Surface coating of steel molds and their components for plastic injection molding

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Master Dissertation

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Abstract

This master's thesis focuses on the application of coating treatments for molds and their components in the context of MUROPLAS, a mold company serving the hospital sector. The primary objective is to address the challenge of defects arising in components after injection molding. This research aims to enhance the quality of molded parts through the implementation of coatings on critical components, as well as improve the overall cycle time of each injection.

The first case study investigates the occurrence of component offset defects caused by excessive wear in mold cavities, with a specific focus on Polyvinyl Chloride (PVC) plastics. PVC plastics are known to be highly aggressive to mold cavities due to the release of gases during the heating process, making effective mold protection crucial. The analysis emphasizes the importance of implementing a Physical Vapor Deposition (PVD) coating as a preventive measure against wear and to mitigate the detrimental effects of PVC on mold cavities. Although the application of PVD coating has not yet been carried out, its potential as the optimal solution is highlighted based on the research findings.

The second case study explores the application of coatings on inserts placed within a tubular component. Four different inserts are compared, with two groups having different surface roughness values. Within each group, one set of inserts is coated with Electroless Nickel adding Teflon (PTFE), allowing for a comparative analysis of the results. The electroless nickel coating provides corrosion resistance and durability, while the Teflon coating offers low friction properties. By evaluating the performance of the coated inserts with varying surface roughness, the study aims to identify the influence of coatings on cycle times and optimize the injection molding process.

The research methodology involves experimental analysis, data collection, and comparative evaluation of the different inserts and coatings. The findings are expected to contribute to the understanding of the benefits and limitations of coating treatments for molds and their components, specifically in terms of defect reduction, cycle time optimization, and the impact of surface roughness.

Keywords: mold coatings, injection molding, component defects and mold defects, PVD coating, Electroless Nickel + Teflon coating, cycle time optimization, PVC plastics, surface roughness.

Resumo

Esta dissertação de Mestrado foca na aplicação de tratamentos de revestimento para moldes e seus componentes no contexto da MUROPLAS, uma empresa de moldes que atende o setor hospitalar. O objetivo principal é abordar o desafio de defeitos que surgem nos componentes após a moldação por injeção. Esta pesquisa visa aprimorar a qualidade das peças moldadas por meio da implementação de revestimentos em componentes críticos, bem como estudar possíveis melhorias no tempo total de ciclo de cada injeção.

O primeiro caso de estudo investiga a ocorrência de defeitos de descentramento de componentes causados por desgaste excessivo nas cavidades do molde, com foco específico em plásticos de Policloreto de Vinila (PVC). Os plásticos de PVC são conhecidos por serem altamente agressivos às cavidades do molde devido à libertação de gases durante o processo de aquecimento, tornando a proteção adequada do molde crucial. A análise enfatiza a importância da implementação de um revestimento por Deposição Física de Vapor (PVD), mais concretamente o TiN como uma medida preventiva contra o desgaste e para mitigar os efeitos prejudiciais do PVC nas cavidades do molde. Embora a aplicação do revestimento PVD ainda não tenha sido realizada, o seu potencial como solução ideal é destacado com base nos resultados da pesquisa.

O segundo caso de estudo explora a aplicação de revestimentos em insertos colocados dentro de um componente tubular. Quatro insertos diferentes são comparados, sendo dois grupos com valores de rugosidade superficial diferentes. Dentro de cada grupo, um conjunto de insertos é revestido com Níquel Eletrolítico sem corrente com adição de Teflon (PTFE), permitindo uma análise comparativa dos resultados. O revestimento de níquel eletrolítico proporciona resistência à corrosão e durabilidade, enquanto o revestimento de Teflon oferece baixo coeficiente de atrito. Ao avaliar o desempenho dos insertos revestidos com diferentes rugosidades superficiais, o estudo tem como objetivo identificar a influência dos revestimentos nos tempos de ciclo e otimizar o processo de moldação por injeção.

A metodologia de pesquisa envolve análise experimental, análise de dados e avaliação comparativa dos diferentes insertos e revestimentos. Espera-se que os resultados contribuam para a compreensão dos benefícios e limitações dos tratamentos de revestimento para moldes e seus componentes, especificamente em termos de redução de defeitos, otimização do tempo de ciclo e o impacto da rugosidade superficial.

Palavras-chave: revestimentos para moldes, moldação por injeção, defeitos de componentes e de moldes, revestimento PVD, revestimento de Níquel Eletrolítico + Teflon, otimização do tempo de ciclo, plásticos de PVC, rugosidade superficial.

Ackowledgements

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"Nunca é tarde para ser o que poderíamos ter sido."

António Lobo Antunes

Contents

List of Figures

List of tables

1. Introduction

This document consists in the master thesis for the conclusion of the Master's degree in Mechanical Engineering at Faculty of Engineering of the University of Porto (FEUP), specialisation of Materials and Manufacturing Technologies.

This first chapter portrays the theoretical component of the thesis, which starts with a briefly description of the company, Muroplás, and the emergence of the theme of this project. Finally, the different phases necessary for the execution of the defined objectives are mentioned, through the structuring of this work in its various topics.

1.1. Project Background and Motivation

In the sense of progress, there is a need to combine coatings with molds and study their advantages either, as initially discussed, in the protection of mold components, mainly in the use of plastics such as PVC, with a view to reducing all the necessary maintenance that these gases cause in the components (corrosion) as well as, idealized during the work, the possibility of optimizing injection parameters to increase the quality of the parts as well as cycle time reductions. As a result, finding effective solutions to mitigate these defects and improve cycle times is crucial for Muroplás and its customers in the hospital sector.

This master's thesis aims to address the challenges through the implementation of coating treatments for molds and their components. By exploring the potential benefits of coatings, the goal is to enhance the quality of molded parts and optimize the injection molding process.

1.2. Company overview and their challenges

"Muroplás – Indústria de Plásticos, S.A." was founded in 1989 and has become a national and international reference in engineering and quality in high-demand areas through the development of plastic component solutions. The company offers customers the realization of specific project needs, providing integrated solutions that encompass product development, mold production, and injection of the final product.

MUROPLAS
PLASTIC ENGINEERING

Figure 1 - Logo Muroplás - Indústria Plásticos, S.A.

Muroplás activity focuses primarily on four areas of specialization: medical, automotive, electrical, and electronics. The main application area is the medical industry, where the company develops components for medical devices used for diagnostic or therapeutic purposes. This includes infusion systems, hemodialysis equipment, radiology systems, infusion pumps, central catheters, and IV chambers, among others.

The field of mold manufacturing plays a critical role in various industries, including the hospital sector. MUROPLAS, a mold company specialized in serving the hospital sector, faces a significant challenge regarding defects in molded components after injection molding. These defects can compromise the functionality and quality of the final products, leading to increased costs and decreased customer satisfaction. The increase in demand and demand from the market represents a challenge for companies, as for them to continue to be up to the challenges imposed, they must be dynamic and must be willing to take risks to the point of being able to adapt and innovate.

1.3. Project main goals

The purpose of this work is to understand the relation between the coatings applied into the mold cavitys, their components (movable components) and the injected parts and the mold without defects in order to maximize production and prevent unnecessary maintenance, which would lead to production stoppages, wasted time spent cleaning the affected zones and possible replacement of those mold components. This defects are usually burn marks, corrosion and some pitting zones in metal parts caused by some more aggressive plastics and their gases such as PVC and others.

Another objective of this study is to find if cycle times could be reduced, even with small improvements, applying coatings with demolding characteristics that may allow a faster demolding of the part without compromising its quality.

After studying this two relationship, another objective will be to understand if the coating investments would be worth it in long term.

1.4. Thesis Structure

This thesis is divided into 4 main chapters, that are organized as follows:

- **Chapter 1 – Introduction:** Short presentation of Muroplas company as a model industry of components for the hospital sector, as well as the main challenges and objectives of this work.

- **Chapter 2 – State of art:** Divided into several subtopics, addressing various themes introducing mold coatings, such as metals used for molds, injected plastics, injection molding machine and its process, component defects, and coating techniques.

- **Chapter 3 – Case Studies:** Presentation of two distinct case studies showcasing possible applications of coatings. The first case focuses primarily on protective characteristics for the mold cavity, preventing defects in both the mold and the component. The second case focuses on demolding characteristics to study their behavior.

- **Chapter 4 – Conclusions and Future Work:** Most important conclusions of this project and Some possible future work that could further continue the study related to coatings in the mold industry-

2. State of art

The use of polymeric materials in the mold industry has been significantly increased since the beginning of the century which has led to the refinement and development of advanced manufacturing processes due to their versatility, cost-effectiveness, durability and ease of production. Today, plastics are used in almost every area and have transitioned from a “cheap” substitute for metal and glass to the material of choice providing almost unlimited design freedom, unique properties and significant cost savings.

Figure 2- Molded small and large technical (engineering) products (Ress and Catoen, 2006)

However, the production of polymeric parts on a large scale also poses some challenges, including the need to prevent defects in both the parts and their molds that can lead to significant production losses, increased costs, and even product failures, especially in the highly regulated hospital industry.

In this literature review, we will explore the various types of coatings used in the production of polymeric parts in injection molding, with a particular focus on their applications in the hospital industry. We will also examine the key factors that influence coating performance and discuss the latest developments in coating technology. By gaining a deeper understanding of the use of coatings in polymeric part manufacturing, we can better appreciate the importance of this technology in meeting the evolving needs of the hospital industry.

2.1. Coatings introduction and materials

To address the challenges, many manufacturers have turned to coatings as a way to improve the performance and lifespan of their molds and parts. Additionally, there are some polymers, such as PVC, that can be highly corrosive to molds and their components due to their gases, leading to a shorter lifespan and increased maintenance cost. Coatings can offer a range of benefits, such as increased wear resistance, improved release properties and enhanced corrosion resistance. Its even possible to improve the quality of the products while reducing downtime and maintenance costs of the molds and components.

2.1.1. Metal materials and heat treatments.

One critical aspect of mold designs is the selection of the appropriate material, especially the type of steel used.

These molds are specially designed and crafted to shape various plastic products and to withstand the rigors of mass production. This makes steel the ideal material to use in plastic manufacturing, as their positive qualities, such as high durability and temperature resistance are qualities needed to produce the best products (Kho, 2019). Choosing the wrong type of steel can lead to issues such as excessive wear and tear, cracking, and reduced tool life, all of which can result in production delays, increased costs, and compromised product quality.

The choice of steel for injection molds depends on various factors, including the material being molded, the size and complexity of the part, and the desired tool life. However, some common types of steel used for injection molds of plastic parts are:

- P20 (1.2311): P20 is a pre-hardened, low-alloy steel that is widely used for medium to large injection molds. It offers good toughness, excellent machinability, and moderate resistance to wear and corrosion.
  Applications: Molds for plastics made in pieces up to 400mm thick and structures for molds.

- H13 (1.2344): H13 is a hot work tool steel that is suitable for high-volume production of plastic parts. It offers excellent heat resistance, high wear resistance, and good toughness. Eventually, H-13 tooling surfaces will become susceptible to corrosion brought about by chemically enhanced plastics, moisture, humidity, and cooling water contamination (Kaysun Blog, 2020).
  Applications: Molds for termoplastics.

- 420 (1.2085): 420 is a chromium stainless steel that is suitable for injection molds of small to medium-sized parts. It offers good wear resistance, good corrosion resistance, and moderate toughness.
  Applications: Injection and compression molds for corrosive plastics and work in humid atmospheres. High temperability (AÇOS, 2022).

Other steels that may be used for injection molds include NAK80, 718, and 2316.

The following Table 1 presents the standards and chemical composition of some of the most used steels in the industry, this information is contained in the online catalog of the company "Ramada Aços", leaders in various steel solutions based in Portugal.

Table 1- Chemical composition of the most used steels (AÇOS, 2022).

Norms				Chemical Composition						
AISI	EURONORM	DIN	W.Nr.o	C	Si	Mn	Cr	Mo	Ni	V
P20	40 CrMnMo 7	40 CrMnMo 7	1.2311 1.2312	0,36	0,30	1,45	1,95	0,20	-	-
H13	X40 CrMoV5-1	X40 CrMoV5-1	1.2344	0,40	1,00	0,40	5,20	1,30	--	1,00
420	X41 Cr 14	X42 Cr 13	1.2083 mod	0,38	<1,10	<1,00	13,60	-	-	0,30
1045	C 45 E	Ck 45	1.1730 1.1191	0,45	<0,40	0,65	-	-	-	-

It is usual for these steels to come already with quenching and tempering heat treatments to achieve the hardness and stiffness properties desired and necessary for this application. Table 2 summarizes the most used metals and their properties after being treated.

Table 2- Heat treatment and toughness informations (AÇOS, 2022).

AISI	Delivery State	Toughness (HB máx.)	Heat Treatment (ºC)			
			Annealed	Tension Reduction	Hardening	Tempered
P20	Treated	270/350	710-740	-	840-870	180-650
H13	Annealed	235	850	550-650	1020-1050	180-700
420	Annealed	190	860	650	1000-1025	200-600
1045	Natural	207	650-700	-	820-860	150-550

2.1.2. Plastics materials in medical applications

In 2010 the global medical device industry were estimated to be between US $220 and $250×10^9$ in value. This industry continues to show a healthy growth rate overcoming many economic downturns or slowdowns. Figure 3 shows the growth from 2000 projected to 2013 (Sastri, V. R. 2010).

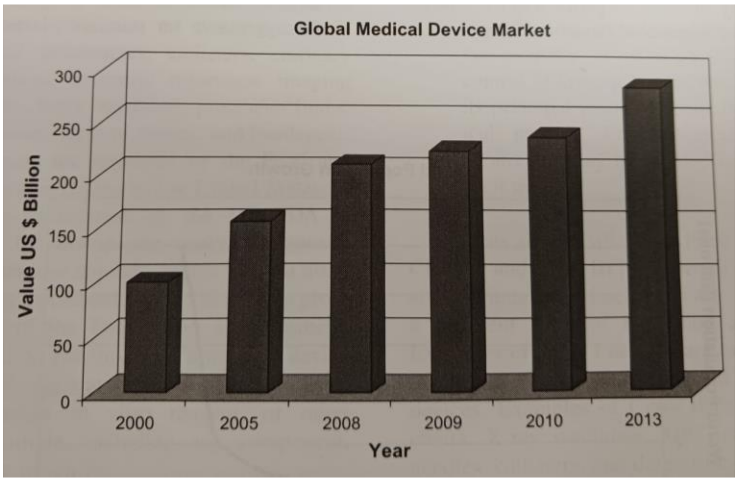

Figure 3- Global medical device market size, 2000 to 2013 (Sastri, V.R. 2010).

On a more recent analyses, the global medical devices market was valued at US$ 550 billion in 2021, Figure 4, and is expected to reach US$ 850 billion by 2030, poised to grow at a compound annual growth rate (CAGR) of 5.5% during the forecast period 2022 to 2030 (Precedence Research 2022).

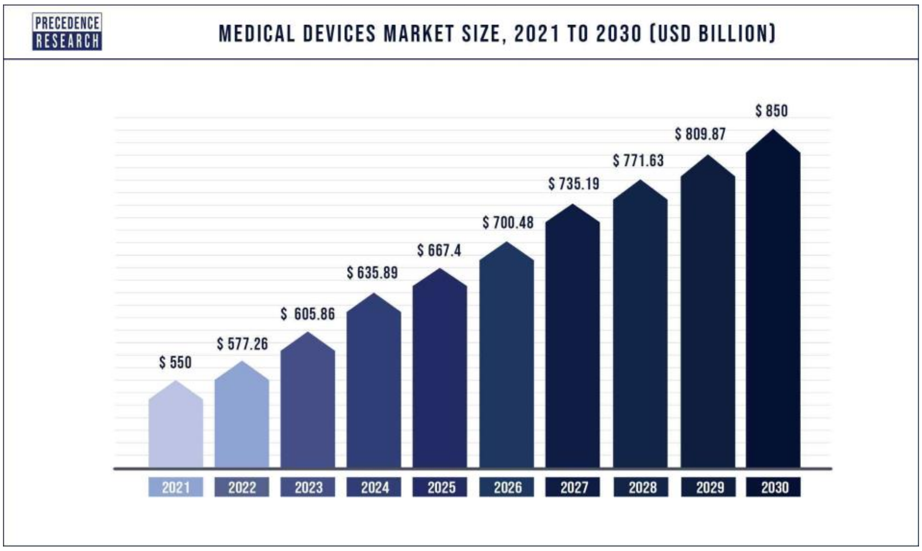

Figure 4- Global medical devices market size, 2021 to 2030-USD Billion (Precedende Research 2022).

The United States has about 40% of the global market share, followed by Europe, Japan and the rest of the world, Figure 5. In addition to population growth, populations are aging in countries like the United States, Western Europe, and Japan. People over the age of 65 will increase dramatically over the next 10-20, this is something is currently happening. This demographic require more healthcare diagnostics and surgical procedures like cardiovascular and orthopaedic operations.

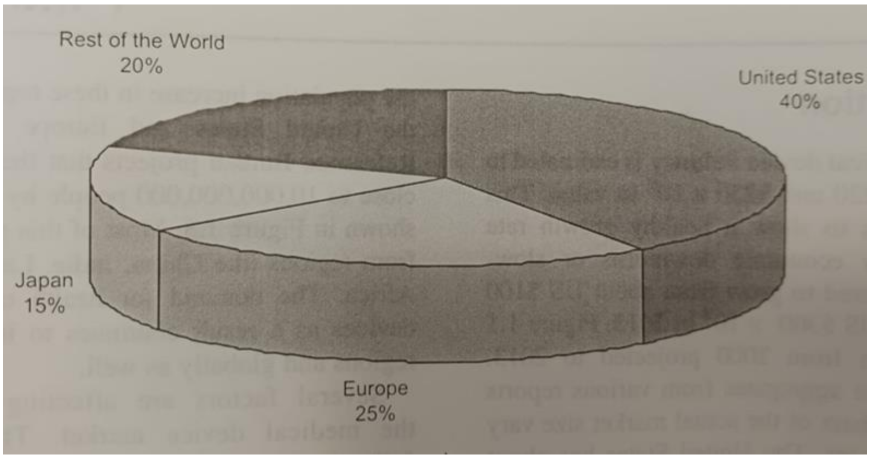

Figure 5- Global medical device market share by region (Sastri, V. R. 2010a).

Plastic can be classified into four main categories:

- Commodity thermoplastics include polyvinyl chloride, polyolefins and polystyrene.
- Engineering thermoplastics have improved thermal and mechanical properties over commodity thermoplastics. This polymer family is made up of acrylics, polycarbonates, polyurethanes, acetals, polyesters and polyamides;
- High temperature thermoplastics have very high temperature resistance along with excellent strength, stiffness and toughness. Materials in this family include polyimides, polyetherimides, polysulfones, fluoropolymers etc;
- Other polymers that are used in medical device applications include styrenics, silicones, thermoplastic elastomers and thermosets (Sastri, V. R. 2010a).

Table 3 summarizes the use of various plastics in medical applications.

Table 3- Summary of plastics in medical device applications.

Property	Commodity Plastics	Engineering Thermoplastics	High Temperature Engineering Thermoplastics and other Polymers
Percent usage in medical device applications	70% of all plastics	20% of all plastics	10% of all plastics
Type of plastics	• Polyethylene • Polypropylene • Polystyrene • Polyvinyl Chloride	• Polyamides, nylons • Polyesters • Polycarbonates • Polyurethanes	• Polyimides • Polyether imides • Polysulfones • Fluropolymers

		• Acrylics • Acetals	• Liquid crystalline polymers • Biopolymers • Thermosets and adhesives
Medical device applications	• Tubing • Films, packaging • Connectors • Labware • IV bags • Catheters • Face masks • Drug-delivery components • Housing • Luers • Connectores	• Surgical instruments • Balloons • Blood set components • Blood bowls • Blood oxygenators • Syrings • Moving parts and components • Luers • Catheters	• Surgical instruments • Surgical trays • Syringes • Implants • Dental implants • Bone implants • High precision parts • Electronic components

In the past year of 2022, Muroplás had these amounts of material used, summarize in Table 4, in Kg, with Terluran GP-35 Natural occupying the top of the table with 165025Kg used, corresponding almost to 20% of all of materials usage, followed by ABS HF 380.

Terluran GP-35 is a thermoplastic polymer that belongs to the family of polypropylene (PP) plastics and is a high-quality, impact-resistant material that has good chemical resistance and can withstand exposure to high temperatures.

