00%

Figure 115 Toroid mould cost by Boothroyd, Dewhurst and Knight method

Figure 116 Toroid mould cost by Boothroyd, Dewhurst and Knight method

Figure 117 Toroid mould cost % by Boothroyd, Dewhurst and Knight method

DOUBLE CAVITY MOULD COST

<table>
<thead>
<tr>
<th>BOOTHROYD, DEWHURST and KNIGHT MODEL</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Die Cost Estimate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD[€]</td>
<td>Die Cost</td>
<td>332.76 €</td>
</tr>
<tr>
<td>AD [cm²]</td>
<td>Die Area</td>
<td>216.00</td>
</tr>
</tbody>
</table>

Time to Form Cavity and Core
### Time to manufacture the profile based on the complexity

<table>
<thead>
<tr>
<th>tc [h]</th>
<th>Time to manufacture the profile based on the complexity</th>
<th>46.49</th>
</tr>
</thead>
</table>

### Complexity of the part

| Xp [dimensionless] | Complexity of the part | 159.79 |

### Profile perimeter

| P [cm] | Profile perimeter | 27.01 |

### Length of the object

| L [cm] | Length of the object | 7.74 |

### Width of the object

| W [cm] | Width of the object | 0.59 |

### Correction Factor for the size

| FS [dimensionless] | Correction Factor for the size | 1.20 |

### Length of the object

| L [cm] | Length of the object | 7.74 |

### Width of the object

| W [cm] | Width of the object | 0.59 |

### Complexity of the part

| Xp [dimensionless] | Complexity of the part | 159.79 |

### Correction Factor for the tool thickness

| FD [dimensionless] | Correction Factor for the tool thickness | -0.32 |

### Required production volume in number of shots

| V [integer] | Required production volume in number of shots | 10000 |

### Thickness of the body being formed

| h [cm] | Thickness of the body being formed | 0.43 |

### Ratio of peak stress as a ratio to the tool strength

| α/ν [dimensionless] | Ratio of peak stress as a ratio to the tool strength | 0.40 |

### Time to fabricate the mould

<table>
<thead>
<tr>
<th>tc [h]</th>
<th>Time to manufacture the profile based on the complexity</th>
<th>46.49</th>
</tr>
</thead>
</table>

### Correction Factor to account for die life

| FT [dimensionless] | Correction Factor to account for die life | -40.88 |

### Total time to fabricate the mould

| tT [h] | Total time to fabricate the mould | 17.74 |

### Mould fabrication costs

| CT [€] | Cumulative mould cost for a multiple cavity mould | 1'167 € | CHF 1'741 |
|--------|--------------------------------------------------------|-------|
| CD [€] | Die Cost | 333 € | CHF 497 |

### Toolmaker's hourly rate for mould fabrication

| R [€/h] | Toolmaker's hourly rate for mould fabrication | € 47.00 | CHF 70 |

### Cumulative mould cost

| tT [h] | Total time to fabricate the mould | 17.74 |

### Price of the mould to the customer

| CP [€] | Price of the mould to the customer | 1'167 € | CHF 1'741 |

### Cumulative mould cost for a multiple cavity mould

| CT [€] | Cumulative mould cost for a multiple cavity mould | 1'167 € | CHF 1'741 |

### Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2

| CA [dimensionless] | Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2 | 0 |

### Target profit per job (0.05 - 0.4) usually 0.07

| P [dimensionless] | Target profit per job (0.05 - 0.4) usually 0.07 | 0 |

### Total cost

| CUSTOMER PRICE | 1'166 € | CHF 1'741 |

| COST % | Material Cost | 332.76 € |
Labour cost | 833.95 €
---|---
TOTAL MOULD COST | 1,166.71 €
Material % | 28.52%
Labour % | 71.48%
TOTAL MOULD COST | 100.00%

Figure 118 Double Cavity cost by Boothroyd, Dewhurst and Knight method

Figure 119 Double Cavity mould cost by Boothroyd, Dewhurst and Knight method

Figure 120 Double Cavity mould cost % by Boothroyd, Dewhurst and Knight method
3. HES-SO VALAIS TOOL COSTING METHOD

The methods explained above are conceived to give an estimated cost, for industry moulds with several cavities, mobile elements, protrusions, bumps or patches. This complexity form produces difficult to set a reliable cost method.

