Universidade do Minho
Escola de Engenharia

Core back moulding, adhesion optimization in the joining area.

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration. I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

ABSTRACT

When industries need to make components with two or more materials using just one mould and one machine, they use multi-material injection moulding techniques. One of these techniques is the core back moulding that allows the subsequent injection of two different materials without opening the mould, commonly used for parts with simple geometry, normally a rigid part involved with an elastomer. These moulds are very complex in its structure, therefore the design of the mould, its construction and assembly need to be carefully done to avoid part defects. Moreover, multi-material injection moulding may be a challenge regarding the adhesion between materials, being dependent on materials compatibility, materials rheological characteristics and injection moulding conditions used.

The present dissertation addresses the development of a core back mould for the production of a complex bi-material part for the automotive industry and the study of the processing conditions that best promote the adhesion between the materials used. For that different tools where used such as Solidworks for the mould design, and DOE for the design of experiments.

The mould development went through several steps such as the design of the injection, cooling, ejection and gas trap systems. Then the mould components were machined and assembled. Finally, the mould was tested and the parts were analysed. A study about the adhesion of the materials in this type of moulds and how the processing conditions influence the interface quality was realised. To simplify that study, a Design of Experiments was performed. This method is used to reduce the number of tests, assuring the reliability of the results. Finally, to analyse the adhesion of the parts, tensile tests were performed.

It was concluded that the mould had a good performance. Parts were successfully made and the strength of the joints evaluate. It was concluded that the adhesion between materials was more efficient in the part extremities comparing with the middle zones. These results are attributed to the location of the gate and also the complex geometry of the part. Furthermore, the processing conditions influence the strength of the joint region. The set of values that would optimise PP/EPDM joints are the injection temperature of the second material of 200ºC, the mould temperature of 40ºC and the injection pressure of 80bar.

Keywords: adhesion, core back, multi-material, polymers.

RESUMO

Quando as indústrias necessitam de fazer componentes com dois ou mais materiais utilizando apenas um molde e uma máquina, utilizam técnicas de moldação por injeção multi-material. Uma destas técnicas é a moldação *core back* que permite a subsequente injeção de dois materiais diferentes sem abertura do molde, normalmente utilizada para peças com geometria simples, como uma peça rígida envolvida com um elastómero. Estes moldes são muito complexos, pelo que a conceção do molde, a sua construção e montagem precisam de ser realizadas cuidadosamente para evitar defeitos nas peças. Além disso, a moldação multi-material pode ser um desafio no que respeita à adesão entre os materiais, dependendo da compatibilidade dos materiais, características reológicas e condições de processamento.

A presente dissertação aborda o desenvolvimento de um molde *core back* para a produção de uma peça bi-material para a indústria automóvel e o estudo das condições de processamento que melhor promovem a adesão entre os materiais utilizados. Para isso são utilizadas diferentes ferramentas, tais como Solidworks para o desenho do molde, e DOE.

O desenvolvimento do molde passou por várias etapas, tais como a conceção dos sistemas de injeção, arrefecimento, ejeção e escape de gás. Em seguida, os componentes do molde foram maquinados e montados. Finalmente, o molde foi testado e as peças foram analisadas. Foi realizado um estudo sobre a adesão dos materiais neste tipo de moldes e como as condições de processamento influenciam a qualidade da interface. Para simplificar esse estudo, foi realizado um Design of Experiments. Este método é utilizado para reduzir o número de ensaios, assegurando a fiabilidade dos resultados. Finalmente, para analisar a adesão das peças, foram realizados ensaios de tração.

Concluiu-se que o molde tinha um bom desempenho. As peças foram produzidas com sucesso e a resistência da zona de união foi avaliada. Concluiu-se que a adesão entre os materiais era mais eficiente nas extremidades das peças, em comparação com as zonas médias. Estes resultados devem-se à localização do ponto de injeção e também à complexa geometria da peça. Além disso, as condições de processamento influenciam a resistência da zona de união. O conjunto de valores que otimizariam a adesão da peça PP/EPDM são a temperatura de injeção do segundo material de 200ºC, a temperatura do molde de 40ºC e a pressão de injeção de 80bar.