Thermoplastic elastomer (TPE) as a lot of use in this company too, the "PURELL RP 374R TRANSARENT" with 92 tons of material used. It is a soft, flexible, and transparent material that is known for its good chemical resistance, biocompatibility, and ease of processing and is suitable for use in a variety of medical applications such as seals, gaskets, tubing, and other flexible components.

Table 4- Summary of the most used materials in the company, class and quantity (tons).

Row Labels	Class	Name	Sum of Quantity (tons)
TERLURAN GP-35 NATURAL	PP	Polypropylene	165,0
ABS HF 380 OA679-B WHITE	ABS	Acrylonitrile butadiene styrene	105,9
PURELL RP 374R TRANSPARENT	TPE	Thermoplastic elastomer	92,0
PS AC 7240 NATURAL	PS	Polystyrene	57,7
PVC AM289/F W2107 TRANSPARENT	PVC	Polyvinyl chloride	43,2
ERACLENE MS 80 U NATURAL	MBS	Methacrylate butadiene styrene	41,2
ALCUDIA PE 019 NATURAL	PP	Polypropylene	39,9
SASOL HNR100 NATURAL	HDPE	High-density polyethylene	38,3
TERLUX 2812 HD TRANSPARENT	PMMA	Poly(methyl methacrylate)	35,7
KEPITAL F20-03 NATURAL	PA	Polyamide	28,2

Other materials such as PS (Polystyrene), PVC (polyvinyl chloride), PE (polyethylene) are used frequently too, with PVC being the cheapest but one of the most difficult material to use in the injection molding industry. This material is characterized by being very sensitive to temperature and easily degraded, but it has a much higher chemical resistance when compared to other plastics, an essential aspect for systems in contact with medications\treatment and diagnostic solutions.

Figure 6 shows a typical application of PVC of tubular devices, courtesy of Muroplás.

Figure 6- Typical application of PVC of tubular devices (Muroplás).

Exposing PVC to temperature can lead to the formation of hydrochloric acid (HCl) gas from chlorine atoms during processing initiating the process of degradation of PVC which results in deterioration of the physical and chemical properties of the material which is often visible by its discoloration to yellowish tones (Silva, S. 2020).

The HCl gas can react with the metal surfaces of the mold, causing corrosion and pitting, which can ultimately lead to mold failure. To minimize the risk of mold degradation when processing PVC, it is important to use molds that are designed for PVC processing and have appropriate surface coatings or platings to protect against corrosion. Next figure 7 shows an example of some pins showing burn marks due to gases released after injection. This phenomenon can be minimized having some preventive measures and additional care to avoid these problems, however they are always possible to appear and the appropriate coating would be an extremely effective additional measure.

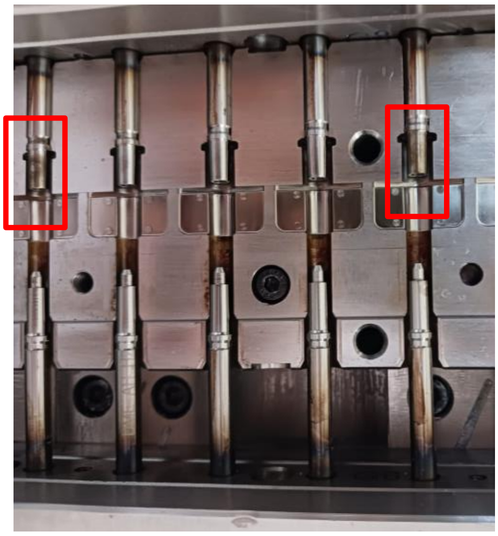

Figure 7- Typical defect in inserts for components with through holes.

2.2. Injection molding

Injection molding is the most popular process for manufacturing thermoplastic products and consists of injecting molten plastic material from a reservoir (heated cylinder) into a closed mold, allowing the plastic to cool down and solidify, and ejecting the finished product from the mold (Bryce, D. M. 1996).

Its is a near net-shape manufacturing process that can produce parts having good surface quality and accuracy and is a suitable process for mass volume production due to fast cycle time (Banerjee, A. G. 2006). The costs associated to molds are relatively high when compared to other processes, and therefore advisable for parts with high complexity and large production series.

2.2.1. Molding equipment

For this process is necessary a injection molding machine with the basics components: 1) an injection unit, 2) a clamping unit, 3) a mold, and 4) a controller, and a characteristic scheme can be seen in Figure 8.

The injection unit and the clamp unit serve separate primary purposes, and they complement each other. However, a machine may be purchased and build with virtually any combination of injection unit and clamp unit because each is independent of the other (Bryce, D. M. 1996).

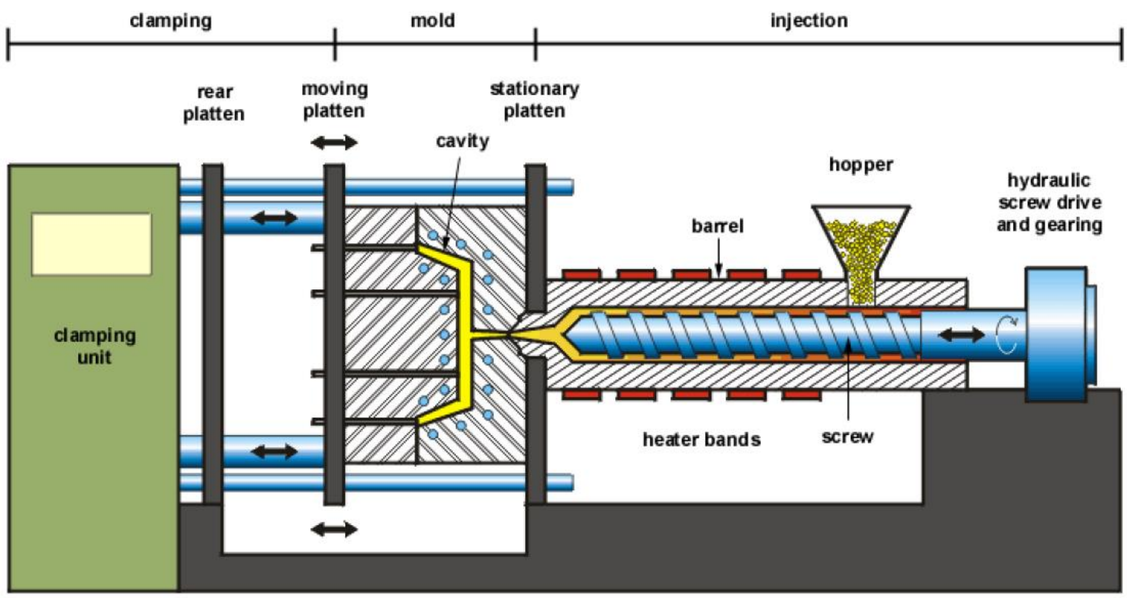

Figure 8- Schematic of a typical injection molding machine (Banerjee, A. G. 2006).

It should be noted that the scheme shown represents a single material injection machine, SMM (Single material molding) but can also exists a MMM (Multi material molding) which refer to the class of objects in which different portions are made of different materials. Let us briefly discuss MMM although it is not the main focus of this work.

Molded multi material objects allow signification reduction in assembly operations and production cycle times. In MMM, multiple different materials are injected into a multi stage mold, the sections of the mold that are not to be filled during a molding stage are temporally blocked. After the first injected material sets, then one or more blocked portions of the mold The costs associated to molds are relatively high when compared to other processes, and therefore advisable for parts with high complexity and large production series.

2.2.1.1. The Injection Unit

The purpose of the injection unit is to force or inject the molten plastic into the mold under pressure. The injection unit consists of a plastic-feeding hopper, a heated barrel (heating cylinder), a screw, an injector, and an outlet nozzle. All of these components work in conjunction to feed the plastic, melt it, and then inject it into the mold. There are many different injection unit configurations available, based on the needs of the particular molding job.

Idealy, the injection unit should be sized so that it contains two full cycles worth of material. In other words, 50 percent of the capacity of the injection cylinder should be emptied each time a cycle is completed. The 50 percent rule is ideal but shot size sould never be less than 20 percent or more than 80 percent of cylinder capacity (Bryce, D. M. 1996), and this parameter, the constant values of the material percentage used, is extremely important for the repeatability of the process.

The Heating Cylinder and Injection Screw

The most important part of the injection unit is the heating cylinder, also called the barrel. The outside of the barrel has heated bands strapped to it and those bands are electrically activated. There are three heater zones: rear, center and front, seen in Figure 9.

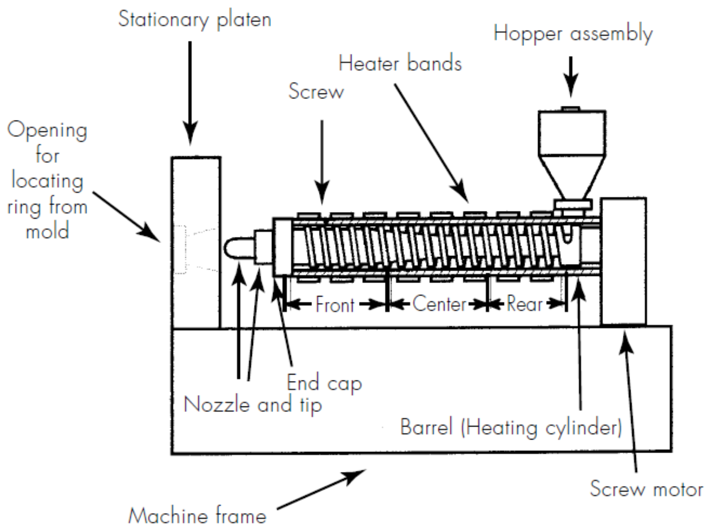

Figure 9- Injection unit components. (Bryce, D. M. 1996)

Each zone is individually controlled by an electrical unit located in the control panel of the machine.

Other important component of the injection unit is the injection screw that is placed inside the heating barrel. The primary function of the screw is to auger fresh material from the hopper area into the heating area of the barrel, the secondary function is to mix and homogenize the molten plastic.

The screw also generates heating to raise the temperature of the plastic, this increase in temperature is due to the friction created between the surface of the screw flights and the inside wall of the barrel, usually 0.008 to 0.013 cm. As the material is brought forward along the screw flights, the diameter of the screw increases and the plastic is squeezed which generates the heat, called shear effect. The screw provides additional heat, and this effect reduces the amount of electricity required to heat the plastic completely, however to much shear can tear up the plastic molecules and degrade the material. The molten plastic accumulates at the end of the cylinder until the required amount is in the viscous state for the plunger to move the screw, pushing the plastic into the mold (Bryce, D.M. 1996).

The Clamping unit

The clamping unit is responsible for keep the mold close to avoid material leaks during injection and to hold the parts when solidifying with the desire shape. The clamping mechanism is either a hydraulic press or a mechanical lever system and must be strong enough to resist the large forces generated by the injection pressure on the mold walls. Additionally, the clamping unit must incorporate some sort of ejector device to facilitate part removal from the mold.

Normally the force rating is stated in tons (kilonewtons), so a specific machine having a taring of 200 tons (1780 KN) is capable of producing a maximum clamp force equivalent to a total of 200 tons. The amount of force used needs to be carefully determined in orden to prevent defects in the parts, such as flash if a lower force is applied as well to avoid several damages in the injection mold or the press if too much clamp force is used.

2.2.1.2. The mold and components

The injection mold is a sophisticated system that must meet numerous demands required by the injection molding process concurrently. The mold's main role is to enclose the polymer melt inside the mold cavity, ensuring complete cavity filling to create a plastic component whose shape mimics the mold cavity. Another key function of the mold is to effectively transfer heat from the hot polymer melt to the coolant circulating through the mold, enabling the production of injection-molded products in a consistent and speedy manner. Additionally, the mold must eject the part efficiently and uniformly without causing excessive stress to the molded parts, making it another critical responsibility of the mold.

Without entering into to much detail about the mold components, Figure 10 illustrates the fundamentals of a mold.

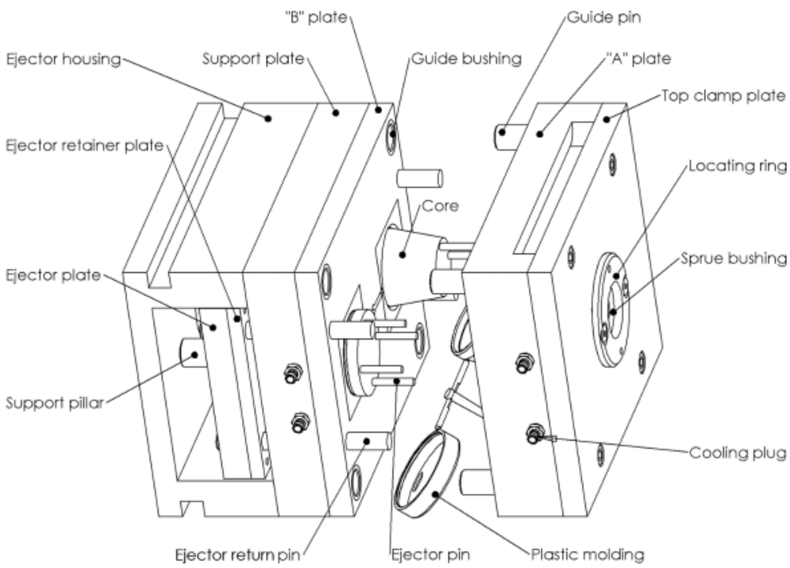

Figure 10- View of molding ejected from injection mold.

Figure 11 presents a mold for two different molded parts attached to the same feed system. This mold is called a two-plate, cold-runner, or two-cavity family mold. The term "family mold" refers to a mold in which multiple diferent components produced at the same time, most commonly to be used in a product assembly. The term "two-cavity" refers to the fact that the mold has two cavities to produce two moldings in each molding cycle. The three-plate is so named since it provides a third plate that floats between the mold cavities and the top clamp plate, for the provision of a feed system that traverses parallel to the parting plane, which lead to more waste of material as well as higher costs of production.

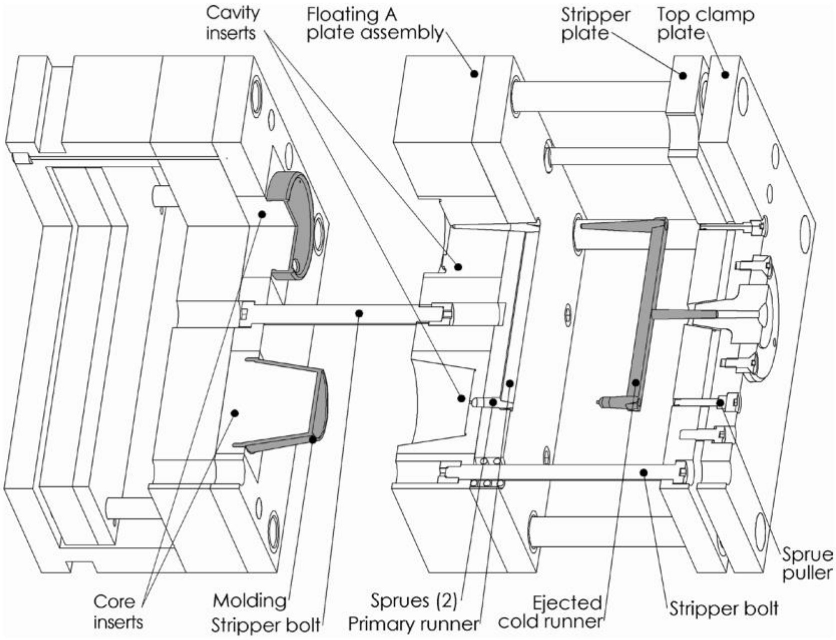

Figure 11- Section of an open three-plate mold.

The three-plate mold overcomes two significant limitations of two-plate molds. Firstly, it allows for primary and secondary runners to be placed in a plane above the mold cavities, providing flexibility in gating locations for improved cost and quality of moldings, especially for molds with many cavities. Secondly, the three-plate mold facilitates automatic separation of the feed system from the mold cavities, which enables easy de-gating for smoother operation of the molding process (Kazmer, D. O. 2016).

Cold Runners

Cold runners are a simpler and more economical type of runner system used in injection molding and is a channel in the mold that delivers molten plastic from the injection molding machine nozzle to the mold cavities. Cold Runners rely on the temperature of the molten plastic to fill the mold cavities. Once the plastic has cooled and solidified in the cold runner, it is ejected along with the part, resulting in waste material, which is the biggest disadvantage of this method, this excess can represent more material than the material used in the parts, and in the medical industry the materials needs to present high quality so the recycled materials are avoided as much as possible.

One advantage of cold runners is their simplicity and low cost. They are easy to set up and operate, requiring minimal maintenance and specialized knowledge. They are also versatile and can be used with a wide range of plastic materials and part designs.

As can be seen in Figure 12, normally the injection system consists of three main components: first the sprue, the main material entry channel, the runners and sub runners that distribute and guide the material to the different attack points of the cavities which are the gates, material entry point. Their location is extremely important, as they determine the behavior of the flow inside the cavity as well as the geometry of the gate, Figure 12 (b).

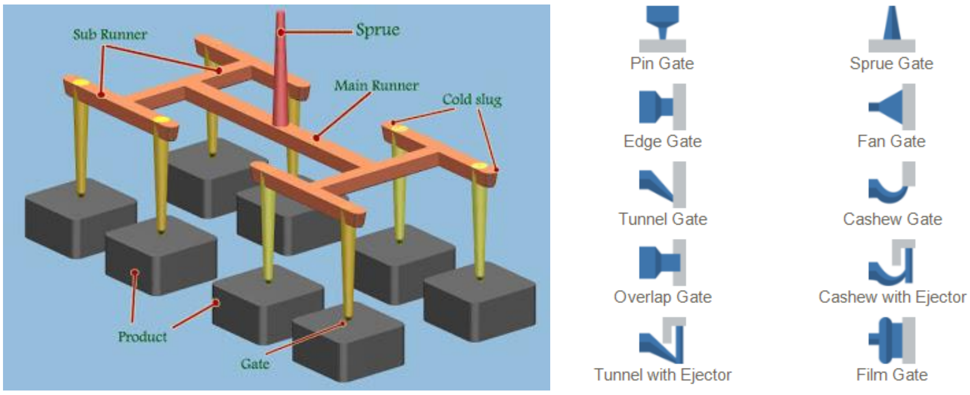

Figure 12- (a) Runner system construction in injection mold (Guan Xin 2022), (b) Type of gates (moldex3D).

Hot runners

Hot runner molds offer advantages over three-plate molds while avoiding their drawbacks, but they do come with their own set of challenges. The term "hot runner" refers to the heated feed system that remains in a molten state throughout the molding process. This eliminates the need for material or cycle time to transport the melt from the molding machine to the mold cavities and ejecting only the part resulting in improved efficiency (Kazmer, D. O. 2016).

Figure 13 shows a carburetor used in the hot half of the mold, cortesy of Muroplás, representing the hot runners. This type of components are very complex and difficult to produce with high quality, thats why some companies choose to out-sourcing this components from companies more specialized in the subjected. In this case is a mold with 64 cavitys representing a very complex hot runner part, and this cost can vary from tens to hundreds of thousands euros. The balance between the waste of material, the slower cycle times of the cold runner and the cost of a hot runner system needs to be studied in advance to see if it is worth the investment.

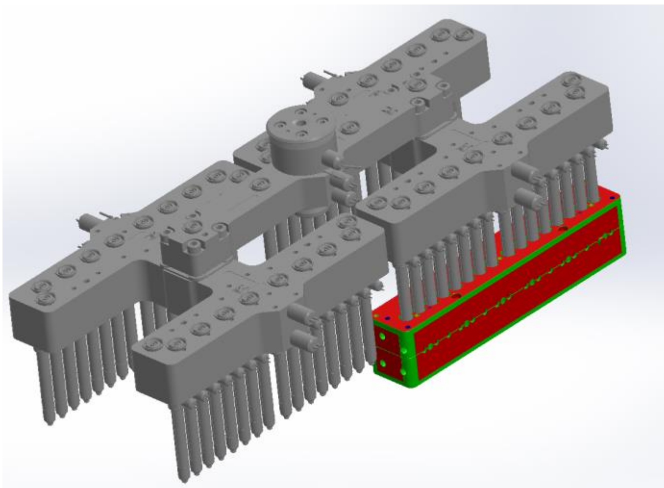

Figure 13- Carburetor used in a hot half of the mold, Muroplás cortesy.