To avoid this problem and give the possibility to estimated the mould cost before its manufacturing, in the following part it is development an own cost method, adapted to HES-SO Valais kind of moulds, machines and possibilities.

Considerations:

- Complete mould includes: fix, mobile and ejector plaque.
- This model simplifies the different kinds of machining and its complexity.
- No design costs consider.
- No milling cutters or other accessories for machining cost are considered.
- No logistic, inspection, extra movements cost are considered.
- No mobile parts and extra-tool are considered.
- No profit and administrative cost are included.

Total Cost:

\[ C_{\text{TOTAL}} = C_{\text{MATERIAL}} + C_{\text{LABOUR}} \]

Material Cost:

\[ C_{\text{MATERIAL}} = C_{\text{PLATES}} + C_{\text{EJECTORS}} \]

- \( C_{\text{MATERIAL}} \) [€]: Total Material Cost
- \( C_{\text{PLATES}} \) [€]: Total plates cost
- \( C_{\text{EJECTORS}} \) [€]: Total ejector cost

Plates Cost

\[ C_{\text{PLATES}} = C_{\text{FIX}} + C_{\text{MOBILE}} + C_{\text{EJECTOR}} \]

- \( C_{\text{FIX}} \) [€]: Fix plate rectified cost
- \( C_{\text{MOBILE}} \) [€]: Mobile plate rectified cost
- \( C_{\text{EJECTOR}} \) [€]: Ejectors plate rectified cost

Note:
Cost of mobile and fix plates, with 216 cm² of surface and 2 cm of height, about 350€. (500 CHF).
Cost of ejector plate, about 65€ (100 CHF)
Ejectors Cost:

\[ C_{EJECTORS} = C_{UNIT} \cdot n + C_{2UNIT} \cdot n + ... + C_{nUNIT} \cdot n \]

- \( C_{UNIT} \) [€]: Unit cost of each type of ejector.
- \( n \) [integer]: Number of ejector of each type.

Note:
Ejector average cost about 3 – 6€ (4.5 – 8 CHF)

Labour Cost:

\[ C_{LABOUR} = C_{UNIT} \cdot (T_{SETUP} + T_{FIX-MOBILE} + T_{EJECTORS}) \]

- \( C_{LABOUR} \) [€]: Total labour cost
- \( C_{UNIT} \) [€/h]: Toolmaker's hourly rate for mould fabrication
- \( T_{SETUP} \) [h]: Setting up and maintenance time (average)
- \( T_{FIX-MOBILE} \) [h]: Total time fix and mobile plates
- \( T_{EJECTORS} \) [h]: Total time ejector plate

Fix-Mobile Plates Cost:

\[ t_{FIX-MOBILE} = t_{BASE} + t_{COMPLEXITY} \]

- \( t_{FIX-MOBILE} \) [h]: Time to machining chamfered corners and main holes (4 screws + 2 positions) to fix and mobile plaque (About 5h)
- \( t_{BASE} \) [h]: Time associated to part and runner machining, to obtain this value it is necessary use a parameter that includes the main mould complexity characteristics: Perimeter, length and width.
- \( t_{COMPLEXITY} \) [h]: Time to machining chamfered corners and main holes (4 screws + 2 positions) to fix and mobile plaque (About 5h)

- \( X_{p} \) [dimensionless]: Complexity of the part

\[ X_{p} = \left( \frac{P}{L} \right) \cdot \left( \frac{P}{W} \right) \]