Palavras-chave: adesão, core back, multi-material, polímeros.

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LIST OF ABBREVIATIONS

DOE – Design of Experiments

EPDM – Ethylene Propylene Diene Monomer

LSR – Liquid Silicone Rubber

MPR – Melt Processible Rubbers

SBS – Styrenic Block Copolymer

PP – Polypropylene

TPE – Thermoplastic Elastomer

TPO – Polyolefin Thermoplastic Elastomeric

TPU – Thermoplastic Polyurethane Elastomer

TPV – Elastomeric Alloy Thermoplastic Vulcanized

CNC – Numeric Control Computed

EDM – Electrical Discharge Machining

1. INTRODUCTION

This chapter aims to introducing the project, starting with a framework where the requirements for the development of this dissertation are presented. Thereafter, the definition of objectives and the methodology used to achieve them. Lastly, the structure of the document is displayed.

1.1 Framework

With the high competitiveness existing in the current market, imposed by the high level of competition, companies are daily pressured by customer demands. Automotive industry is an example of this situation, being one of the markets where the imposition of customer requirements is most notorious. Due to that, the developed parts for this industry must comply with all their functions.

When dealing with multi-material injection components, the goal is to combine different materials in the same part, for the same application. Therefore, it is necessary to ensure proper adhesion between them, in order to obtain a quality part with a resistant joining line. That can be sometimes very challenging [1,2].

AUTOMOLDES is a company dedicated to the development of injection moulds. It was proposed to AUTOMOLDES to make a core back mould to produce parts of two specific materials and optimize the adhesion between them. This study is of great importance because adhesion in the joining area is still a little unknown subject for the company, as well as the core back technology [3].

Core back moulding has some advantages comparing to other multi-material technologies, such as: it is an economical technique and it has a compact tool size. However, its biggest disadvantage is that it is only viable for simple geometries [1,4].

As in all multi-material methods, there are lots of parameters that can influence the interface quality of the components, such as: interface compatibility, interface temperature and interface stress. The variation of certain processing conditions changes these parameters, and, consequently, affect the adhesion of the interface either positively or negatively [2].

Design of experiments (DOE) is a statistic tool that can predict the efficiency of a process using a minimal number of experiments. In this particular case, with just some tests, DOE can predict which injection parameters have more influence on the adhesion between both material of the part. Therefore, DOE was applied in this project [5].

1.2 Objectives

The development of this dissertation has the main purpose of developing a core back mould and determine the optimal processing conditions that promote adhesion between two materials of a component made by this technique. In order to meet these objectives, some secondary objectives, were stablished, namely:

1. To study the core back technology and develop a mould with these characteristics;

2. To apply the DOE method to determine the optimal processing conditions to improve adhesion;

3. To carry out the injection tests and perform tensile tests to study the quality of the adhesion in the joint regions of the part.

Thus, the following tasks were performed:

1.1. Study the core-back concept:

- Technology;
- Advantages and disadvantages.

1.2. Development of a core-back mould:

- Mould design;
- Mould construction;
- Mould test.

2.1. DOE analyse to determine the optimal processing conditions:

- Define the processing conditions to study;
- Define the low and high levels to study in each condition;
- L4 array.

2.2. Perform the injection tests with the input of DOE:

- Mould test;

3.1. Mechanical analysis:

- Tensile tests;

- Study the quality of the adhesion between both materials obtained on the parts.

Annex A shows a schedule that presents a temporal forecast of all tasks to be performed.

1.3 Document Structure

This dissertation is structured in 5 chapters. Figure 1 illustrates the relationship between the chapters and the objectives.