This configuration of hot runners are not suitable for all type of materials. While hot runners offer many advantages in injection molding, they are not always suitable for processing certain types of plastics, such as PVC. PVC, or polyvinyl chloride, is a thermally sensitive plastic that requires careful processing to avoid degradation and discoloration. The high processing temperatures required for hot runners can cause PVC to break down and release corrosive gases, which damage the hot runner system rapidly and contaminate the finished parts. As a result, cold runner systems are often used for PVC injection molding. Cold runners can help to maintain the temperature of the PVC and reduce the risk of degradation, while also allowing for greater control over the filling process and minimizing waste material.

Cooling System

Cooling channels are an important aspect of the injection molding process. These channels are designed to quickly and efficiently remove heat from the molten plastic as it solidifies, allowing for faster production and better quality parts. There are many possible configurations of cooling channels. Conventional cooling channels, baffles, serpentine, parallel configuration etc, Figure 14 shows some usual layout of convention cooling channels.

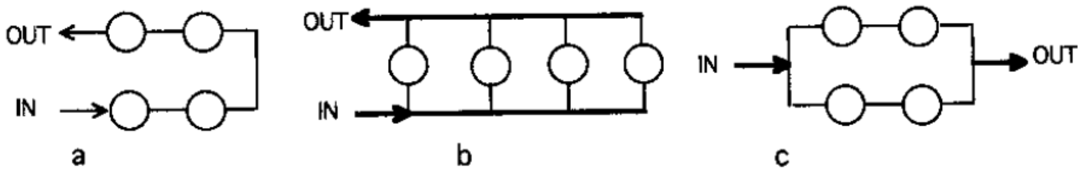

Figure 14- Schematic layout of (a) series cooling, (b) parallel cooling, and (c) series-parallel cooling, (Ress, H. 2001)

Holes are made in the plates through which a fluid, usually water, will circulate, which will have both its inlet and outlet temperatures controlled. Buffles and bubblers, as it can be seen in Figure 15 are used to reach areas of the mold that the refrigeration system alone would not reach. Thermal pins can be used as well for the same goal.

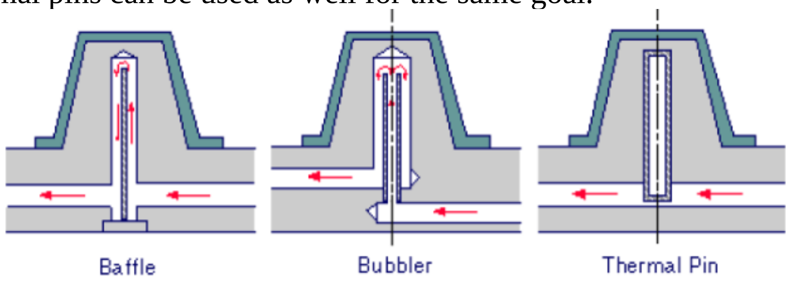

Figure 15- Baffles, Bubblers and Thermal pin schemes (CNF Molds & Plastic 2011).

Reducing cooling time can help improve the overall efficiency of the injection molding process, which can lead to cost savings and increased productivity.

Cycle time

The cycle time in the injection molding process is a crucial parameter that directly affects the productivity and efficiency of the manufacturing process. It refers to the total time required to complete one cycle of the injection molding process, including the filling, cooling, and ejection stages, Achieving a shorter cycle time is desirable as it allows for increased production output and reduced manufacturing costs. However, it is essential to maintain a balance between cycle time and the quality of the molded parts. A too-short cycle time may lead to insufficient cooling, resulting in defects such as warpage or sink marks.

Several factors influence the cycle time in injection molding. The complexity of the part design, the type of material being used, the mold temperature, and the machine parameters all play a role. Optimizing these factors can help reduce the cycle time without compromising the part quality. The injection process typically follows a cyclic pattern that can be divided into three main stages: filling, compaction, and cooling.

The filling stage commences with the closure of the mold, where the plastic material stored in the injection cylinder is conveyed by the rotating screw towards the mold. Once the desired volume of molten plastic is achieved, the screw halts its movement and proceeds to inject the material into the mold cavity. In the compaction phase, the spindle maintains the applied pressure in order to counteract the effect of contraction of the material during cooling (back pressure). This pressure is maintained until the part has cooled down enough to solidify and then the mold can be opened and the part ejected. This stages can be seen in Figure 16.

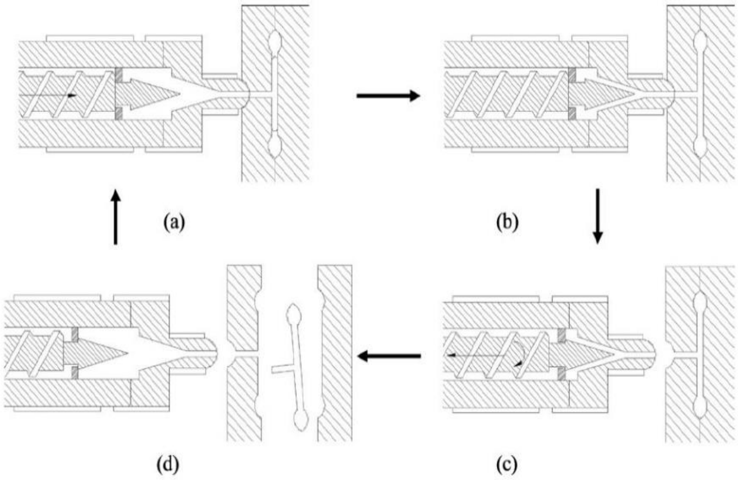

Figure 16- Cycle time, (a) Close mold, (b) filling, (c) compaction, (d) mold opening and extration.

The next cycle starts with closing the mold. To have an idea of times in each stage, Figure 17 shows the normal time needed to each stage in seconds. The general behaviour in an injection cycle is to have a cooling phase that is much higher than all other stages, normally 50% of the process.

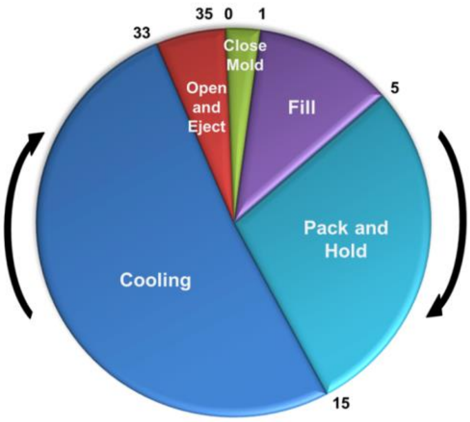

Figure 17- Cycle time in injection molding (Yasa et al, 2015).

Next Figure 18 elucidates about the profile of typical pressures throughout the process.

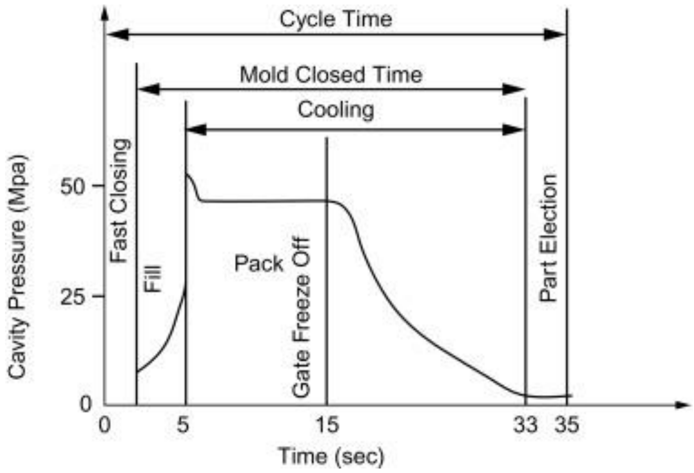

Figure 18- Cavity pressure over injection time.

2.3. Common plastic injection molding defects and causes

Plastic injection molding is a widely used manufacturing process for producing complex and high-quality plastic parts. However, despite its many advantages, the process can be vulnerable to a variety of defects that can compromise the quality of the final product. These defects can result in various issues such as reduced strength, impaired functionality, and visual defects that affect the aesthetics of the product. Therefore, it is crucial for manufacturers to understand the common defects that can occur in plastic injection molding and their causes, in order to develop effective strategies for preventing and managing them.

Understanding the types of defects that can occur in injection molded parts is important because coatings can help prevent or mitigate some of these defects. For example, coatings can improve the release properties of the mold, which can reduce the likelihood of defects like sticking or warping. Coatings can also improve the wear resistance of the mold, which can prevent defects like surface scratches or corrosion etc. In this context, this topic aims to provide an in-depth analysis of the common defects in plastic injection molding pieces, their components and their underlying causes, as well as exploring strategies for preventing and mitigating these defects.

A study that took place over a 30-year span (1963 to 1993) by Texas Plastic Technologies analyzed the root causes of the most common injection-molding defects and did not include those defects resulting from poor basic product design. The study concluded that those defects could be the result of one or more of the following factors:

- The molding machine;
- The mold;
- The plastic material;
- The molding machine operator.

Figure 19 shows the percentage that each of these itens contributed for the defects. It’s possible to see that the first place to look for a solution to a defect is the machine containing about 60% of the report problems. Because of the large number of parameters and the variability of the parameters and the way they all interact, many solutions may exist for a single problems, likewise, many problems may be fixed by using a single solution (Bryce, D. M. 1996).

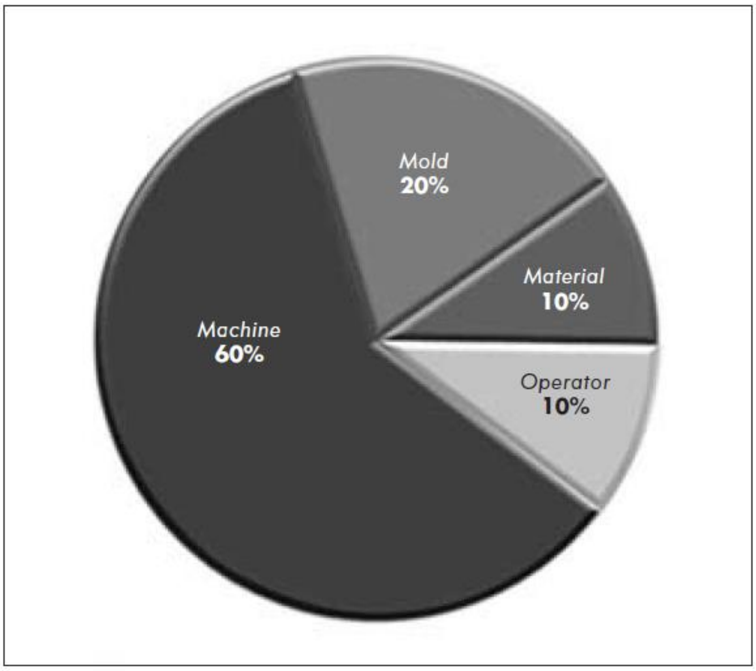

Figure 19- Distribution of defect causes (Bryce, D. M. 1996).

The following pages lists some of the most commong molding defects, not all-inclusive, and at the end a resume table of the those causes related to machine, mold, material and operator.

Flow lines

Flow lines, Figure 20, are off-color lines, streaks, and other patterns that appear on the surface of a part. These are caused by the shot of molten plastic moving at different speeds throughout the injection mold, which ultimately causes the resin to solidify at different rates. This is often a sign that injection speed and/or pressure are too low.

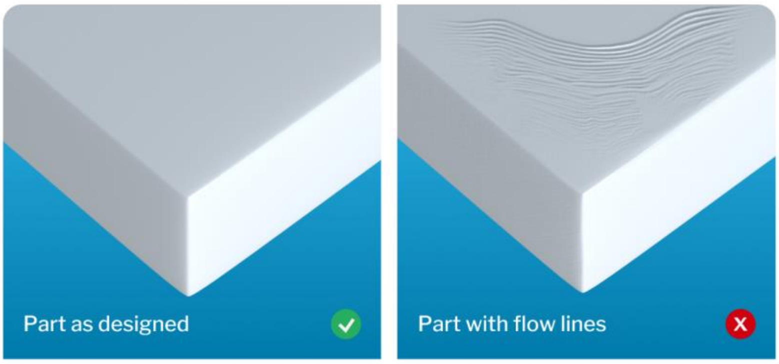

Figure 20- Flow lines (Fast Radius 2022).

Flow lines can also appear when plastic moves through parts of the mold with different wall thicknesses, due to the pressure drop — which is why maintaining consistent wall thickness or ensuring that chamfers and fillets are an appropriate length is critical. Placing the gate in a thin-walled section of the tool cavity can further help to reduce flow lines (Fast Radius, 2022).

Sink marks

Sink marks, seen in Figure 21, occur when the surface of the part sinks or becomes depressed due to uneven cooling or filling of the mold. This defect is especially common in thick sections of a part, where the cooling time is longer and the plastic is more likely to shrink as it solidifies. The tickers mass stays hotter longer and continues to shrink after the surrounding nominal wall thickness solidifies and is no longer capable of packing out the thicker area. As this hot mass continues to shrink it pulls the solidified skin towards the center of the hot mass creating a depression or sink mark in the part (Bryce, D. M. 1996).

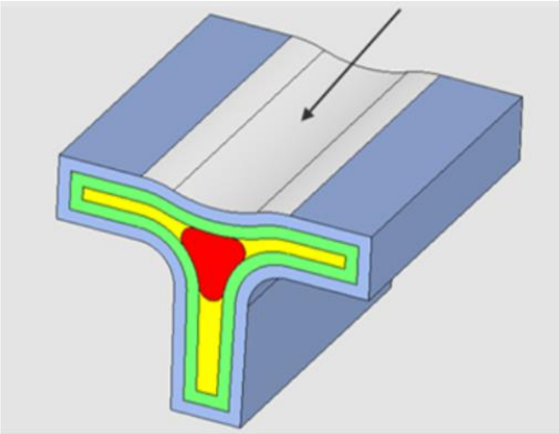

Figure 21- Sink Marks phenomenom (PTAPlastics).

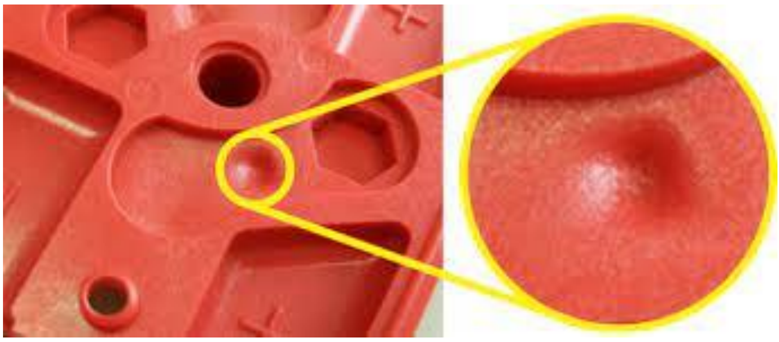

Figure 22- Sink mark, typicall example (Dienamics, 2014).

An indicator that the plastic needs more time inside the mold to properly cool and cure, sink marks may sometimes be remedied by reducing the thickness of the thickest wall sections, which helps to ensure more even and thorough cooling. Inadequate pressure in the mold cavity or higher-than-desirable temperatures at the gate can also contribute to the development of the defects.

Weld Lines and meld lines

Weld lines and meld lines are another common defect in injection molded parts that occur when two or more flow fronts of molten plastic meet and bond together during the injection molding process. This can occur when the plastic flow encounters an obstacle, such as a pin, insert or boss, or when the flow fronts from different gates meet. The result makes a weaker part and has a visible line or seam on the surface of the part where the plastic has bonded together.

The difference between a weld and meld line is determined by the angle, Θ Theta, at which the converging flow fronts meet. The difference can be seen in Figure 23.

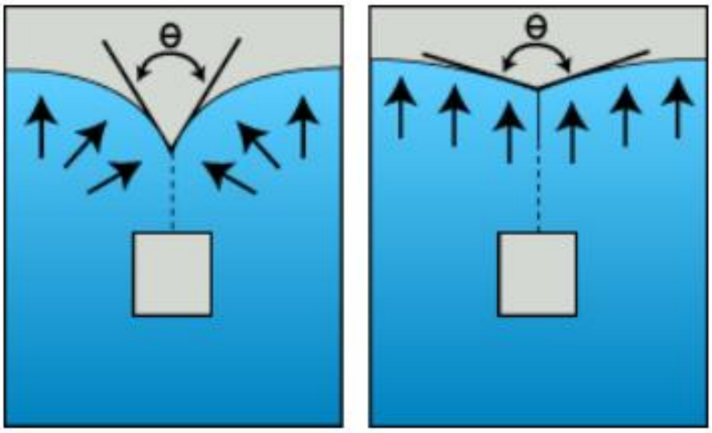

Figure 23- Angle Teta at which the converging flows front meet (Autodesk, 2015).

In the above figure the converging flow fronts (indicated by black arrows) meet. If Θ less than 135° a weld line will form. The orientation of the plastic at the weld is therefore perpendicular to the flow path.

If Θ is greater than 135° a meld line will form. The orientation of the plastic molecules is therefore more uniform than the orientation after a weld line has formed. Figure 24 shows a typical weld line when two flows of two different injection points meet.

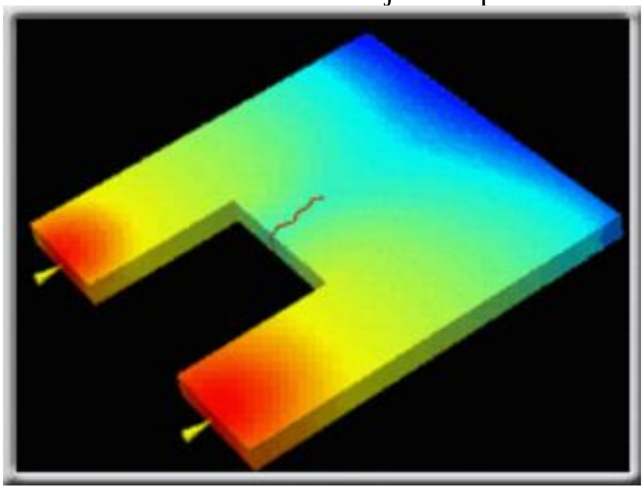

Figure 24- Weld line (Autodesk, 2015).

Meld lines are normally stronger than weld lines and are often much less visible.

Short shoot (Nonfill)

A short shot is a common defect in injection molding that occurs when the mold cavity isn't completely filled with molten plastic during the injection process. This can be caused by a variety of factors, including insufficient injection pressure or temperature, poor venting, or incorrect molding cycle time.

When a short shot occurs, the resulting molded part may be incomplete or have voids, resulting in a product that doesn't meet the desired specifications. This defect can be particularly problematic when the molded part is intended for use in a critical application, as it can compromise the part's structural integrity and potentially lead to failure.

Warping

Warping is another common defect in injection molded parts that occurs when the part experiences uneven cooling during the molding process, Figure 25. This can cause the part to deform or bend out of shape, resulting in a part that is not within the specified tolerances or does not function as intended. Warping is often caused by uneven cooling rates in the mold, which can occur due to variations in the part geometry or the mold temperature.

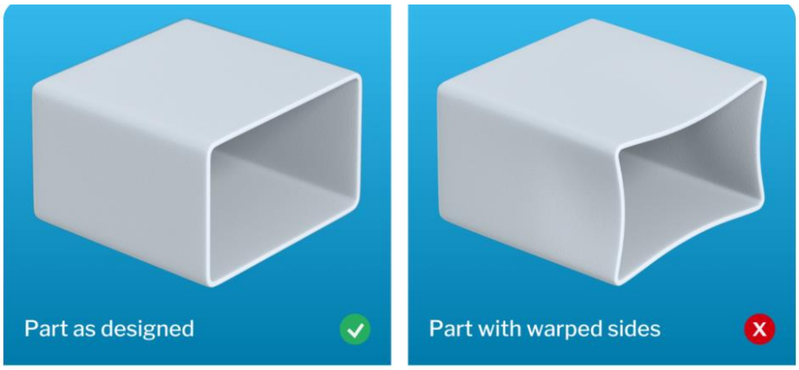

Figure 25- Part as designed and Part with warped sides (Fast Radius, 2022).

Flash

Flash is a common defect that occurs in injection molding, where excess material escapes from the mold cavity, typical route for escape are through the parting line of the mold or ejector pin locations and results in a thin layer of plastic around the edge of the molded part. Flash defects can occur due to several reasons, such as insufficient clamping force, inadequate mold design, excessive injection pressure, or worn-out mold components. Flash not only affects the aesthetic appearance of the molded part but can also cause functional issues, such as interference with mating components or sealing surfaces. Next Figure 26 shows a typical flash defect at the tip of tubular components produce in Muroplás.