- \( P \) [cm]: Profile perimeter
- \( L \) [cm]: Length of the object
- \( W \) [cm]: Width of the object

To calculate a valid equation to obtain the complexity time using parameter \( X_{p} \), it is necessary to interpolate with the known data of our manufactured moulds.
Final Project of Industrial Engineering
«Design and manufacturing of complex moulds for powder injection moulding»

<table>
<thead>
<tr>
<th>HISTORICAL MOULDS COSTS</th>
<th>DOUBLE</th>
<th>TOROID</th>
<th>FLEXION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERIMETER [cm]</td>
<td>54.02</td>
<td>50.78</td>
<td>14.26</td>
</tr>
<tr>
<td>LENGTH [cm]</td>
<td>7.74</td>
<td>14.14</td>
<td>5.00</td>
</tr>
<tr>
<td>WIDTH [cm]</td>
<td>0.59</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>TIME [h]</td>
<td>10.00</td>
<td>7.50</td>
<td>5.00</td>
</tr>
<tr>
<td>XP (P/L)*(P/W)</td>
<td>639.14</td>
<td>364.81</td>
<td>101.62</td>
</tr>
<tr>
<td>VOLUME</td>
<td>9.76</td>
<td>8.47</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Figure 121 Historical moulds costs

\[
\frac{639.14 - 101.62}{10 - 5} = \frac{639.14 - P}{10 - t_{\text{COMPLEXITY}}}
\]

\[
t_{\text{COMPLEXITY}} = 10 - \frac{639.14 - P}{639.14 - 101.62} = 10 - \frac{639.14 - P}{107.51} = 10 - 5.95 + \frac{P}{107.51}
\]

\[
t_{\text{COMPLEXITY}} = 4.05 + \frac{P}{107.51}
\]

Note: \( t_{\text{COMPLEXITY}} \) equation changes if the parameter \( P \) of the new mould is bigger than 639.14.

Ejector Plate Cost:

\[
t_{\text{EJECTORS}} = t_{\text{BASE}} + t_{\text{EJECTOR}} \cdot n + t_{\text{CUT}} \cdot n
\]

\( T_{\text{BASE}} \) [h]: Time to machining chamfered corners and main holes (4 screws + 2 positions) to fix and mobile plaque

\( T_{\text{EJECTOR}} \) [h]: Time associated to drill one ejector (about 0,4h)

\( n \) [integer]: Total Number of ejectors

\( T_{\text{CUT}} \) [h]: Time associated to cut each ejector (about 0,2h)

Mould Price

\[
C_p = C_{\text{TOTAL}} \cdot \frac{1 + C_A}{1 - P}
\]

\( C_p \) [€]: Price of the mould to the customer

\( C_A \) [dimensionless]: Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2

\( P \) [dimensionless]: Target profit per job (0.05 - 0.4) usually 0.07

Accessories

In this method it is included a specific extra-cost for accessories. It is calculated in base to the number of labour hours and material cost.
## TOROID MOULD COST

<table>
<thead>
<tr>
<th>HES-SO VALAIS METHOD</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cm[€]</td>
<td>416.67</td>
<td>625.00</td>
</tr>
<tr>
<td><strong>Fix and Mobile Plates Cost (Rectified)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cfix-mobile[€]</td>
<td>333.33</td>
<td>500.00</td>
</tr>
<tr>
<td><strong>Ejector Plate Cost (Common Steel)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cejector[€]</td>
<td>66.67</td>
<td>100.00</td>
</tr>
<tr>
<td><strong>Ejectors Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cejectors[€]</td>
<td>16.67</td>
<td>25.00</td>
</tr>
<tr>
<td>Nejector[integer]</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>Ceject.averag[€]</td>
<td>3.33</td>
<td>5.00</td>
</tr>
</tbody>
</table>