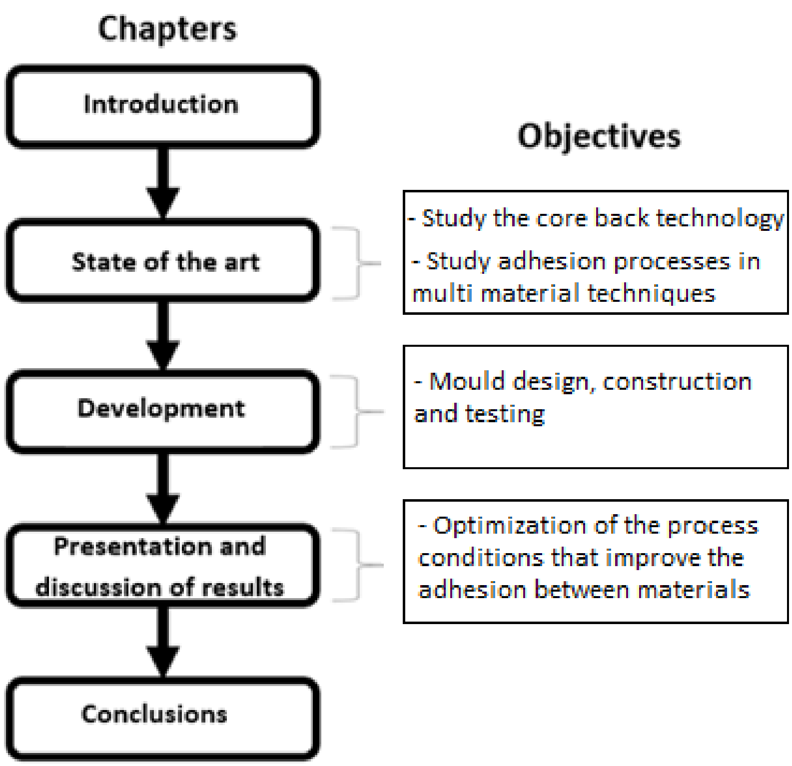

Figure 1 – Dissertation outline and relationship between chapters and objectives.

In chapter 1 is presented a brief introduction to the work and the objectives to be carried out. Is also presented a project scheduling proposal.

In chapter 2 is displayed the state of the art, going through the multi-material moulding technique description and its variants; a detailed description of the core back moulding; an explanation about Design of Experiments tool and a description of the mechanical analysis commonly used to analyse the adhesion in the parts.

In chapter 3 is presented the development of the project, including the mould development, DOE results, the experimental tests, and the characterisation of the parts.

Chapter 4 describes the discussion of the obtained results.

Chapter 5 presents the conclusions reached with the realization of the present study and some reflections for future project.

2. STATE OF THE ART

2.1 Polymers and the automotive industry

Currently, the search for materials with better properties is increasing due to the needs of people's lives. Thus, some traditional materials like glass, iron and paper are not always able to meet the requests of society. One of the materials that can gather important characteristics such as cost/benefit ratio, aesthetics, efficiency and durability are the polymers, then they have a lot of applications [6,7].

Polymers are usually synthetic, most commonly derived from petrochemicals, however, an array of variants are made from renewable materials such as polylactic acid from corn or cellulosic from cotton They can be rigid, flexible, amorphous or semi-crystalline, transparent or opaque materials [7].

These materials have gained a major role during the last few decades, being used in the automotive industry, medical industry, packaging, electronics, etc... The automotive industry is the main market for plastic parts injection companies, accounting for about 70% of its production [7,8].

Nowadays, polymers are used mainly to make cars more energy efficient by reducing weight, together with providing design flexibility, durability, corrosion resistance, toughness, resiliency and high performance at lower cost. Since they have low weight, the automotive industry has achieved a better use of engine power, and due to the smallest amount of processes to obtain a component, lead to a decrease in CO2 emissions and final price of the car [7,8].

Many types of polymers are used in more than a thousand different parts of all shapes and sizes. Plastics are used in exterior and interior components such as bumpers, doors, windows, headlight and side view mirror housing, trunk lids, hoods, grilles, wheel covers, among others [7]. Figure 2 illustrates some examples of polymers used in the cars.