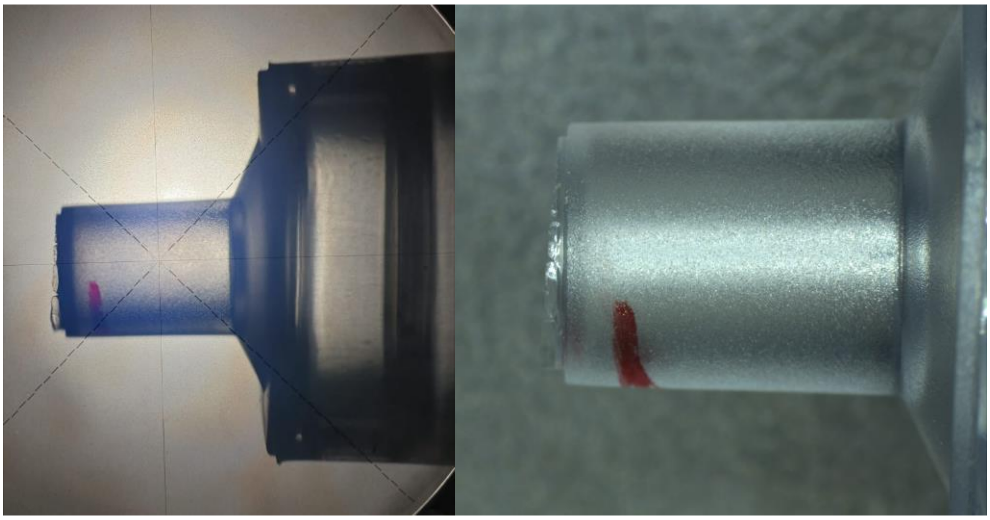

Figure 26- Flash defect, Muroplás.

Burn marks

Burn marks are small, dark or black spots that appear on the surface near the end of the flow path of a molded part. This marks usually are created either by the degradation of the plastic material due to excessive heating or by high injection speeds. Burn marks can also be caused by the overheating of the trapped air.

Blush

Gate blush, or sometimes simply called as blush, seen in Figure 27, is the scar-like, cloudy discoloration near the gate area. It has an inconsistent appearance than the other area. As the name suggests, many of them have a dull appearance, however, some may be mixed with brighter (more glossy) area, and they usually appear in the pattern of circular or fan-shaped, depending on the gate type and flow direction of molten resin inside of the cavity.

Figure 27- Blush defect, (Boyanmfg, 2020).

Black Specks or Streaks

Black specks or streaks in injection molding are visible defects that appear as small black particles or lines on the surface of the molded part. These defects can be unsightly and may reduce the overall quality and functionality of the part.

Some of the most common causes of black specks or streaks in injection molding include contamination such as dirt, dust, or metal particles can become trapped in the mold cavity and cause black specks or streaks in the molded parts, burning if the resin is overheated or held at the wrong temperature for too long, it can begin to degrade and produce black specks or streaks or resin impurities that can sometimes contain impurities or contaminants that can cause black specks or streaks in the molded parts.

To resume all the information about defects, Table 5 shows an organized overview of those defects as well the most common factors and causes that contribute to their appearance, on the other hand, some possible solutions can be tested.

Table 5- Defects and their main causes.

	Factors			
Defects	**Machine**	**Mold**	**Material**	**Operator**
Flow Lines	Inadequate injection pressure	Mold temperature too low	Improper flow rate	Inconsistent cycles
Sink Marks	Insufficient injection pressure or time	Excessive rib thickness	Excessive regrind use	Early gate opening
Weld Lines	Barrel temperature too low	Mold temperature too low	Improper flow rate	Inconsistent cycles
Short Shoot	Insufficient material feed	Insufficient venting	Improper flow rate	Inconsistent cycles
Warping	Inadequate injection pressure or time	Mold temperature too low	Improper flow rate	Improper handling of parts
Flash	Excessive injection pressure	Inadequate mold supports	Improper flow rate	Inconsistent cycles
Black Specks	Excessive residence time in barrel	Sprue bushing cracked	Contaminated raw material	Inconsistent cycles
Burn Marks	Excessive injection speed or pressure	Improper venting	Excessive regrind use	Inconsistent cycles
Blush	Injection speed to fast	Mold Temperature too cold	Excessive moisture	Inconsistent cycles

As it will be seen in the next topic, coatings can help reduce or eliminate some of the defect that are common to appear in plastic injection molding parts.Weld lines in injection molded parts can be reduced by improving the flow of the molten plastic and reducing the friction between the plastic and the mold surface. For example, a coating with good release properties can help the plastic flow more smoothly across the surface of the mold, reducing the likelihood of weld lines. Additionally, coatings can be used to reduce surface roughness or to add texture to the mold surface, which can help hide or minimize the appearance of weld lines.

Coatings can also help prevent or reduce warping in injection molded parts by improving the thermal conductivity of the mold and promoting more even cooling of the plastic. Additionally, coatings with good release properties can help prevent the plastic from sticking to the mold surface, which can reduce the stress on the part during the demolding process and help prevent warping.

2.4. Coating solutions – Surface treatments

Metalilic components such as dies, machinery and moulds are subjected to degradation during plastic transformation processes, plastic injection molding, when working with abrasive fillers and corrosive materials combined with relatively high processing temperatures. This degradation reduces the lifetime of the components considerably and has a direct impact on process productivy and surface finish (Cunha and Andritschky 1999).

2.4.1. Thermochemical treatment methods

Unlike others heat treatment counterparts in molds like tempering, quenching, hardening, thermochemical methods utilize chemical elements that diffuse from a gaseous, liquid or solid state into the material surface to produce a hard, wear-resistant layer. A distinction is drawn between nitriding, carburizing and boriding.

Nitriding

Nitriding, together with ferritic nitrocarburizing, has been and remains the primary thermochemical treatment method, representing the predominant industrial surface modification technologies in terms of volume (Czerwinski, F. 2012).

Nitriding treatment leads to an incorporation of nitrogen into the surface of the steel while it is in ferritic state. The medium determines the temperature and duration of the process. In a bath, the molds are preheated to 400ºC and the nitriding itself is done at 580ºC (Menges *et al*, 2001). The time depends on the desired depth of the treatment and in commercial applications, the typical modified zone is up to 200-300 µm thick, rarely exceeding 600 µm to 1mm. The greatest hardness is achieved immediately at the surface, reaching 800 Brinell or 70\80 HRC for some steels and for typical nitriding steels its around 50 HRC and post-treatments of the surface is unnecessary.

Figure 28 shows the surface hardness in terms of penetration depth.

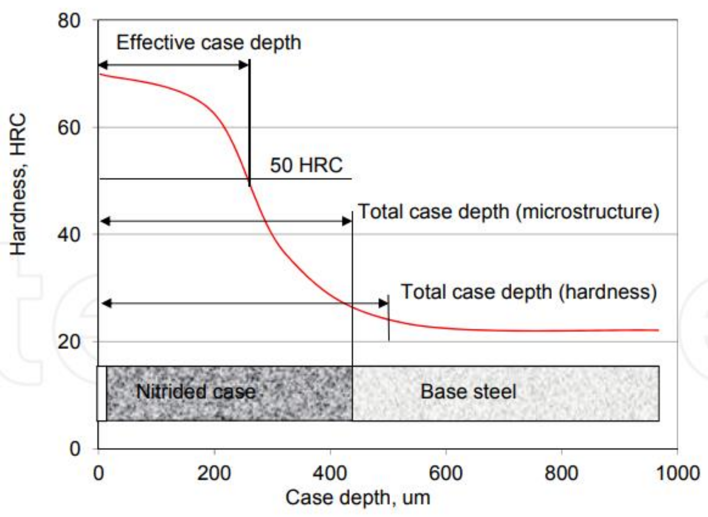

Figure 28- Schematics explaining measurements of total and effective case depths after nitriding (Czerwinski, F. 2012).

Surface hardness is improve as well the wear and corrosion resistance of metal components. In mold industry nitriding treatments are typically applied to sliding components, which come into direct contact with other components such as sliders and lifters and other moving parts of the mold.

Nowadays is commercialized several nitriding technologies available that explores different sources of nitrogen. Without going into great detail about these different technologies they will be briefly described:

- Gas nitriding;
- Liquid salt nitriding;
- Plasma (ion) nitriding;
- Laser nitriding;
- Beam ion implantation;
- Etc.

Carburizing,

Carburizing is a widely employed thermochemical treatment, is a surface hardening process used to enhance the wear resistance and strength of metallic components. In this treatment, the material is exposed to a carbon-rich environment at elevated temperatures. Through the diffusion of carbon atoms into the surface layer of the material, a high carbon concentration is achieved, forming a hardened case while maintaining a relatively softer core. In carburizing, Typically, these surface layers possess a low carbon content, typically less than 0.25%, making them unsuitable for hardening. By subjecting the steel to temperatures ranging from 850 to 980 ºC in a carbon-rich environment, the carbon content is elevated, reaching levels as high as 0.9%. This process allows for the transformation of the surface layers into a hardened state, while maintaining a relatively lower carbon concentration in the core. If the steel is rapidly quenched from the carburizing temperature, the process is referred to as direct hardening (Menges *et al*, 2001).

Boronizing

Another thermochemical treatment commonly used is called boriding or boronizing. Boronizing is a surface treatment process in which boron atoms are diffused into the surface layer of a material, typically steel or other metals, to form a hard and wear-resistant boride compound layer. The treatment is conducted at elevated temperatures between 800 and 1050 ºC in the presence of boron-rich media, such as boron-containing gases or solid boron compounds. During the process, boron atoms diffuse into the material, reacting with the base metal to form a layer of borides. This boride layer significantly enhances the surface hardness, wear resistance, and corrosion resistance of the treated material (Menges *et al*, 2001).

2.4.2. CVD-Chemical vapor deposition

The CVD technique is generally based upon a chemical reaction between a gaseous phase and the heated surface of a substrate in order to produce thin-film of coating. A wide range of metallic, ceramic and diamond-like carbon coatings can be produced by this technique. The CVD reactions generally take place in the temperature range 150-2200 ºC and frequently between 500 and 1100 ºC (Lang, E. 1984). Other authors (Menges *et al,* 2001) claim that chemical reactions take place at temperatures above 800 ºC.

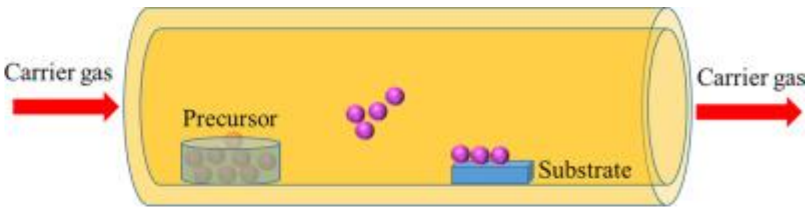

Figure 29- Chemical vapor deposition process (Mittal *et al*, 2021).

The high temperatures needed for this process cause the base material to loose hardness and strength. This disadvantage must be compensated by another heat treatment and associated hardening of the base material. Because of every heat treatment involves risks such as distortion, in 1999, efforts were being made to lower the process temperatures, at the moment temperature of 700 ºC and lower can be applied.

CVD coatings are thicker than PVD and applied at even higher temperatures, and one advantage is that diamond coatings can be applied, offering the highest possible wear resistance and increased tool hardness for extremely long tool like. Don't need to be applied in line-of-sight, so the whole tool can be treated if necessary.

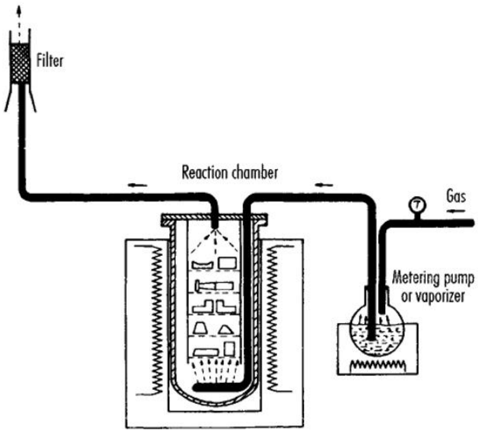

Figure 30- Equipment for depositing titanium carbide, schematic (Menges et al, 2001).

2.4.3. PVD-Physical vapor deposition

PVD is an acronym for Physical Vapor Deposition and are atomistic deposition processes in which material is vaporized from a solid or liquid source in the form of atoms or molecules, transported in the form of vapor through a vacuum or low pressure gaseous (or plasma) environment to the substrate where it condenses, Figure 31. Typically, PVD processes are used to deposit films with thicknesses in the range of a few nanometers to thousands of nanometers, however they can also be used to form multilayer coatings (Mattox, D. M. 2010).

The source is typically a rod or ingot of ceramic or metal (RapidDirect, 2021).

During PVD process, the vaporized material is ionized by the plasma, which consists of high-energy particles that are created by applying a voltage to a gas, such as argon or nitrogen, in the vacuum chamber. The resulting plasma helps to remove any contaminants on the substrate surface and bonds to the tool wall in very thin layers, it's possible to be less than a micron not enough to affect the final part dimensions in most cases, with great adhesive strength.

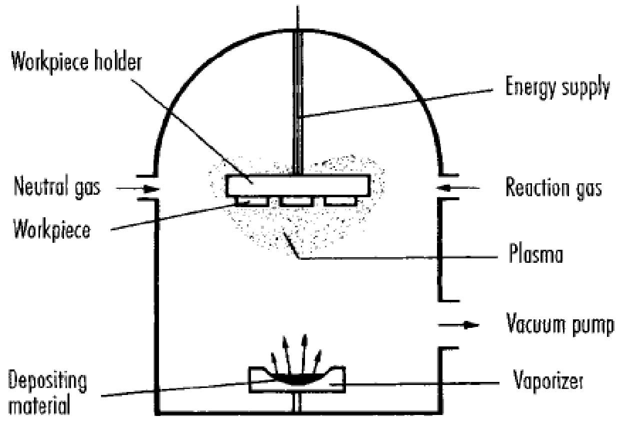

Figure 31- Basics of the PVD technique (Menges *et al*, 2001).

Several common PVD coating processes include:

- Sputter coating, Figure 32 - Is a PVD coating process in which a target material is bombarded with high energy ions. The target material's atoms are ejected or sputtered from the surface and then deposited onto the substrate.
-

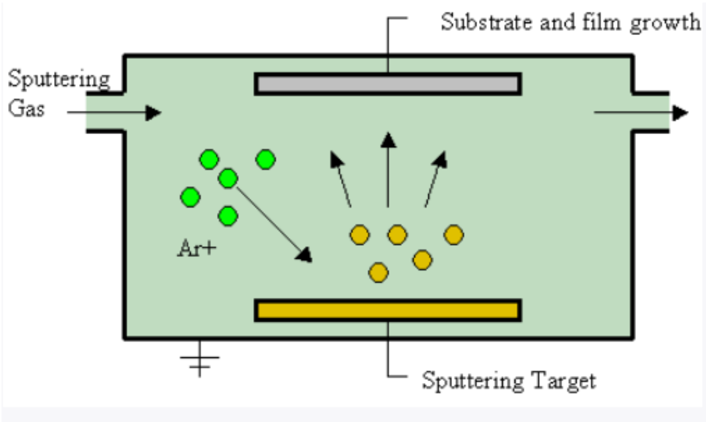

Figure 32- Sputter coating schematic.

- Thermal evaporation, Figure 33 - Thermal evaporation is a PVD coating process in which source material is heated until it evaporates. The vapor is then deposited onto the substrate, forming a thin, uniform layer. This process is often used for coating materials sensitive to ion bombardment or applications requiring a high degree of control over the coating process.

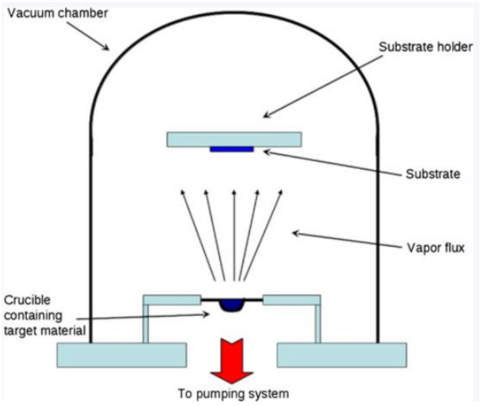

Figure 33- Thermal evaporation schematic.

- Electron beam evaporation, Figure 34 - Electron beam evaporation is a PVD coating process in which a focused beam of electrons is used to heat and evaporate the source material. The vapor is then deposited onto the substrate, forming a coating. This process allows for more precise and controlled deposition of the coating material, which makes it useful for applications where a high degree of accuracy is required.

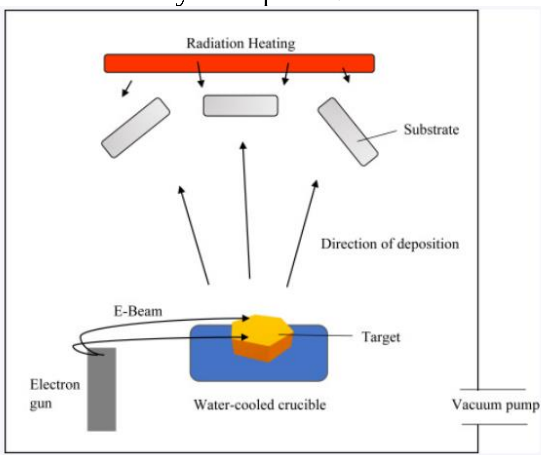

Figure 34- Electron beam evaporation schematic.

- Ion plating, Figure 35 - Ion plating is a PVD coating process in which a gas containing atoms of the coating material is introduced into the vacuum chamber. The gas is ionized, and the ions are then accelerated and directed toward the substrate, where they are deposited to form a coating. This process allows for a more uniform and consistent coating than other PVD processes, making it useful for applications requiring a high degree of uniformity.

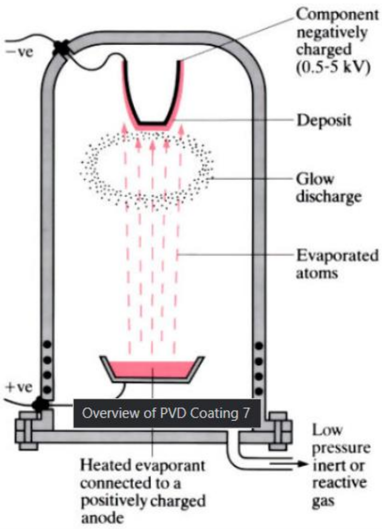

Figure 35- Ion Plating schematic.

Nitride based hard coatings have proven their capability in increasing tool lifetime when being exposed to abrasive and corrosive environments and they are generally deposited PVD deposition techniques (Cunha and Andritschky 1999).

The most common applications on tools are Titanium Nitride, TiN, Titanium Carbo-Nitride (TiCN), Aluminum Titanium Nitride (AlTiN),Chromium Nitride (CrN) Chromium Aluminium Nitride (CrAlN), but there are many more.

Figure 36 and Figure 37 shows a typical visual aspect of a TiN coat and a CrN coat respectively.

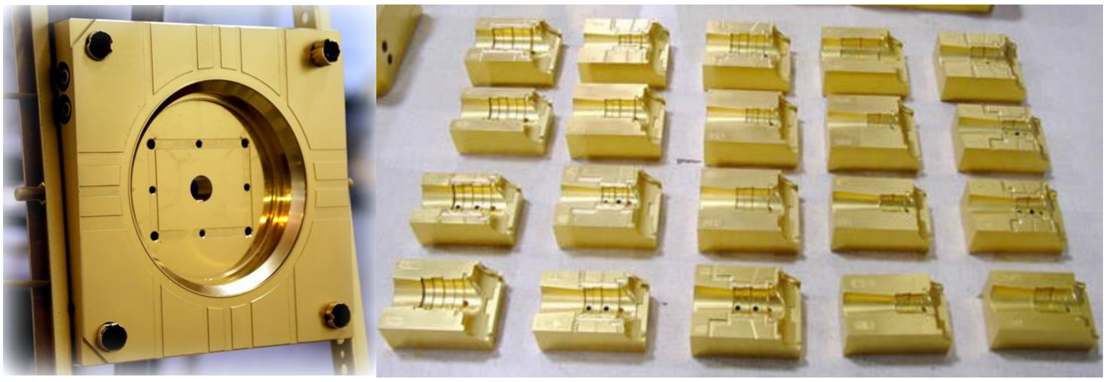

Figure 36- TiN coated mold cavity (Surface Solutions Inc.).