### Labour Cost

<table>
<thead>
<tr>
<th>Labour cost</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lc[€]</td>
<td>825.91</td>
<td>1'238.87</td>
</tr>
<tr>
<td>Lcph[€/h]</td>
<td>46.67</td>
<td>70.00</td>
</tr>
</tbody>
</table>

| Total manufacturing time | 17.70 |

### Fixed Times

| Setting up and maintenance time (average) | 0.25 |

### Fix and Mobile Plates Time Manufacturing

| Total manufacturing of fix and mobile plate | 12.45 |
| Time to machining chamfered corners and main holes (4 screws + 2 positions) | 5.00 |
| Time associated to part and runner machining | 7.45 |
| Complexity of the part | 364.81 |
| Parts+Runner+Accessories perimeter (both plates) | 50.78 |
| Average length of the part | 14.14 |
| Average width of the part | 0.50 |

### Ejector Plate Time Manufacturing

| Total time manufacturing of ejector | 5.00 |
### Time to Machining

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tejecbase[h]</td>
<td>2.00</td>
</tr>
<tr>
<td>Tejeccomplexity[h]</td>
<td>2.00</td>
</tr>
<tr>
<td>Tsinglecut[h]</td>
<td>0.40</td>
</tr>
</tbody>
</table>

### Time to Drilling Ejectors Holes

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nejector[integer]</td>
<td>5.00</td>
</tr>
</tbody>
</table>

### Time to Cut Ejector

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nejector[integer]</td>
<td>5.00</td>
</tr>
<tr>
<td>Tsinglecut[h]</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Cumulative Mould Cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cm[€] Material Cost</td>
<td>417 €</td>
</tr>
<tr>
<td>Clabour [€] Total Labour Cost</td>
<td>826 €</td>
</tr>
</tbody>
</table>

### Accessories Cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP [€] Valve Cost Price</td>
<td>- €</td>
</tr>
<tr>
<td>T [h] Time to manufacture the valve</td>
<td>-</td>
</tr>
<tr>
<td>Material Cost</td>
<td>Material cost</td>
</tr>
</tbody>
</table>

### Mould Price

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP [€] Price of the mould to the customer</td>
<td>1’243 €</td>
</tr>
<tr>
<td>CT [€] Cumulative mould cost for a multiple cavity mould</td>
<td>1’243 €</td>
</tr>
<tr>
<td>CA [dimensionless] Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2</td>
<td></td>
</tr>
<tr>
<td>P [dimensionless] Target profit per job (0.05 - 0.4) usually 0.07</td>
<td></td>
</tr>
</tbody>
</table>

**CUSTOMER PRICE** 1’243 €  CHF 1’864

### COST % G

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>416.67 €</td>
</tr>
<tr>
<td>Labour</td>
<td>825.91 €</td>
</tr>
<tr>
<td>Accessories</td>
<td>- €</td>
</tr>
<tr>
<td><strong>TOTAL MOULD COST</strong></td>
<td>1’242.58 €</td>
</tr>
</tbody>
</table>

**Material %** 33.53%

**Labour %** 66.47%

**Accessories %** 0.00%

**TOTAL MOULD COST** 100.00%

---

Figure 122 Toroid mould cost by HES-SO method

---

Miguel A. Enríquez Baranda
### DOUBLE CAVITY MOULD COST

<table>
<thead>
<tr>
<th>HES-SO VALAIS METHOD</th>
<th>€</th>
<th>CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cm[€]</td>
<td>Material Cost</td>
<td>416.67 €</td>
</tr>
<tr>
<td><strong>Fix and Mobile Plates Cost (Rectified)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cfix-mobile [€]</td>
<td>Fix and mobile plate cost rectified (both)</td>
<td>333.33 €</td>
</tr>
<tr>
<td><strong>Ejector Plate Cost (Common Steel)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C ejector[€]</td>
<td>Ejector plate Cost</td>
<td>66.67 €</td>
</tr>
<tr>
<td><strong>Ejectors Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C ejectors[€]</td>
<td>Ejector plate</td>
<td>16.67 €</td>
</tr>
<tr>
<td>Nejector[integer]</td>
<td>Total number of pin ejector</td>
<td>5.00</td>
</tr>
<tr>
<td>Ceject.averag[€]</td>
<td>Average ejectors cost (8 mm = 8 CHF, 6 mm = 6 CHF)</td>
<td>3.33 €</td>
</tr>
<tr>
<td><strong>Labour Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lc [€]</td>
<td>Labour cost</td>
<td>945 €</td>
</tr>
<tr>
<td>Lcph [€/h]</td>
<td>Toolmaker’s hourly rate for mould fabrication</td>
<td>46.67 €</td>
</tr>
</tbody>
</table>
### Final Project of Industrial Engineering