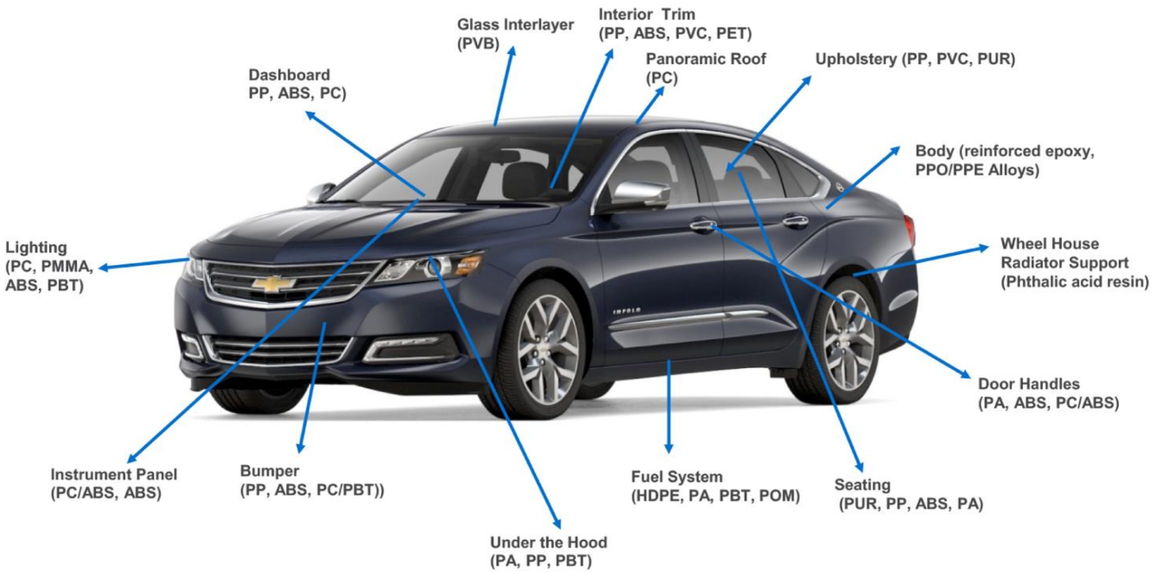

Figure 2 – Polymer applications in automotive components [8].

The application of polymeric materials allows more freedom in design and approximately 82% of an average vehicle's weight gets recycled [9].

Some advantages of increased applications of plastic materials in transport vehicles include [9]:

- Minimal corrosion, allowing for longer vehicle life;
- Substantial design freedom, allowing advanced creativity and innovation;
- Flexibility in integrating components;
- Safety, comfort and economy;
- Recyclability.

Since future trends are high-performance cars with greater comfort, safety, lower prices, style and eco-environment friendly, the use of polymers is expected to increase [9].

2.2 Polymer processing techniques

There are several techniques of polymer processing and each one has a different purpose. However, all the traditional methods go through the same steps: at first, heating is given, in order to melt the polymer. In a second phase, the polymer is moulded to acquire a certain shape, and, finally, the polymer is cooled and, when properly cooled, it is ejected [10].

The processing technique selection depends on many factors, such as: production rate, dimensional precision, surface finish, the shape of the part and size of the final product. Some of the various existing polymer processing techniques are [10,11]:

Injection moulding: Consists of melting and forcing the plastic into a mould, where, after being cooled, is ejected with the shape of the mould. It is the most widely used technique of polymer processing;

Extrusion: Is probably the second most used plastic processing technique. It consists of forcing material through a die that will acquire the shape of it;

Blow moulding: Is the process of forming a molten tube of thermoplastic material and placing the preform within a mould cavity and inflating the tube with air, to take the shape of the cavity;

Rotational Moulding: Allows the production of large, hollow and multilayer parts. Polymer powder is introduced into the mould, then is heated, melted and distributed due to the rotation movement imposed according to two axes. Thus, the material acquires the shape of the mould;

Thermoforming: A plastic sheet is heated above Tg and pushed into a mould with vacuum application. This technique is used to create reduced thickness parts;

Calendering: Through heated cylinders rotating at different speeds, the polymeric material is squeezed. Thus, is it obtained flat films, plates and laminates;

Compression moulding: Using a heated plate press, the polymeric material is placed in a mould, where it is fused and compacted in order to obtain parts with the shape of the mould.