Figure 37- CrN coated (Titanit).

TiN is by far the most used and is exceptionally durable and increases hardness, while offering better corrosion resistance, it can withstand the chemical attack of aggressive plastic such PVC resins while enhancing lubricity.

Chromium Nitride (CrN) coatings are often used for molds that require excellent corrosion resistance, such as those used in the food processing industry. They are also used on molds for injection molding, extrusion, and blow molding.

This process can be made nationally for the mold industry, taking the example of the Portuguese company Durit Coatings (Te and M) with its catalog containing the materials most used in this type of coating, as shown in Table 6. The applications can be the mold surfaces, feed channels, ejector pins and some movable components (which is the case of the study) and they named the principal advantages of this application:

- Increased longevity of components;
- Cost reduction;
- Reduction of downtime/maintenance;
- Increased global productivity;
- Better end product quality.

Table 6- PVD catalog of DuritCoatings for mold industry.

	Color	Hardness HV	T.Máx service (ºC)	Friction Coeficient	Thickness (µm)
HardTiN		2600	650	0,7	2-5
HardTiL		3300	850	0,5-0,7	2-5
HardCrom		2700	900	0,3-0,4	2-5
DiExtra		2700	400	0,3	2-5

HardTiN (TiN) - Titanium Nitride,

HardTiL (AlTiN) Aluminum Titanium Nitride

HardCrom (CrN) Chromium Nitride

DiExtra- DLC, Diamond-like-carbon.

There are some literatures that that proves the advantages of these treatments, despite ensuring better protection of molds and components, ensuring longer lifetimes and reducing maintenance and stoppages, another very important aspect is the possibility to reduce the friction coefficients with this PVD coatings. Bobzin *et al*, in 2017 made a study where a chromium-based nitride coating was deposited on one of the micro-structured mold, H11 steel, by mens of middle frequency magnetron sputtering (mfMS), the coating CrAlN contained approximately 51% chromium, 30% aluminum and 19% nitrogen and it was experimentally seen that the coefficient of friction measured using a pin on disc tribometer reduces about 11% and 17% for the used plastics in those tests, therefore, a lower wettability in contact with the plastics melt analyzed by means of high temperature contact angle measurements was achieved for coated surfaces. This means a lower amount of shear energy required for the separation of the solidified plastics from the surfaces, improving process repeatability (Bobzin *et al*, 2017).

Its possible to observe in Figure *38* the coefficient of friction of the substrate H11 coated with CrAlN as well as of an uncoated reference agains counterparts made of the two tested plastics. A positive characteristics is that the CrAlN coating exhibits a lower CoF in comparison to both uncoated substrates.

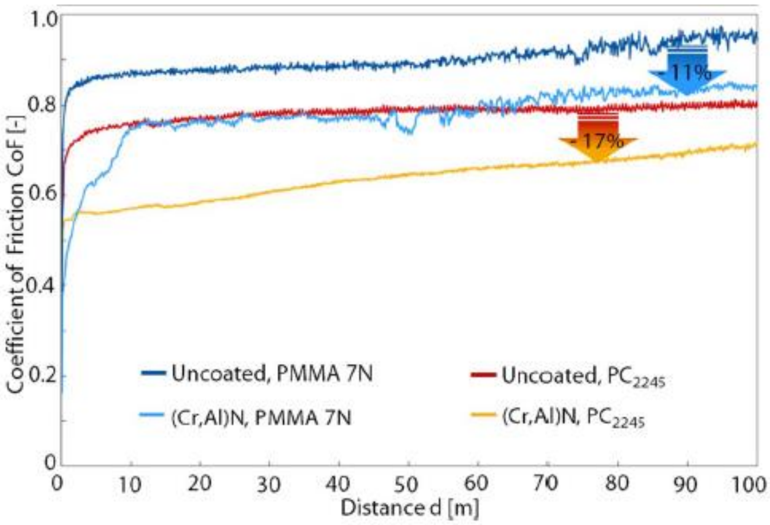

Figure 38-Tribological investigantions between CrAlN coating as well as uncoated H11 against tested plastics.

Some advantages of CVD over PVD are:

- High purity - The use of gas avoid the impurities of liquid coating processes.
- Uniform coating - CVD uniformly coats a substrate regardless of the shape to produce an even coating. Not a line-of-sight application so it can be applied to hidden areas, Figure 39;
- Application variety, such as holes and walls;
- Cost – CVD systems cost less than PVD systems.

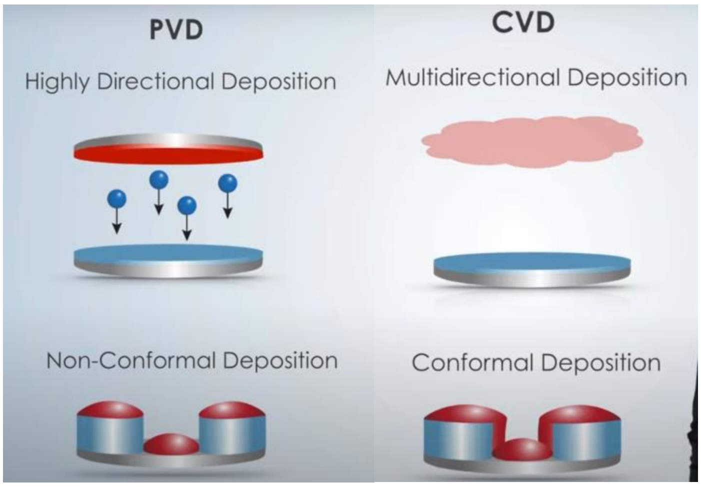

Figure 39- Main differences between PVD and CVD.

Some advantages of PVD:

- Higher temperature resistance;
- Abrasion and impact resistance;
- Environment friendliness – Unlike CVD, PVD does not produce hazardous byproducts and does not use hazardous gases in its processes. PVD uses high power electricity or lasers to gasify the coating material;
- Wear-resistant coating (Stoner, J. 2022).

2.4.4. Plating–Electroplating and Electroless Plating

Plating is a manufacturing process in which a thin layer of metal coats a substrate material. During processing, some polymeric materials release chemically aggressive substances, mostly hydrochloric or acetic acid, in this cases molds and their components are frequently protected by electrolytic plating with chromium or nickel (Menges *et al*, 2001). This process is typically accompanied through two strands:

- Electroplating - which involves passing an electric current through a solution containing a dissolved metal, causing the metal ions to bond with the surface of the material being plated. Electroplating needs an electrolyte solution that is made by a molten salt solution of desired metal, containing both positive, and negative ions (Mittal *et al*, 2021);
- Electroless plating - is an aqueous reduction process in which metal is deposited from solution, often under a catalytic action that can be adapted to promote deposition on a metal surface (Gabe, 1978). Electroless plating is often used to deposit nickel or copper metal and more recently alloys of Nickel-Boron

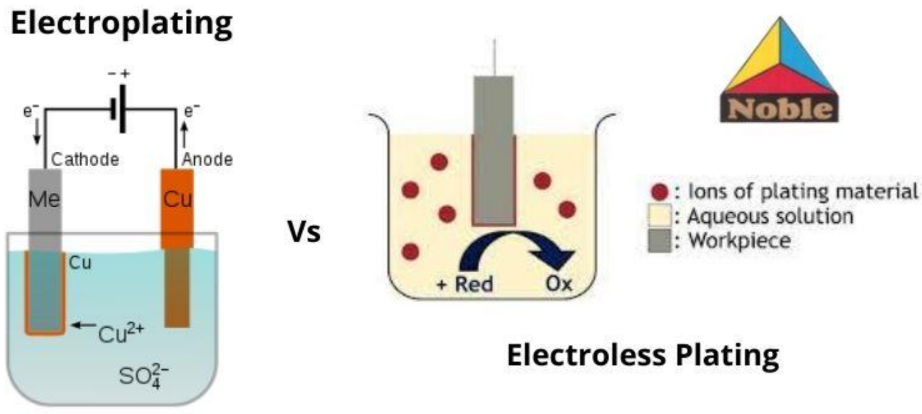

Figure 40- Electroplating Vs Electroless Plating (Noble, 2021).

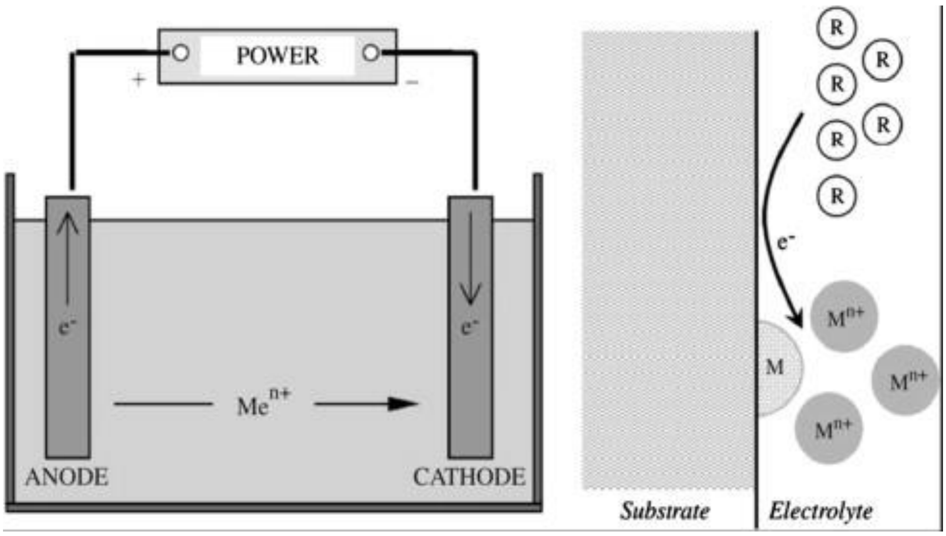

Figure 41- Cell set up for (left side) electrolytic deposition process plus external power source; (right side) electroless deposition with reducing agent R as the source of electrons (Sudagar *Et al*, 2013).

In either case, the technique results in one or several of the following benefits:

- Improved corrosion resistance;
- Decorative appeal;
- Increased solderability;
- Enhanced strength;
- Reduced friction;
- Altered conductivity;
- Enhanced paint adhesion;
- etc

Electroless plating is used for a wide range of applications including decorative coatings, corrosion protection and wear resistance. This method has received considerable attention over the last few years while more inconvenient, hazardous and expensive than aqueous deposition certain advantages are apparent (Gabe, 1978, p.70).

- Electroless plating can produce thinner and more uniform coatings with complex shapes or internal surfaces than electroplating.
- Electroless-plated parts tend to be harder and less porous, which enhances wear and corrosion protection. It's also easier to achieve the desired coating thickness because of the uniformity of the deposit. What's more, electroless plating is better suited to working with parts featuring complex shapes or numerous recessed areas on the surface.
- Electroplating is permanently effective only if there is a uniform thickness of the deposit and sharp edges are avoided (Menges *Et al*, 2001a).
- Electrodeposition requires the use of a conductive surface, while electroless plating can be used on non-conductive surfaces with the appropriate pre-treatment.

However, electroless plating is generally slower and requires more preparation and pre-treatment steps than electrodeposition.

STEPS FOR ELECTROLESS PLATING

In the electroless plating process, the substrate to be plated is first cleaned and activated with a series of chemical treatments to ensure good adhesion of the coating. The substrate is then immersed in a plating bath that contains the metal ions and a reducing agent. The reducing agent on the surface of the substrate causes the metal ions in the solution to be reduced and deposited onto the surface of the substrate as a thin, uniform coating. The electroless plating process can also be used to deposit various metals, including nickel, chrome, copper, gold, silver, and platinum, and can be tailored to meet specific coating properties, such as hardness, corrosion resistance, and electrical conductivity.

Applying the plating process to the mold industry there are two materials that should be highlighted for their constant use:

- Chromium - Eletroplating Hard Chrome
- Nickel - Electroless Nickel (EN)

However, there are some potential drawbacks to using hard chrome coatings. For example, the plating process can be environmentally hazardous due to the use of hexavalent chromium. Additionally, the hard chrome coating may be prone to cracking or peeling if the underlying metal surface is not properly prepared or if the coating is subjected to high levels of stress or impact.

As for hazardous waste and toxic chemicals, traditional hard chrome plating can produce hazardous waste and use toxic chemicals such as hexavalent chromium. Hexavalent chromium is a known carcinogen and can pose serious health risks to workers and the environment if not handled properly. The disposal of the hazardous waste generated during the plating process can also be problematic, and many countries have regulations governing its disposal. "Exposure to hexavalent chromium during the electroplating process can pose serious health risks, including lung cancer, eye and skin irritation, and other respiratory issues” (Liu and Lu, 2018).

Use of electroless nickel plating + Teflon (Tribocoat)

For this report it is known that electroless nickel plating is widely used in the plastic injection mold industry to coat the molded areas of the cavity and core of the part, as well as its components that will be in contact with the material to be injected during the process, due to the low cost of the process when compared to other types of existing coatings for these applications, as well as its ability to withstand unwanted reactions with other types of more aggressive plastic materials, such as PVC.

There are several suppliers of this type of surface treatments in the country, however, due to the geographic proximity between the two companies and the relationship of trust that they have already established over the years, the treatments will be in charge of the company *Mold-Tech–Tratamento e Revestimentos de Metais, Lda Maia*, with several headquarters spread across the globe.

This company has a particular variant process of the electroless nickel in which Polytetrafluoroethylene (PTFE) is added to the nickel-plating bath to produce a composite coating. The commonly known brand name of PTFE-based composition is Teflon and is a type of fluoropolymer that is commonly used as a solid lubricant due to its low friction coefficient and high resistance to heat and chemicals (PVC).

When PTFE is present in the nickel coating, it can form a low-friction surface that helps to reduce the coefficient of friction between two surfaces in contact. This makes the coated parts more resistant to wear and reduces the need for lubrication, which can reduce maintenance costs and increase the lifespan of the coated parts.

The PTFE content in electroless nickel coating can be controlled by adjusting the amount of PTFE powder added to the bath, and this company provides two different solutions, a Low Teflon (Electroless Nickel with 7% PTFE composite coating) and Hight Teflon (Electroless Nickel with 20% PTFE composite coating), the specifications can be seen in Figure 42 below:

Mold-Tech Tribocoat® HT (High Teflon) Specifications	
Type of Coating:	Electroless Nickel with 20% PTFE (Teflon) Composite Coating
Thickness Range:	0.0002 to .00020 inches +/- 0.0001 uniform across all coated surfaces
Lubricity:	Coefficient of friction 0.04
Corrosion Resistance:	Over 300 hours salt spray @0.001 thick build
Hardness:	40 Rc - 50 Rc after 500ºF for 2 Hours
Wear Resistance:	14MG. Tabor CS-10 wheel w/ 1 kg load
Operation Range:	-50ºF to +750ºF
Max Size - Steel:	64” long x 32” wide x 43” deep
Max-Size Aluminum:	72” long x 36” wide x 43” deep
Lifting Capacity:	20 tons

Mold-Tech Tribocoat® LT (Low Teflon) Specifications	
Type of Coating:	Electroless Nickel with 7% PTFE (Teflon) Composite Coating
Thickness Range:	0.0002 to .00020 inches +/- 0.0001 uniform across all coated surfaces
Lubricity:	Coefficient of friction 0.06
Corrosion Resistance:	Over 300 hours salt spray @0.001 thick build
Hardness:	52 Rc - 55 Rc after 500ºF for 2 Hours
Wear Resistance:	14MG. Tabor CS-10 wheel w/ 1 kg load
Operation Range:	-50ºF to +750ºF
Max Size - Steel:	64” long x 32” wide x 43” deep
Max-Size Aluminum:	72” long x 36” wide x 43” deep
Lifting Capacity:	20 tons

Figure 42- Mold-Tech Tribocoat specifications (High and Low Teflon).

In order to carry out this part of the report on Tribocoat, a entry into Mold-Tech's facilities was allowed in order to better understand the various stages of the process. Similar to the one previously described.

Figure 43 shows the result of the process on a steel sample to view the different textures, greater lubrication of the component is noticeable to the touch. Left side tribocoat coating, right side steel.

Figure 43- Sample with Tribocoat treatment (Mold-Tech courtesy).

The process starts, first of all and daily, with the verification of the amount of nickel deposition in a rectangular specimen during 1 hour of bathing. The operator weighs the specimen, before and after the bath, and depending on the weight gain the increase in thickness gained of the specimen is identified, in microns, in this case was about 5.7 micros. This test serves to determine the bathing time of certain components to be coated, depending on the desired thickness for different applications and to ensure that the concentration of the nickel ions and reducing agent in solution are controlled. The rest of the steps were not explained in depth, namely the type and composition of the bath used in each stage that are part of the internal know-how, limiting the explanation to the basics and its functions.

The process of coating the Muroplás pins started with the following steps, all of them in carried out in PP, polypropylene, works tubs/Vats with about 182cm long, 91cm wide and 109cm deep :

1. Manual placement of pins in a perforated plate to hang the components. In this case, with lightweight components its easy to handle manually, however this process can coat part of the mold (cavitys, cores) up to 20 tons and in those cases, common industrial cranes are used.
2. Surface preparation. Chemical Degreaser during 10-30min depending on the pieces sizes for a first superficial cleaning.
3. Surface preparation. Eletrolytic degreasing, where the part is immersed in and electrolytic solution, typically an alkaline solution, and an electric current is passed through the solution and the piece. This current, with the help of a current inverter to change the direction of the current, causes the grease and other contaminants to be remove into smaller molecules, which are then carried away by the solution.
4. Pickling is used to remove oxidation and tarnish films to enable good nickel/metal adhesion to develop at the outset coating. Acid dip techniques are often used followed immediately by rinsing (Gabe, 1978).
5. Nickel Strike, known as activation - similar to electroplating – with a solution containing nickel, wich will initiate the deposition of the electroless nickel coating followed by a cleaning step on distilled water. This step is necessary if

the base metal does not contain or has very low percentages of nickel in its constitution, <0.8%.

6. Nickel deposition, the piece is then submerged in the solution containing the reducing agent and the source of nickel ions that react to deposit the nickel layer onto the surface. This layer thickness can be controlled considering the test carried out initially on the specimen. In this case bath took 70min to ensure the desire thickness increase of 6-8 microns.
7. Post Heat-Treatment to improve its properties of nickel having in mind the base metal for the time and temperature of the tempering treatment. In this case, about 2\3h in a 180ºC furnace for the 1.2516 steel.
8. Quality Control: The final electroless nickel coating is inspected for thickness, adhesion, and other properties to ensure it meets the desired specifications.

Figure 44 shows the two pins, before and after the coating.

Figure 44- Muroplás pins, before (down) and after (up) the treatment.

3. Detailed presentation of the problem, Case Studies

3.1. MO0712-49

The first case study selected was mold 712, in this specific case the component 49 (712-49) Figure 45.

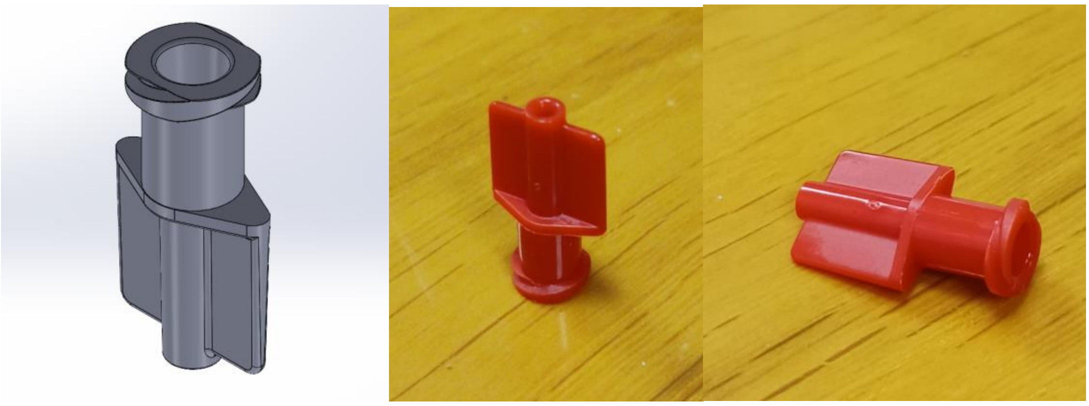

Figure 45- Component 49 of mold 712, (a) definition drawing, (b) and (c) real component, courtesy Muroplás.