**Design and manufacturing of complex moulds for powder injection moulding**

<table>
<thead>
<tr>
<th>Ttotal [h]</th>
<th>Total manufacturing time</th>
<th>20.25</th>
</tr>
</thead>
</table>

#### Fixed Times

<table>
<thead>
<tr>
<th>tsetup [h]</th>
<th>Setting up and maintenance time (average)</th>
<th>0.25</th>
</tr>
</thead>
</table>

#### Fix and Mobile Plates Time Manufacturing

<table>
<thead>
<tr>
<th>tmobile and fix[h]</th>
<th>Total time manufacturing of fix and mobile plate</th>
<th>15.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>tfmbase[h]</td>
<td>Time to machining chamfered corners and main holes (4 screws + 2 positions)</td>
<td>5.00</td>
</tr>
<tr>
<td>tgeometric [h]</td>
<td>Time associated to part and runner machining</td>
<td>10.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Xp [dimensionless]</th>
<th>Complexity of the part</th>
<th>639.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>P [cm]</td>
<td>Parts+Runner+Accessories perimeter (both plates)</td>
<td>54.02</td>
</tr>
<tr>
<td>L [cm]</td>
<td>Average length of the part</td>
<td>7.74</td>
</tr>
<tr>
<td>W [cm]</td>
<td>Average width of the part</td>
<td>0.59</td>
</tr>
</tbody>
</table>

#### Ejector Plate Time Manufacturing

<table>
<thead>
<tr>
<th>tfixmob[h]</th>
<th>Total time manufacturing of ejector plate</th>
<th>5.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>tejecbase[h]</td>
<td>Time to machining chamfered corners and main holes (4 screws + 2 positions)</td>
<td>2.00</td>
</tr>
<tr>
<td>tejecComplexity[h]</td>
<td>Time to drilling ejectors holes</td>
<td>2.00</td>
</tr>
<tr>
<td>Tsinglecut[h]</td>
<td>Average Drilling time</td>
<td>0.40</td>
</tr>
<tr>
<td>Nejector[integer]</td>
<td>Total number of pin ejector</td>
<td>5.00</td>
</tr>
<tr>
<td>tejectors cut[h]</td>
<td>Total Time to cut ejector</td>
<td>1</td>
</tr>
<tr>
<td>Nejector[integer]</td>
<td>Total number of pin ejector</td>
<td>5.00</td>
</tr>
<tr>
<td>Tsinglecut[h]</td>
<td>Average cut time</td>
<td>0.20</td>
</tr>
</tbody>
</table>

#### Cumulative Mould Cost

<table>
<thead>
<tr>
<th>Cm[€]</th>
<th>Material Cost</th>
<th>417 €</th>
<th>CHF</th>
<th>625</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clabour [€]</td>
<td>Total Labour cost</td>
<td>945 €</td>
<td>CHF</td>
<td>1'418</td>
</tr>
</tbody>
</table>

#### Valve Cost

<table>
<thead>
<tr>
<th>CP [€]</th>
<th>Valve Cost Price</th>
<th>280 €</th>
<th>CHF</th>
<th>420</th>
</tr>
</thead>
<tbody>
<tr>
<td>T [h]</td>
<td>Time to manufacture the valve</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Material Cost | Material cost | 47 € | CHF | 70.00 |