Besides these conventional techniques there are many more, that were created to overcome inherent process weaknesses and to increase productivity. Some examples are of these non-conventional methods are [12-15]:

Multi-material moulding: It is a strand of injection moulding that consists of produce parts made of different materials or the same material with different colours. It is made all at once, using just one mould, what avoids post processing operations;

Twin screw extrusion: This method differs from typical extrusion method because in this case there are two screws, parallel and rotating of an eight-shaped section. It is a process essentially used for compounding and processing complex polymeric materials;

Injection welding: This method has the aim of moulding hollow parts with a complex geometry. The process starts with the injection of two halves of the part, then, the mould opens and place the two halves in front of each other. After that, the mould closes and it is injected a welding ring between the parts along them grooved border;

Fluid/Gas assisted injection moulding: This process has the same principles as the injection moulding but is assisted by the introduction of a fluid (usually water) or gas into the mould. The material is pushed by the fluid against the mould walls, resulting in a fast cooling;

Back-moulding: Consists of moulding a plastic over a layer of a substrate previously placed in the moulding wall. This layer can be textile, fabric, plastic or paper label or even a decorative film;

Stack/Tandem moulds: These methods are used for high productions. Consist in two-level moulds, two sets of cavities, with the aim of moulding more parts per cycle;

Powder injection moulding: This technique is used to produce parts of metal or ceramic with complex shapes. The metal or ceramic is compounded with polymer into pellets, then it is injected using the conventional method of injection moulding. After that, the part is heated and by the sintering process the metal or the ceramic welds together.

In this dissertation the parts under study were performed by a strand of injection moulding, namely multi-material injection moulding, therefore this study is focused on this technique.

2.3 Injection Moulding

Injection moulding has been manufacturing various automotive components for years. Demands for cost reduction and environment-friendly products are increasing with the development of the automotive industry and the new components. It's a method typically chosen when it is intended to make components with complex geometries. The facility of processing polymers, the ease of the material to acquire the mould contours, the complex designs, the highly efficient cooling systems and the possibility of automating the process are some of the innumerable examples why this technique is chosen [1,16].

Injection moulding is a repetitive process based in melting and forcing polymeric material into a mould cavity, where it is held for a certain period, until it cools and be ready to be removed in a solid-state, replicating the shape of the mould. This process requires an injection machine whose type and size depends on the various requirements of the final product. Some of these requirements are: the component dimensions, the number of parts produced per cycle and the way the component will be injected. These influence the mould size and, consequently, the size of the injection machine [10].

It is a cyclic process, more specifically, a set of operations which take place between the production of two consecutive sets of parts. The cycle starts with the closing of the mould, then, the injection of molten material is given. After that, is necessary to continue pressurizing after the mould filling, in order to reduce the contraction effects from cooling. Afterwards, the plasticization and the cooling occur at the same time, and, finally, the mould opens and eject the parts. The industries purpose is to make this cycle as short as possible in order to produce more parts in less time [15].

2.3.1 Processing parameters

The quality of the components made by injection moulding process depends on the conditions under which are processed, called "processing parameters". Therefore, an optimal combination of the processing parameters leads to improvement of the part quality.

Figure 3 illustrates an Ishikawa diagram, where all the processing parameters of the injection moulding process are presented.