The functioning of the component and its assembly in others will not be relevant for the study, there is only interest in its geometry and material. The material is a "PVC AM955 W3153 RED"

For the production of this component, a mold with 64 molding cavities is used, capable of producing 64 pieces simultaneously for each injection cycle. For this, a fixed molding plate, as its possible to see in Figure 46, is used, with the specific assembly of several components for the production of the desired part.

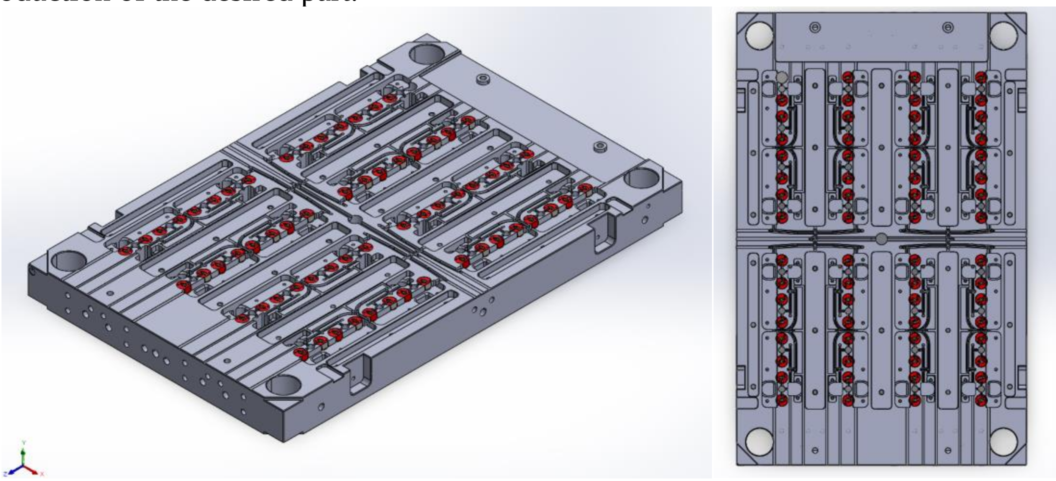

Figure 46-Fixed molded plate, (a) Isometric view, (b) Top view.

This mold is a mold for drawers, called Mold Type B within the company and each piece is produced with the aid of a insert produced specifically for this part reference, Figure 47, and by mobile drawers, Figure 48, hence the designation Mold for drawers.

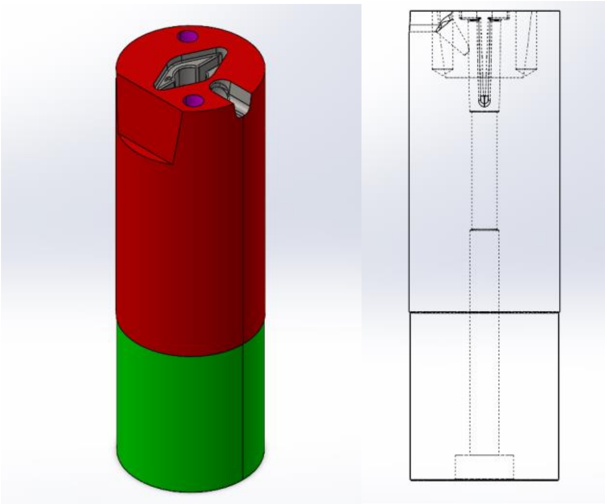

Figure 47-Insert of 49 component, (a) SolidWorks view, (b) Transparent view.

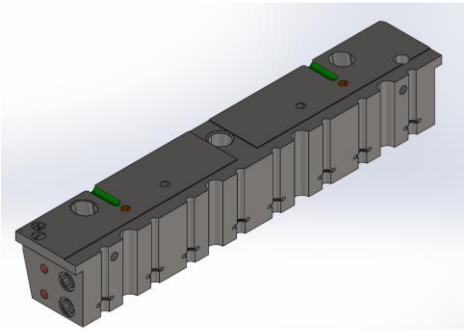

Figure 48- Mobile drawer.

The set of inserts and movable drawers can be seen in Figure 49 below.

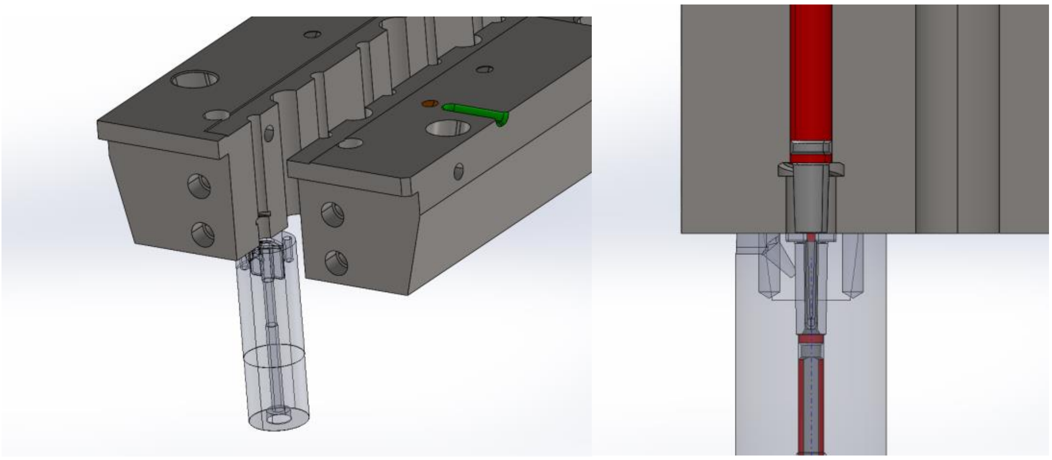

Figure 49- Set of inserts and movable drawers.

This component features a through-hole, for which two pins are inserted to shape the piece. These pins will always be in contact with the injected material and will also be subject to significant wear and corrosive reactions. Therefore, their coating must be taken into account from the outset.

The 'final' result of the entire molding area of the component is then presented below in Figure 50 and Figure 51, of course, in a simplified manner since presenting the entire mold for the study becomes irrelevant.

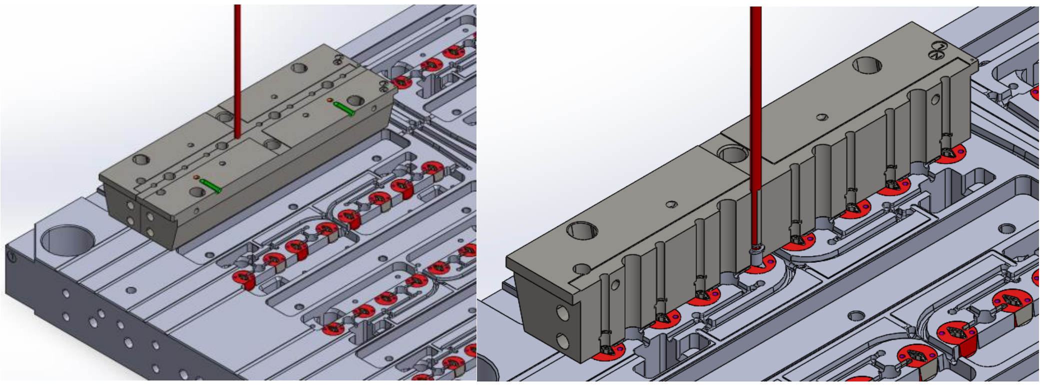

Figure 50- Final set result of mold 712.

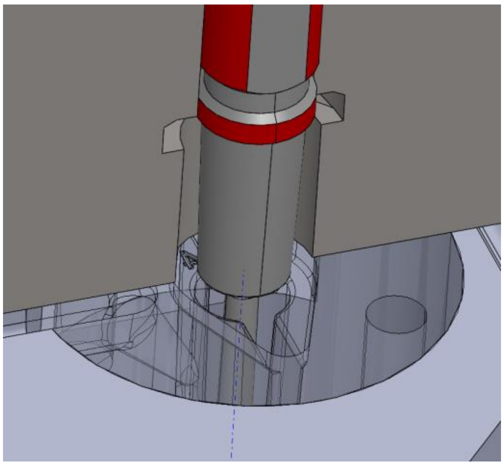

Figure 51- Final set result of mold 712, zoom section.

After the introduction of the piece and mold structure, it is now possible to describe in detail the defects that have been recurring in this component. It should be noted that this is an 'old' component, and many pieces have been produced over the years. As a result, its components (slides, pins, inserts) have undergone maintenance processes multiple times, which will be explained later, or even been remanufactured to ensure the quality of the component.

However, it serves as an example for future work at Muroplás with the aim of making the absence of these defects a recurring feature in their production. The existence of these defects, if any, causes problems and delays in various sectors.

3.1.1. Diagnostic 712-49

The diagnosis was conducted on 01-03-2023, during which several components showed off-center cavities between the fixed insert and the movable slides, resulting in the production being interrupted.

For comparison purposes, two images taken in the laboratory of two components with different cavities are shown in Figure *52*, clearly highlighting the difference between a misaligned component and another component that meets production standards.

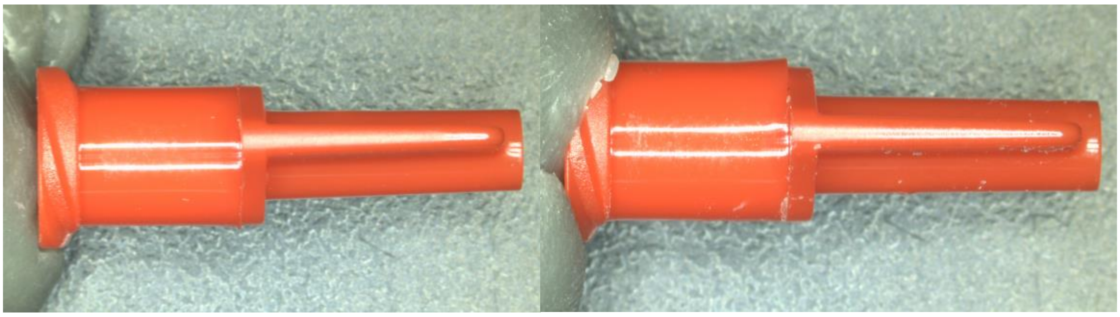

Figure 52-Component (a) without off-center, (b) with off-center.

In the initial phase, the area where excessive misalignment occurs in the component is noticeable, specifically in the molding cavity of the movable slides.

An inspection on a mitutoyo PJ 300 profile projector, Figure 53, can also be conducted to better perceive the dimensional variation. In this case, a component (part from cavity 57) with significant variation was selected for the study.

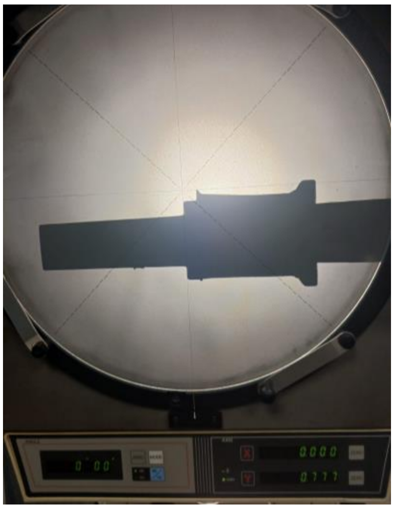

Figure 53- Dimensional inspection on a profile projector.

3.1.2. Causes of dimensional variation

In the initial phase, the area where excessive misalignment occurs in the component is noticeable. This occurs in the molding cavity of the movable slides.

In this case, similar to what happens with many mold components, the cause of the defect stems from the lack of material in the slides, specifically, the excessive removal of material. Over time, these areas have undergone multiple cleaning and polishing processes due to the tendency to develop stains or burns during the production of PVC components.

Referring back to the previously mentioned Figure 49, this newly edited image shows the wear that has occurred after successive cleaning and polishing of the movable slide area, Figure 54.

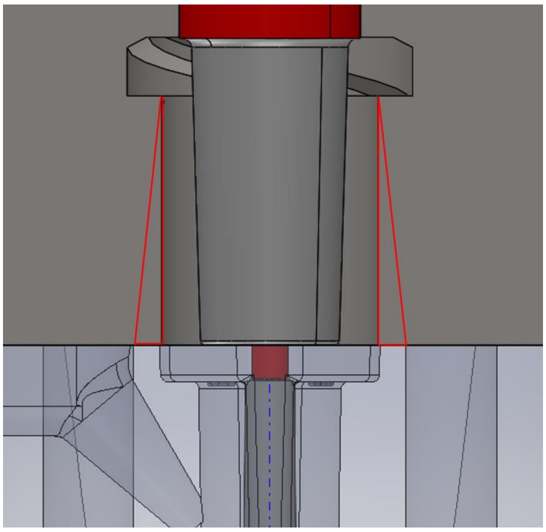

Figure 54-Highlighted zone of the wear in mobile drawers.

It is notable that in this area of the component, a phenomenon occurs that leads to the appearance of stains on the steel of the movable slides. There may be an excessive concentration of pressure, temperature, or even material flow in this region, causing issues.

In the next section, the filling simulation of the component will be addressed in an attempt to obtain some answers that, up until now, remain unanswered.

3.1.3. Moldex3D 0712-49 Simulation

The initial analysis conducted revealed higher temperatures precisely in the worn area, on the gate side. As a result, there was greater material removal on that side, leading to more noticeable marks on the movable slides of the mold. This type of analysis can be beneficial in future projects to determine critical areas during the filling process.

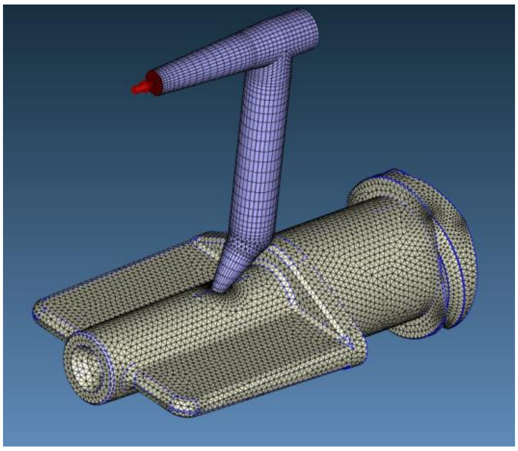

Figure 55- Moldex3D filling simulation of component 0712-49.

The cross-sectional view of Figure 56 shows in more detail the concentration of higher temperatures during the filling process of the component. This higher temperature in the material removal zone is mainly due to the viscous frictional forces during the passage of the plastic on the mold walls, and due to the fact of "throttling" when changing the section of the component. It is also perceivable that this increase in temperatures is almost uniform throughout the filling until the end of the part, where its possible to find another temperature concentration.

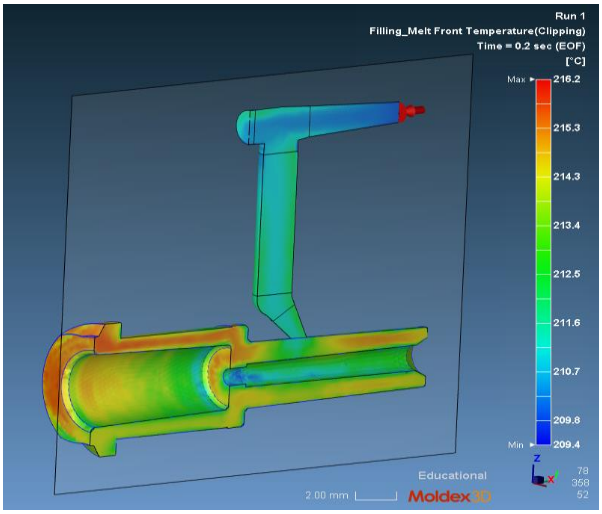

Figure 56- Cross sectional view of component, temperature analyses.

A possible solution would be the PVD-TiN coating, used for PVC injection molds, in these zones most affected by the temperature during the injection of the part. However, the most important thing would be to make an economic assessment to understand whether this operation would be profitable. These drawers have been used for some years now, where the biggest problem and loss of production is due to the maintenance of the mold after use. The most probable situation in this situation would probably be that there is no need for coating, however, in future projects for very large productions of PVC components it could be very advantageous.

3.2. MO0637-12 (Reduce Cycle Time , tribocoat).

The second case-study is the analysis of the mold 0637, more precisely component 12 of this mold (0637-12) as it can be seen in Figure 57. This component is a tubular part used for medical applications, serum chamber in infusion serum system.

Figure 57- Tubular component, Serum Chamber in infusison serum system.

For the production of this component a 32 cavity mold is used to produce simultaneously the 32 parts in each cycle of injection, Figure *58* shows an isometric view of the two halfs of the mold, (a) movable half and (b) fix half, highlighting the fact that this is a hot runner mold and as a carburator on the fix half.

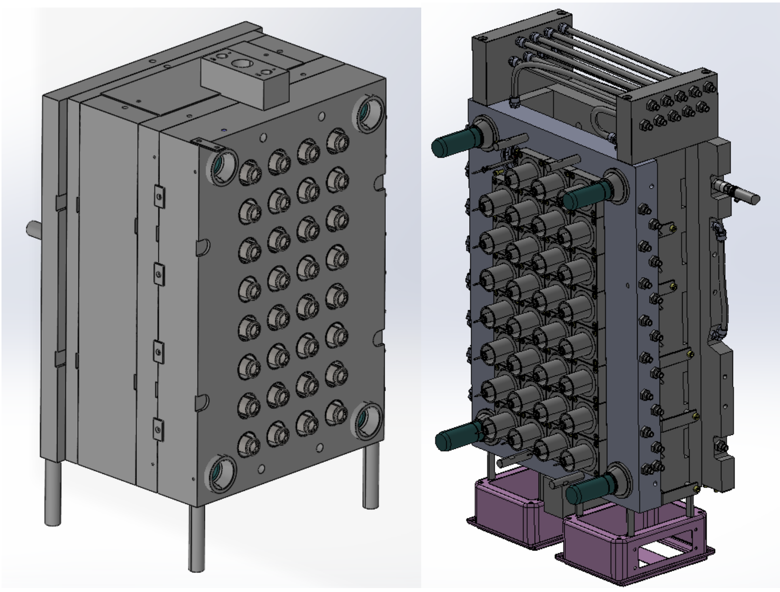

Figure 58- Mold 0637 with the component 12, (a) movable half, (b) fix half.

Regarding the operation of the mold to produce this component, two notable features are the two required inserts. One is in the fixed part, responsible for molding the interior of the tube (refer to Figure 59 (a)), while the other is in the movable part (refer to Figure 59 (b)), responsible for molding the exterior. In the first insert, the hot runner system is also present, which serves as the injection channel for the material. It has three injection points, each with a diameter of 0.9mm, as highlighted in Figure 60.

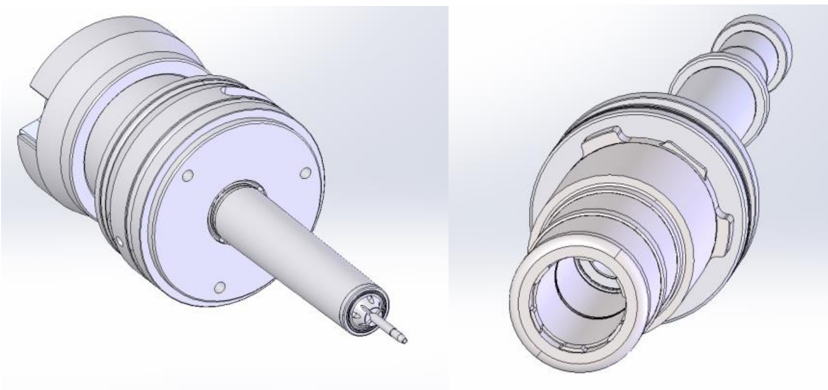

Figure 59-Inserts for the component 42, (a) interior of the tube, (b) exterior of the tube.

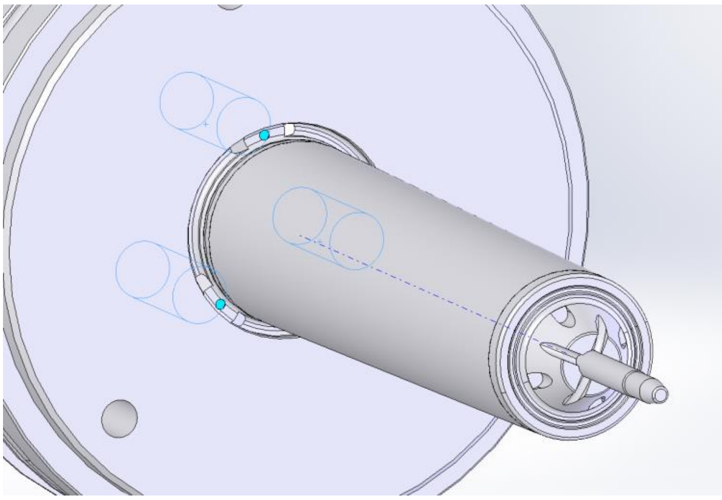

Figure 60- Injection points.