#### Mould Price

<table>
<thead>
<tr>
<th>CP [€]</th>
<th>Price of the mould to the customer</th>
<th>1'642 €</th>
<th>CHF</th>
<th>2'463</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT [€]</td>
<td>Cumulative mould cost for a multiple cavity mould</td>
<td>1'642 €</td>
<td>CHF</td>
<td>2'463</td>
</tr>
<tr>
<td>CA [dimensionless]</td>
<td>Fixed administrative cost, interest rates, amortized (0.2 to 0.4) usually 0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Final Project of Industrial Engineering

« Design and manufacturing of complex moulds for powder injection moulding »

<table>
<thead>
<tr>
<th>P [dimensionless]</th>
<th>Target profit per job (0.05 - 0.4) usually 0.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUSTOMER PRICE</td>
<td>1'642 €</td>
</tr>
<tr>
<td>CHF 2'463</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COST % G</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>416.67 €</td>
</tr>
<tr>
<td>Labour</td>
<td>945.00 €</td>
</tr>
<tr>
<td>Valve</td>
<td>280.00 €</td>
</tr>
<tr>
<td>TOTAL MOULD COST</td>
<td>1'641.67 €</td>
</tr>
</tbody>
</table>

| Material %        | 25.38%                                        |
| Labour %          | 57.56%                                        |
| Valve %           | 17.06%                                        |
| TOTAL MOULD COST  | 100.00%                                       |

Figure 125 Double Cavity cost by HES-SO method

Figure 126 Double Cavity mould cost by HES-SO method

Figure 127 Double Cavity mould cost % by HES-SO method
6.3 PIM TECHNOLOGY VIABILITY

The approach to cost reduction is based on the 80 – 20 rule, which means that 20% of the design features can control 80% of total costs. The idea seeks to reduce efforts, looking to this critical 20% of design features.

In the following part, some rules and recommendations are described, which can be useful to decrease the PIM costs and to improve the technology application. Among the critical 20% of design features, one considers those that can significantly reduce from simple considerations.

1. PART SHAPE REQUIREMENTS

- Surface finish increase considerable post-sintering cost: Using a rippled or textured surface hat avoid polishing.

- Nonstandard materials: Use common materials if possible and maybe graduate to a stronger or more corrosion resistant material with a lower cost if it is a widely used alloy.

- Combine parts were possible to eliminate assembly, inventory and time spent in moulding.

- Components with uniform thickness are easier to mould.

- Components with thick sections on a component slow the moulding cycle

- Improve the quick ejection.

- Flat surface for sintering and debinding avoids the cost of special fixtures
- Justified every tight tolerance

- Increase the tool life, when material requires it (abrasive ceramic particles) with coating technologies.

### 2. PRODUCTION QUANTITIES

- Look for purchasing quantities that enable better cost efficiencies at PIM producer.

- Reduce orders number reducing to minimal creating a low set up and maintenance costs.

- Minimum PIM Quantities per year:
  - Metals: up from 500 units per year
  - Ceramics, cemented carbide: around 200 units per lot
  - Standard quantity: 300,000 units per year

### 3. EQUIPMENTS COST

- Furnace represents top equipment cost, for this reason it is necessary to analyze the production requirements:
  - Around 60 Kg per day: Furnace cost of 200,000€
  - Around 300 Kg per day: Furnace cost of 600,000€
  - Continuous furnace: Furnace cost from 300,000€ to 1,000,000€

- Furnace represents top equipment cost, for this reason it is necessary to analyze

- Mixing Equipment cost from 10,000€ to 80,000€

- Moulding Machines cost from 90,000€ to 240,000€

- Small vacuum cost from 6,000€ to 12,000€

Manufacturing costs are highly variable, so this chapter only provide a rough view across the industry. However, many components have been successfully converted to PIM with at least a 30% price reduction.

In case of hard material manufacture (such as high strength stainless steels, electronic packaging materials, oxide ceramics, cements and cemented carbides and
refractory metals), PIM has shown at least a 75% cost savings compared with machining. Some devices used in automobiles, computers, electronic systems or industrial hardware show an occasional 20-fold reduction.
7 CONCLUSIONS AND PERSPECTIVES

Five moulds for injection moulding have been designed. Two of them have been built and successfully tested with MIM and CIM feedstocks respectively.

Toroid parts have been injection moulded with soft ferromagnetic materials (Fe-2.7%Si). The green parts have been successfully debinded and sintered.

In addition, green ceramic parts have been injection moulded in a double cavity mould, which includes a switch valve as a special feature. It allows changing the feedstock flow to the wanted cavity, reducing both set up time and costs.

A comparison between three cost calculations for mould manufacturing has been made. A simple method has been proposed, which has the advantage to be adapted to HES-SO Valais moulds and its specifications.

After the data analysis performed during the design and experimental stages, the following points can be highlighted:

The trapped air inside the mould cavity makes difficult the solidification process. Therefore it is recommended to use vents to avoid this problem.

When the feedstock crosses the cold nozzle, it suffers a suddenly cooling that worsens the injection moulding, making mould filling difficult. A hot runner system can help to reduce this problem.

Mould temperature is one of the factors with more influence during injection moulding. Room temperature cannot be enough to allow a correct process. A possible solution could be to preheat both fix and mobile mould halves by a water circuit that flows inside the plates or supports (a standard in the injection moulding industry).

Microstep mould must be manufactured in two steps:
  o Main cavity by electroerosion.
  o Runners and others by machining.

A new system to pick up the parts after the injection moulding could avoid possible part cracks. In addition it can be studied a way that allows the storage during
the process, reducing injection moulding time and avoiding mould opener in each step.

The cost method developed by “Boothroyd, Dewhurst and Knight” present too much influence of thickness correction factor. Usually reducing this factor in 10%, produces a reduction of 50% in the final cost. The width ratio causes similar problem. These sensitive coefficients limit the usefulness of this method.
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9 ANNEXES

ANNEXE I: ARBURG INJECTION MACHINE SPECIFICATIONS

ANNEXE II: MOULDS PLANS

Toroid
- Toroid specimen
- Fix plate of toroid mould
- Mobile plate of toroid mould
- Ejectors plate of toroid mould

Dog-Bone
- Dog-Bone specimen
- Fix plate of dog-bone specimen mould
- Mobile plate of dog-bone specimen mould
- Ejectors plate of dog-bone specimen mould

Flat
- Flat specimen
- Fix plate of flat specimen mould
- Mobile plate of flat specimen mould
- Ejectors plate of flat specimen mould

Double Cavity
- Fix plate of double cavity tensile test mould
- Mobile plate of double cavity tensile test mould
- Ejector plate of double cavity tensile test mould
- Cylindrical valve in or
- Hexagonal valve in or
- Key prototype I
- Key prototype II

Microstep
- Microstep specimen
- Fix Plate of microstep mould
- Mobile Plate of microstep mould
Final Project of Industrial Engineering
"Design and manufacturing of complex moulds for powder injection moulding"

- Ejector Plate of microstep mould

*Hot runner sketch*

**ANNEXE III: MOULD ASSEMBLY**

**ANNEXE IV: MOULDS PROPERTIES**
- Toroid mould
- Dog-Bone specimen mould
- Flat specimen mould

**ANNEXE V: THERMAL CYCLE**
- Suggested Moulding Conditions for ADVAMET Feedstocks
- Thermal Debinding of ADVAMET Feedstocks
- Thermal Debinding (Complex) of ADVAMET Feedstocks
- Debinding and sintering cycle graphics

**ANNEXE VI: PIN EJECTORS SPECIFICATION**
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