The assembly can be seen in Figure 61, and an attached drawing provides a detailed definition of the components for better understanding. Other components are required and are part of this set of inserts, such as the tubular shape extractor, central tip, and its extractor, movable cooling sleeve, among others, which can be reviewed in the attachments.

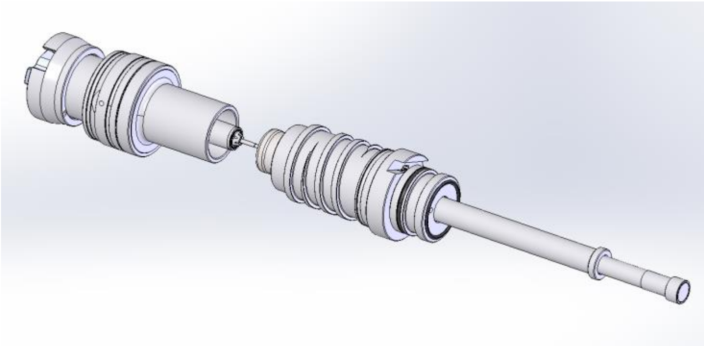

Figure 61-Assembly of the 2 inserts and other components.

In a cross-section view, it is possible to gain a better understanding of the behavior and interaction of the entire assembly, as shown in the next three figures, Figure 62, Figure 63 and Figure 64. This includes the hot runner system, the injection points, and the coupling of the two inserts to shape the tube.

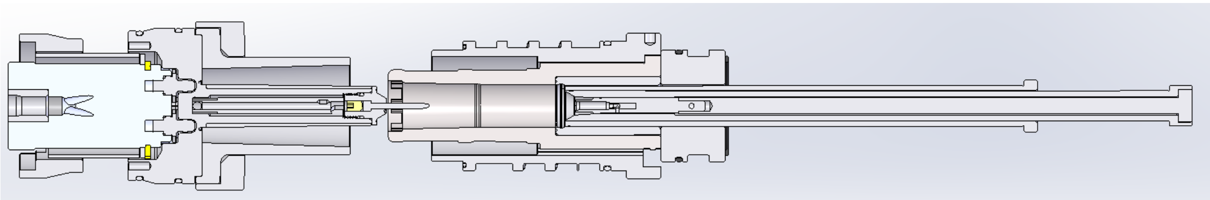

Figure 62-Geral view of all the components.

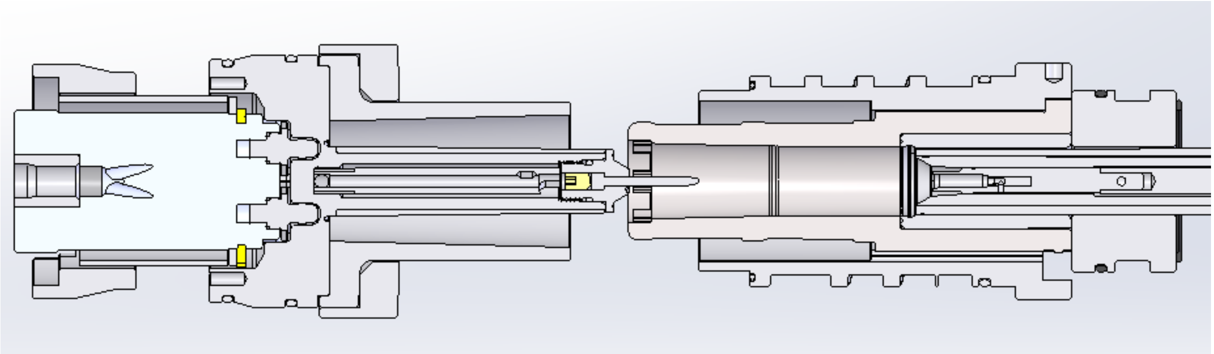

Figure 63- Both inserts with the open mold.

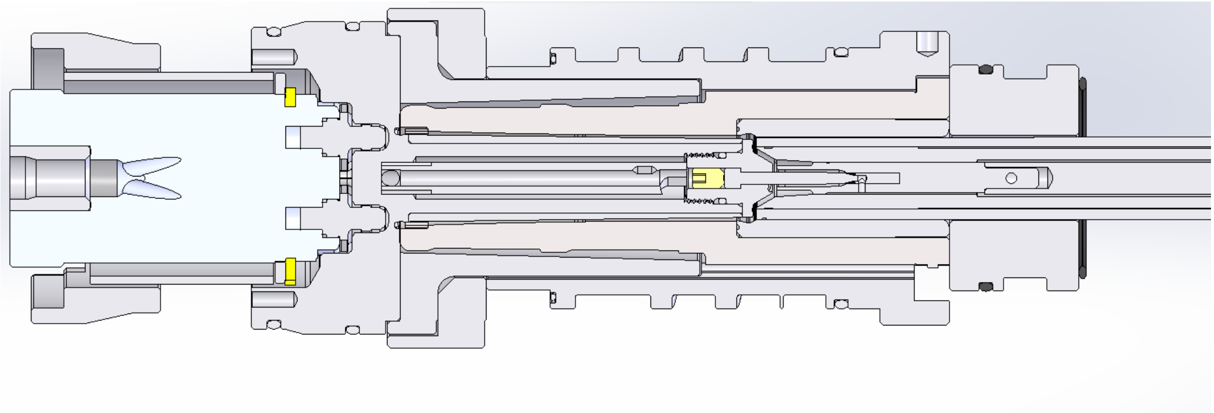

Figure 64- Both inserts with the mold close.

3.2.1. Diagnosis

This component was chosen for study, with the main objective of understanding if there is the possibility of reducing cycle times, with the use of an adequate coating in the most critical areas of the mold. Having this in mind, the first topic seen before studied the behavior of the mold components to understand which one would benefit most from the treatment.

After internal review, it was decided that the strategy to be adopted would be to coat the implant in the fixed part of the mold, by Electroless Nickel + PTFE, because there are a potencial time gain in the mold opening, currently it needs about 5 seconds to cool down and separate the inserts. The main goal is to understand whether it is possible to proceed with an early opening of the mold (movable part movement) without the occurrence of a flow defect in the part, due to the shear forces at higher temperatures between the plastic and insert, since it is possible that the part needs that additional time to cool down.

Another important aspect to have in mind is the final finish obtained in the plastic part. Since this is an ideally transparent component, it often does not happen (component is extracted with low surface quality, opaque, but acceptable) due to the fact that it is necessary to have higher roughness on the inner insert than on the outside, to facilitate the removal of the fixed part of the mold. Higher roughness means that the air will have ease “enter” the spaces between the part and the insert. In case that the inner insert is extremely polish, when opening, the piece would stick to the fixed part, due to the local build up of adhesion forces, since the insert on the outside of the piece would be rougher and the demolding would be facilitated in that zone, which is not what is desired.

In short terms, the two main goals is to study the effects on the cycle time for different inserts and in addition to observe if the quality of the part can be improved due to a lower roughness on the inner insert.

3.2.2. Mold preparation and assembly

Taking as a starting point the change in the insert of the fixed part, a solution found for not having coatings in unnecessary areas, which would be associated with high costs, was to implement a coated bushing around the previously machined insert by removing the necessary material. Figure 65 shows the dimensions of the Bush used, enhancing the inclination of the outer wall to facilitate the dismantling of the piece.

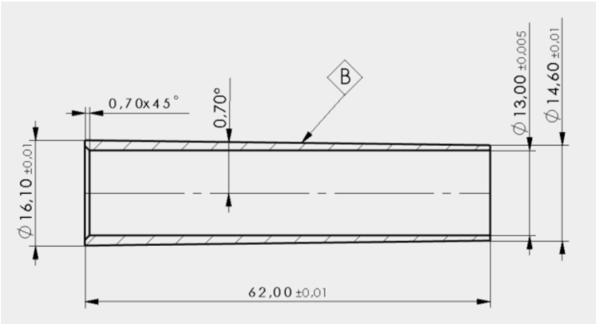

Figure 65- Definition drawing of the used bush, dimensions.

Figure 66 shows the insert with(a), and without(b) the bush in place to an easy visualization of the problem.

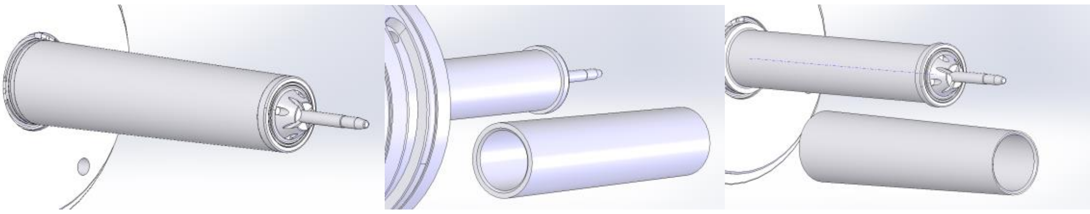

Figure 66-Insert (a) with bush, (b) without bush.

With this change, it is only necessary to ask to coat the bushing produced specifically for this purpose, significantly reducing the area to be coated. In this case, two bushings underwent treatment and no care was taken to cover the bushing so as not to coat the inside, which made it possible to reduce the area even further. In the future, if intend to re-coat similar components and in large quantities, it is advisable to find a way to cover the tops in order to cover only the outside in the bath.

With the limitation on the use of the mold currently in production, 0637-12, it is possible to test the process in a prototype mold (0509), a mold with only one cavity that is often used to test parts before moving on to the production of the final mold. For this is only necessary to assembly the insert components in the mold. In Figure 67 (a) its possible to see both parts as well as movable (b), and fix part (c) of the mold.

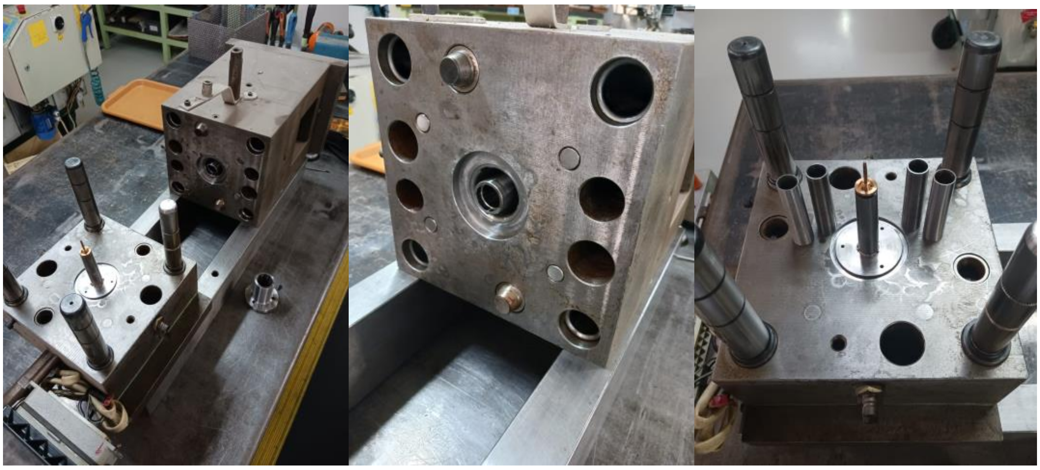

Figure 67-(a) 0509 mold, (b) movable half, (c) fix half.

For the execution of this work, four bushing components were produce with different finish parameters, two of them with super-polish characteristic and two with some rough finish with the objective of verifying if there are any correlation between high\low roughness and the injection parameters that will be study. Of these 2 groups of bushings, polished and unpolished, one bushing of each was coated with the Electroless Nickel+PFTE treatment, which is the main goal of this tests, additionally it's possible to verify if there are differences between the roughness of those two components before and after the coating.

For un-polish characteristics, a sandpaper P500 was used in a conventional lathe machine with low rotation speed, 115RPM, Figure 68. The "P500" designation on sandpaper typically refers to the grit of the sandpaper, which indicates the roughness or roughness of the surface it can polish. The lower the grit number, the rougher the sandpaper and the more material removed during the polishing process.

Figure 68- Un-polishing the bush on a conventional lathe machine, manual work.

For the polish characteristics, a sandpaper P800 was first used, followed by a P1200 and a 17 µm diamond past with high rotation speed, 1400rpm. Diamond past is a water-based polishing compound that is used for polishing the surfaces of many types of materials. The paste consists of microscopic diamond particles (diamonds being the hardest natural material around) that act as an abrasive to scrub, smooth and polish surfaces. Figure 69 shows the use of this diamond past.

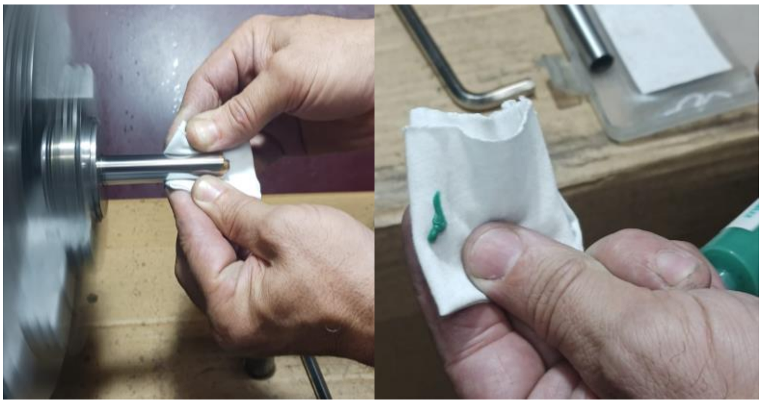

Figure 69-Polishing the bush with diamond past.

The roughness measurement, *Rz* which is a average *Rz* value over assessment length, took place in the DeMec workshops at the FEUP facilities with a surface roughness measuring instrument from Mitutoyo, Figure 70, and the results before and after coating can be consulted in Table 7. Was selected to the coating treatment the components 2 and 4, with the lower and higher roughness, to check the results after another surface roughness measurement. Components with the coating treatment also was mesured the arithmetic average value of filtered roughness profile deviations from the mean line, *Ra*.

Figure 70-Surface roughness measuring instrument from Mitutoyo, FEUP facilities.

Table 7- Roughness measurements of the four bushes used.

	Before		**After**			
Component	Roughness (µm)	Mean Roughness (µm)	Roughness - Rz (µm)	Mean Rz (um)	Roughness Ra (um)	Mean Ra (µm)
1	0.409	**0.258**	-	-	-	-
	0.187		-		-	
	0.178		-		-	

2	0.154	**0.216**	0.280	**0.212**	0.023	0.027
	0.161		0.175		0.031	
	0.332		0.182		0.027	
3	0.726	**0.918**	-	-	-	-
	1.045		-		-	
	0.983		-		-	
4	0.803	**0.959**	0.826	**0.831**	0.120	0.136
	1.079		0.947		0.207	
	0.995		0.721		0.082	

Next Figure 71Figure *71*, shows the four components tested in this study. Is easy to see the difference in color and texture of each pair. On the left side starts by the bush number "1" followed by the other 3 by order. Electroless Nickel + Teflon presents a more darker color.

Figure 71- The four bushes used.

The first conclusion is that the difference between the surface roughness does not have impact in the roughness after the coating of Electroless Nickel + Teflon, one simple explanation is that the nickel starts the process by filling uniformly with very small particles of nickel, less than microns, so its normal that, even with roughness, the coating does not change the values.

3.2.3. Tests and results

The injection tests took place at the Muroplás facilities on a Arburg allrounder 420c Golden Edition machine, Figure 72, and the concept was to determine optimal parameters for both uncoated bushings but with different surface finishes, compare those two tests and then move on to the tests with the two coated bushings and then analyse and compare the results presented.

Figure 72- Injection molding machine, Arburg allrounder 420c Golden Edition.

The first tested bush was the standard bush, already being used in the standard 32 cavity mold discussed earlier that is continuously in production, the bush number 3 with high surface roughness and without the nickel coat. The first tests were defined to achieve similar parameters with the model mold parameters but first it was necessary to define the amount of material to be injected in each injection cycle since the number of cavities and the length of the runners is totally different. Figure 73 shows that evolution until constant and full injected parts could be produced.

Figure 73- Evolution on quantaties of material, parameter tuning.

After some more iterations, the full parameters could almost match the already used in the 32 cavity mold, and that parameters sheet is in appendix section.

A first attempt to optimize the parameters was made in the first bushing used, and the most relevant parameters would be:

- Mold temperature (fixed half) Ti=60ºC;
- Cooling time (mold close), ti=5sec;
- Ejection time (mold open), ti=3sec.

As you can see in the parameters sheet, the cycle time, which is already quite low at 10s, may have some room for optimization taking into account the three most relevant parameters, all of them with some dependence between them.

Firstly, the temperature of the fixed part of the mold was reduced to 40ºC, with the aim of trying to reduce the cooling time, since the colder mold would extract more heat from the component, theoretically making it possible to open the mold faster. However, this test failed at is first attempt since a reduction in mold temperature would more quickly lead to a temperature equilibrium between the moving part and the fixed part after small cycles, a problem that will be discussed later in this analysis. After the first injection the component would be stuck on the fixed part, with a decrease of 0.5sec in total cycle time.

Bush Nº 1 and 2 (Polish)

As for the polished bushings, both prevented a single successful injection of this component correctly. The extremely low roughness of both bushes, either with the coating with its lubricating characteristics, either without these coating, the components would be stuck in the fixed half due to the increase of the friction coefficient in that area. Some studies have being done in this field, Pouzada *et al* in 2006 have done an experiment to understand the relationship between forces needed during the ejection phase of the injection molding and the surface finish, the coefficient of friction at the ejection stage depends on the surface texture of the core and the temperature at ejection. They state that "The forces to be overcome at this stage result from the combined effect of the shrinkage of the moulding material and the coefficient of friction between the moulded material and the core", an scheme of this phenomenon can be seen in next Figure 74.

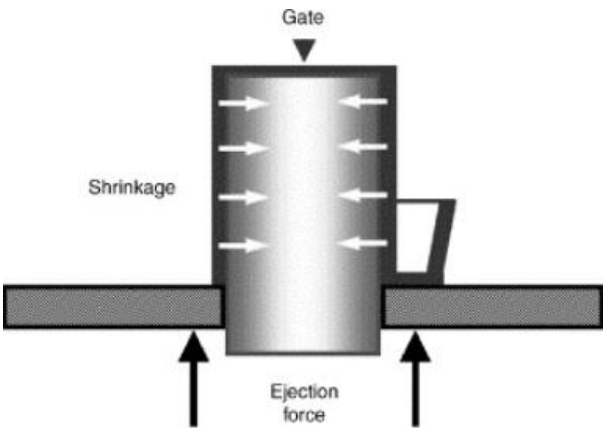

Figure 74- Shrinkage and ejection force in deep core moldings.

Reinforcing the fact that polished bushings make component extraction difficult, this article proved that in all scenarios, there is a consistent pattern where the coefficient of friction tends to rise with the roughness, which can be attributed to the expected impact of surface asperities on mechanical interactions. However, when the roughness is minimized to the extent of highly polished surfaces (with a height roughness, Rt, below 1 µm), there is an observed elevation in the coefficient of friction. This increase primarily stems from the dominant influence of adhesion forces between the surfaces. This phenomenon is noticeable across various types of polymeric materials, including both semi-crystalline, refer to Figure 75, and amorphous counterparts, refer to Figure 76, (Pouzada *et al.* 2006).

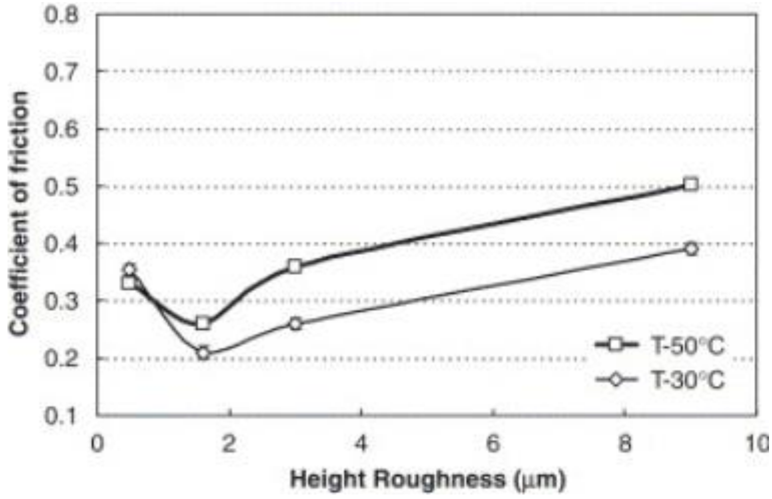

Figure 75- Dependence of the coefficient of friction on the surface roughness for the case of a HDPE (HE 7013 from Borealis)

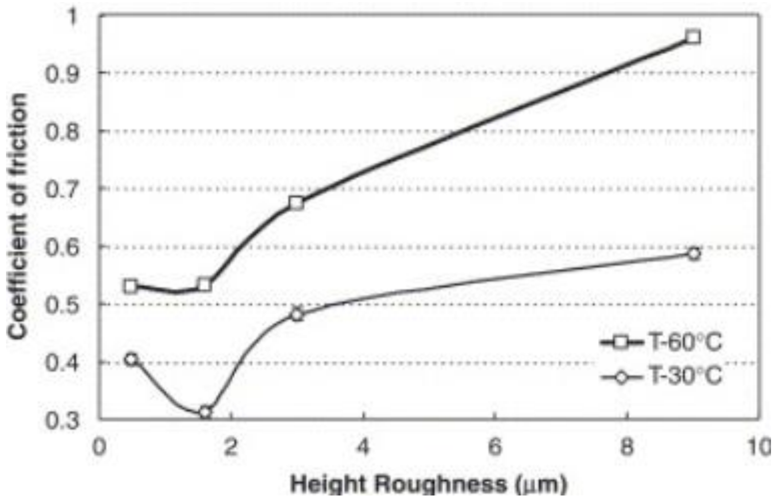

Figure 76- Dependence of the coefficient of friction on the surface roughness for the case of a PMMA (Plexiglas 7N from Degussa).

This increase of the coefficient of friction made it impossible to eject the part in this test, and from the literature is possible to achieve an optimal interval of roughness to a optimization of cycle time in this type of tubular components for future works in the company. In this mold configuration the goal is to have higher friction forces in the movable half than in the fix half in order to “grab” the component in the opening phase, however, this friction cannot be indefinitely large, since the extractors, also these tubular ones, have to be able to extract the part without causing large indentations in the component and also to prevent flow defects in the surface of the component.

Bush Nº4 (Standard bush with coating)

The final bushing tested would be the one with the most possibility of good results in the injection since it had the benefits of some roughness of the bushing itself as well as the lubricating characteristics of the coating.

Returning to the same parameters of the first test, this bushing did not present problems in the first injections as expected, however, it also got stuck after 18\20 cycles and this was due to the temperature balance of the fixed and mobile part of the mold after some cycles. This phenomenon was an important aspect throughout this trial, as it precluded a more careful and rigorous analysis, and the conclusions of this final test. Although the results were satisfactory in the first cycles, due to an inadequate configuration of the mold, (insufficient cooling system to cool the inner zone of the insert of the moving part), although it manages to maintain its temperature of 20ºC of most of its structure, the area of the injected part begins to increase its temperature cycle after cycle, either from the plastic injected at high temperatures and from the contact of the two halves of the mold, transferring more heat from the hot half (fixed) to the cold half (movable), which means that the "counter-contraction" of the part (being colder on the outside, it holds better to the outer insert), is no longer significant and the contraction to the inner insert becomes relevant, trapping the component.

The needed of a additional component, the Centering Bush, necessary to ensure the centering of the component throughout the operation, makes it even more difficult to cool the part.

Previously seen Figure 64, slightly modified in Figure 77, shows what was explained, highlighting the component in red and the cooled area in blue, as well the centering bush.

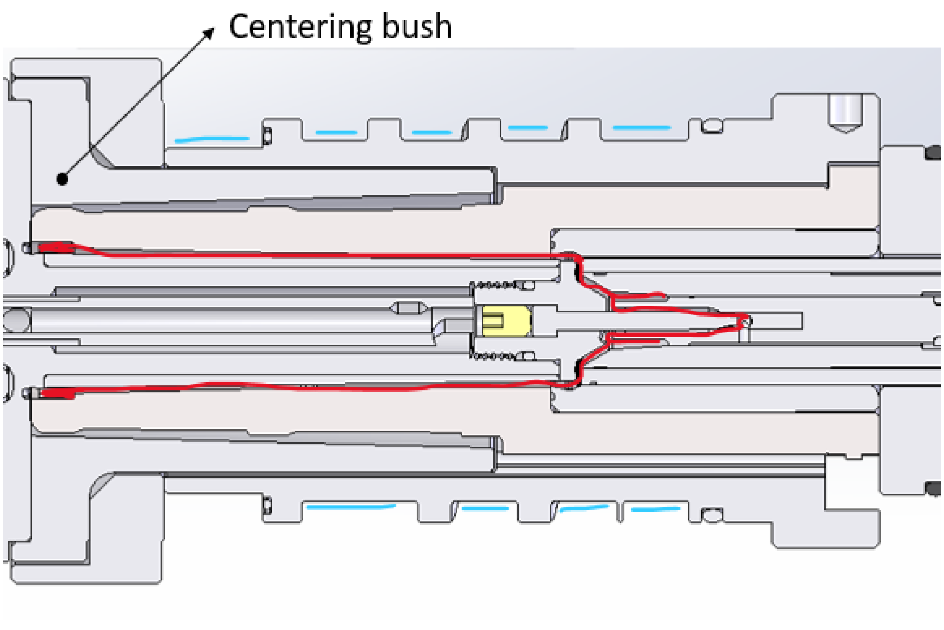

Figure 77- Inserts mechanims showing the part (red) and water incooling system (blue).

With this structural limitation of the mold under consideration, the attempt to improve the parameters is compromised right from the start, however some adjustments were possible to be made.

The mold temperature was reduced to 40ºC, similar to the first test, and then we could see improvements in the number of successive injections compared to the first test, it was possible to inject 6 to 7 pieces before the temperature reached equilibrium. With this improvement it is now possible to reduce the cooling time, (trying to take the parameters to their limit) since the part would theoretically need less time to cool down when the mold is colder. This reduction of 0.5 seconds was possible to achieve in the total cycle time with the same 6 to 7 pieces injected.

The last parameter tested was the decrease in the extraction time after opening the mold, however an increase in this parameter is usually positive for the quality of the entire injection process, being only harmful in the necessary time, and an increase is advantageous mainly for two reasons:

- More cooling time with the mold open for a good ejected part, without defects.
- Greater cooling of the moving part of the mold increases the number of cycles before a temperature equilibrium occurs.

This reduction by 1sec in ejection time, getting a total cycle time of 8.5s was possible during 2\3 injections while in the first test only the decrease in mold temperature had negative results, meaning a significant improvement in the production of tubular parts, however, reinforcing that the mold geometry itself, with a insufficient cooling system of the moving part, made the various tests and concrete optimization attempts of the process difficult.

In conclusion of this case study, the electroless nickel coating with the addition of PTFE showed great potential for future applications with the improvement achieved in the cycle time of the process for tubular components where different friction forces are necessary for this applications.

4. Conclusions and Future Work

The purpose of this thesis was to determine the advantages and potential of surface coatings in the plastic injection mold industry, particularly in protecting its components and mold surfaces in the most critical areas, especially for the injection of more corrosive plastics such as PVC. The industry has started to use techniques like PVD for cavity protection, where the need justifies the cost of this operation, which is still quite expensive and only necessary for specific components. There are various cases of wear and the occurrence of defects in mold steels, many of which are inherent to the injection process, but some due to maintenance failures or poorly executed prevention measures. Excluding operator error from the list of causes for mold defects, a PVD coating would only ensure mold protection during filling, which often does not pose any problems for a considerable period of time in the company's reality and day-to-day operations.

In relation to another coating applications, designed to increase productivity by optimizing injection parameters, it was found that electroless nickel showed highly promising results for its implementation in the day-to-day operations of the company, particularly for tubular components with medium to large-sized inserts.

It was observed that the surface roughness of the inserts used determines the success of the injection process. Inserts with extremely low roughness in the polished area, due to plastic-metal adhesion forces, make it impossible to extract the component from the fixed part of the mold. In the case of inserts with some roughness, with a minimum frictional force and applying a coating with lubricating characteristics yielded promising results in optimizing and adjusting injection parameters. This made it possible to reduce mold temperatures for shorter cooling and ejected times. Unfortunately, due to the geometric characteristics of the mold used, the cooling system prevented adequate temperature control on the outer insert of the movable half of the mold. As a result, cycle after cycle, this temperature would gradually increase until a temperature equilibrium was reached between the two mold halves, causing sufficient contraction forces to hold the insert in the fixed part of the mold.

Future Work

Regarding future works, as mentioned throughout the report, despite indications of positive results in the use of coated interior inserts for tubular components, the test fell short of expectations due to limitations in the mold itself, which made the tests challenging. It would be interesting, in future works, while maintaining the same approach, to further explore this type of testing in different molds that allow for better cooling of the moving cavities. Additionally, it would be beneficial to understand the influence of the diameter of the inserts in this type of application and to conduct tests on molds that are actually in production, such as mold 0637-12, by replacing the 32 bushings and studying the variations in injection parameters.

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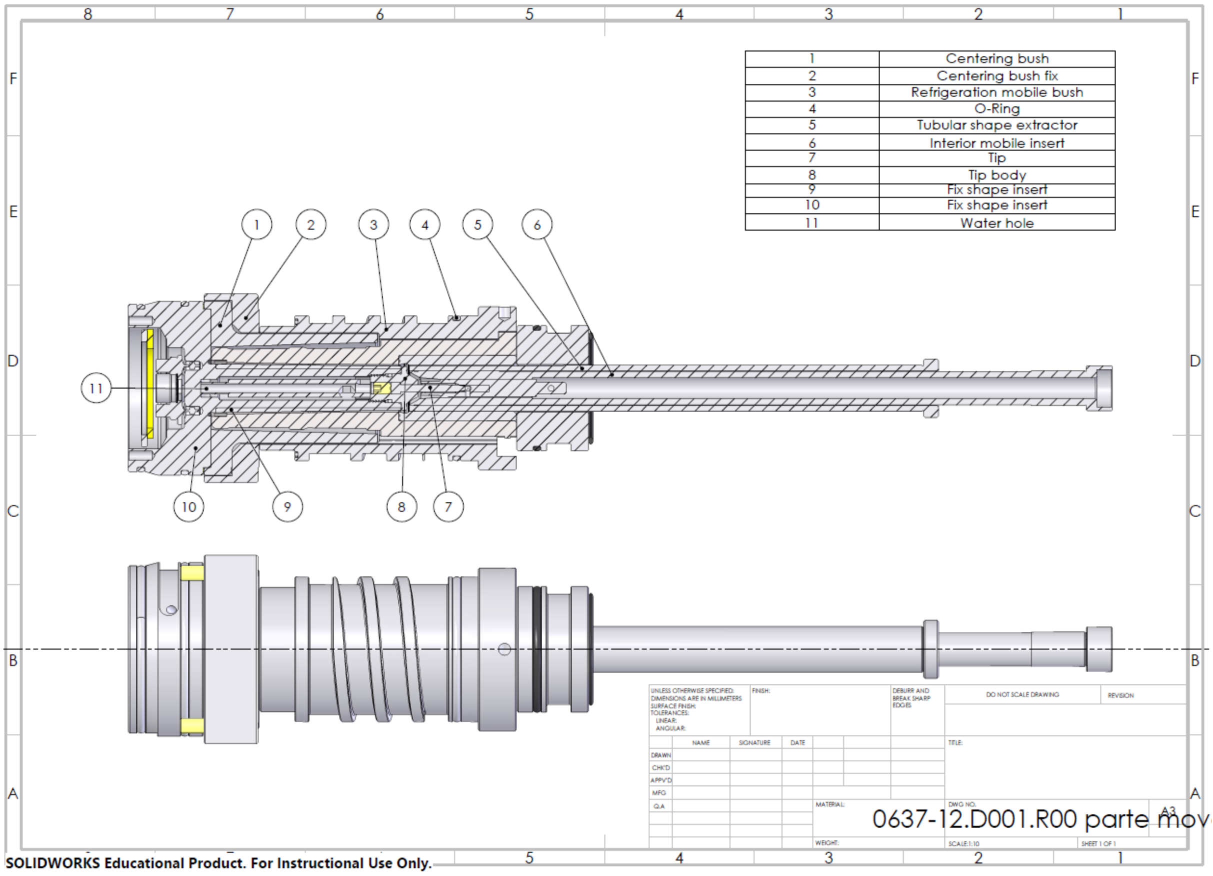
Attachments

CLASSE	FAMÍLIA	MARCA	PERFIS DISPONÍVEIS	NORMAS					COMPOSIÇÃO QUÍMICA %								
				EURONORM	AISI	UNE	DIN	W.Nr.º	C	Si	Mn	Cr	Mo	Ni	V	W	OUTROS
AÇOS PARA MOLDES	0 415	F 10 (a)	Ø ⧄ ⍁ CH.	C 45 E / C 45 U	1045	F-1140	Ck 45	1.1191 1.1730	0,45	≤ 0,40	0,65						Cr+Mo+Ni ≤ 0,63
	0 533/0 538	2311 / 2312	⍁	40 CrMnMo 7	P20	F-5302	40 CrMnMo 7	1.2311 1.2312	0,36	0,30	1,45	1,95	0,20				1.2312 → S+
	0 536	PM 300 IMPAX SUPREME *	Ø ⍁	40 CrMnNiMo 8-6-4	P20	F-5303	40 CrMnMo 7	1.2738 mod	0,37	0,30	1,40	2,00	0,20	1,00			S ≤ 0,010
	0 539	2738 SUPER	⍁	40 CrMnNiMo 8-6-4	P20	F-5303	40 CrMnNiMo 8-6-4	1.2738 mod	0,25	0,35	1,25	1,75	0,45	≤ 0,60			S ≤ 0,030 P ≤ 0,030
	0 545	2738 SUPER HH	⍁	40 CrMnNiMo 8-6-4	P20	F-5303	40 CrMnNiMo 8-6-4	1.2738 mod	0,25	0,12	1,25	1,75	0,45				
	0 535	2738 HH	⍁	40 CrMnNiMo 8-6-4	P20	F-5303	40 CrMnMo 7	1.2738 mod	0,37	0,30	1,40	2,00	0,20	1,00			S ≤ 0,010
	0 532	PM 400 NIMAX *	Ø ⍁						0,10	0,25	2,50	3,00	0,30	1,00			
	0 529	NIMAX ESR * Δ	⍁						0,10	0,30	2,50	3,00	0,30	1,00			
	0 546	MDXTRA HH	⍁		P20			1.2738 mod	0,26	0,35	1,00	1,45	0,55	0,60			Microalloying
	0 548	MDXTRA SHH	⍁		P20			1.2738 mod	0,26	0,35	1,00	1,45	0,55	0,60			Microalloying
	0 544	2711 SUPER	⍁		6 F 2		54 NiCrMoV 6	1.2711 mod	0,30	0,35	0,90	1,15	0,45	1,05			V+
	0 218	CALMAX *	Ø ⧄ ⍁						0,60	0,35	0,80	4,50	0,50		0,25		
	0 280	ORVAR 2M (a) *	Ø ⍁	X40 CrMoV5-1	H13	F-5318	X40 CrMoV5-1	1.2344	0,40	1,00	0,40	5,20	1,30		1,00		
	0 286	MG 50 ORVAR SUPREME * Δ	Ø ⧄ ⍁	X40 CrMoV5-1	H13 Premium	F-5318	X40 CrMoV5-1	1.2344	0,40	1,00	0,40	5,20	1,40		1,00		
	0 290	UNIMAX * Δ	Ø ⧄ ⍁						0,50	≤ 0,50	0,50	5,10	2,30		0,60		
	0 278	VIDAR SUPERIOR * Δ	⍁	X37 CrMoV5-1	H11 Premium	X37 CrMoV5	X38 CrMoV5-1	1.2343 mod ou 1.2340 mod	0,36	0,30	0,30	5,00	1,30		0,50		
	0 886	STAVAX ESR * Δ	Ø ⍁	X41 Cr 14	420	F-5263	X42 Cr 13	1.2083 mod	0,38	≤ 1,10	≤ 1,00	13,60			0,30		
	0 887	MIRRAX 40 * Δ	Ø ⍁	X41 Cr 14	420	F-5263	X42 Cr 13	1.2083 mod	0,21	0,90	0,45	13,50	0,20	0,60	0,25		N+
	0 884	MIRRAX ESR * Δ	Ø ⍁	X41 Cr 14	420	F-5263	X42 Cr 13	1.2083 mod	0,24	≤ 0,50	≤ 1,00	13,30	0,35	1,40	0,35		N ≤ 0,20
	0 886	TYRAX ESR * Δ	Ø ⍁						0,40	0,20	0,50	12,00	2,30		0,50		N+
	0 892	ROYALLOY	Ø ⍁						0,05	0,40	1,20	12,60					N+ Cu+ S ≤ 0,14
	0 893	RAMAX HH *	⍁				X33 Cr S 16	1.2085 mod	0,12	≤ 0,40	1,30	13,40	0,50	1,60	0,20		N ≤ 0,20 S ≤ 0,20



MUROPLAS
PLASTIC ENGINEERING

Molde	Referência	0509-00		Programa	- - -		MÁQUINA	20
	Nº de Molde	0509-00		Robô	Tipo	- - -		
	Nº de cavidades	1	1	Agarra	Referência	- - -	Força de Fecho (kN)	1000

Tempo de ciclo (s)	10	+/- 2

	Material	Características de estufagem: Tempo (h)	Características de estufagem: Temperatura (°C)		
Unidade de Injeção 1	PUREL RP 374R TRANSPARENTE + CAWITON MED PR 2747	- - -	- - -	+/- 10	Estufa 1

Unidade 1	4	3	2	1		
	- - -	- - -	- - -	60	Velocidade Injeção (mm/s)	+/- 10
	- - -	- - -	- - -	120	Pressão Injeção (bar)	+/- 20
	- - -	- - -	- - -	- - -	Etapa	+/- 10
	12				Ponto de Comutação (mm)	+/- 2

Unidade 1	4	3	2	1		
	60				Velocidade 2ª Pressão (mm/s)	+/- 10
	- - -	10	40	45	2ª Pressão (bar)	+/- 20
	- - -	0,1	0,8	0,3	Tempo (s)	+/- 1

Unidade 1	3	2	1				
	- - -	- - -	150		Velocidade Dosagem (rpm)	+/- 10	
	- - -	- - -	10		Contrapressão (bar)	+/- 10	
	- - -	- - -	17		Curso Dosagem (mm)	+/- 10	
	Tempo Arrefecimento (s)		5	+/- 1	Descompressão (mm)	8	+/- 10

Temperatura do fuso (°C)	Zona 8	Zona 7	Zona 6	Zona 5	Zona 4	Zona 3	Zona 2	Zona 1	Flange
	- - -	- - -	- - -	225	220	215	210	205	50
	+/- 10	+/- 10	+/- 10	+/- 10	+/- 10	+/- 10	+/- 10	+/- 10	+/- 10

Canal Quente (°C)													
	Zona 1	Zona 2	Zona 3	Zona 4	Zona 5	Zona 6	Zona 7	Zona 8	Zona 9	Zona 10	Zona 11	Zona 12	+/- 5
	Zona 13	Zona 14	Zona 15	Zona 16	Zona 17	Zona 18	Zona 19	Zona 20	Zona 21	Zona 22	Zona 23	Zona 24	+/- 5
	Zona 25	Zona 26	Zona 27	Zona 28	Zona 29	Zona 30	Zona 31	Zona 32	Zona 33	Zona 34	Zona 35	Zona 36	+/- 5

Circuitos de Águas		
Termorregulador 1 (°C)	60 (PARTE FIXA)	+/- 10
Termorregulador 2 (°C)	- - -	+/- 10
Água Corrente	X (MÓVEL)	
Leitura Molde Fixa (°C)	- - -	+/- 5
Leitura Molde Móvel (°C)	- - -	+/- 5

Tabela de Qualidade		
Pressão de Injeção (bar)	98	+/- 20
Tempo de injeção (s)	0,33	+/- 0.1
Pressão de Comutação (bar)	98	+/- 20
Almofada (mm)	10,3	+/- 0,3

Data	07/06/2023
Operador	- - -
Responsável	Ricardo Campos