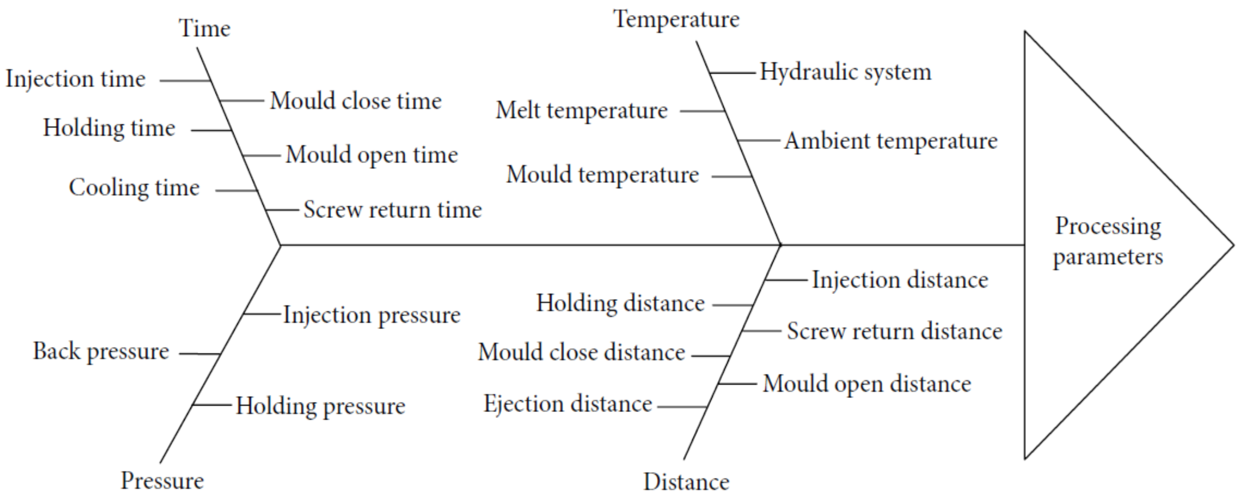

Figure 3 - Ishikawa diagram of processing parameters [17].

As shown in the figure above, there are a lot of processing conditions, and all of them depends on one of the major categories: time, temperature, pressure or distance. The following topics explain what each one consists of [17,18]:

- **Injection time**: the time it takes the screw to move from the injection start position to the position where it is ready to transfer the material to the mould;
- **Mould close time:** the time it takes to close the mould after the ejection phase;
- **Holding time:** the time required for the holding pressure;

- **Mould open time:** the time it takes to open the mould to start the ejection phase;
- **Cooling time:** the necessary time to properly cool the part;
- **Screw return time:** the time the screw takes to return to the start position, after injecting the material;
- **Hydraulic system:** the temperature of the hydraulic cylinder responsible for melt and force the material to the mould cavity;
- **Melt temperature:** the temperature of the material when it is molten;
- **Ambient temperature:** the temperature of the surrounding environment;
- **Mould temperature:** the temperature of the mould, controlled by the water or oil temperature of the cooling channels;
- **Injection pressure:** the pressure on the face of the injection screw when injecting material into the mould;
- **Back pressure:** the pressure that is exerted by the material when the material is injected into the mould;
- **Holding pressure:** the pressure against the cooling material in the cavity while that material solidifies;
- **Injection distance:** the required distance since the injection start position until the mould cavity;
- **Holding distance:** the distance covered by the material during the holding pressure;
- **Screw return distance:** the distance covered by the screw when it returns, after the material injection;
- **Mould close distance:** the route covered by the mould when it closes, after the ejection phase;
- **Mould open distance:** the distance covered by the mould when it opens to eject the parts.
- **Ejection distance:** the necessary route to be covered by the ejection elements to eject the parts.

These conditions can be optimized varying their values; however, they don't have always the same influence on the process.

Depending on the goal, some specific conditions can improve the injection process and make it more efficient, while other conditions may have no influence on the process. In order to preview the influence of each processing condition, there are some quality tools typically used, namely DOE (Design of Experiments), a statistical approach to the investigation of a process, in which it allows judgement on the significance of the variables. This method is explained in detail in section 0 [17].

2.4 Moulds for injection moulding

An injection mould consists, in a simplistic way, in a set of steel plates and other components which, after milling and assembled correctly, are fixed in injection machines to produce plastic parts with a certain shape [4]:

There are three basic stages in the mould: at an early stage, the mould gets the flow of molten material that is injected under pressure into the mould cavity and acquires the desired form. Subsequently, the material remains a certain period inside the mould so that it cools and solidifies. After the material is properly cooled, the mould opens in order to extract the moulded product [15].

The injection mould is constituted by a set of functional units that are essential to ensure components with a good quality [19]:

Moulding zones: Place that forms the part, consisting usually by the core and cavity;

Guiding: Ensure the adjustment and guidance of the mould when it opens and closes on the machine;

Feeding system: Channels where the molten polymer circulates, from the injection nozzle to each moulding zone;

Gas exhaust system: It has the function of extracting air when the casting enters in the moulding zones, to avoid burns on the plastic parts;

Temperature control system: It cools the material with the help of cooling channels that contain a refrigerant (usually water), until it has enough stiffness to be extracted;

Extraction system: Responsible for ejecting the part properly.

Figure 4 represents the typical elements of the mould:

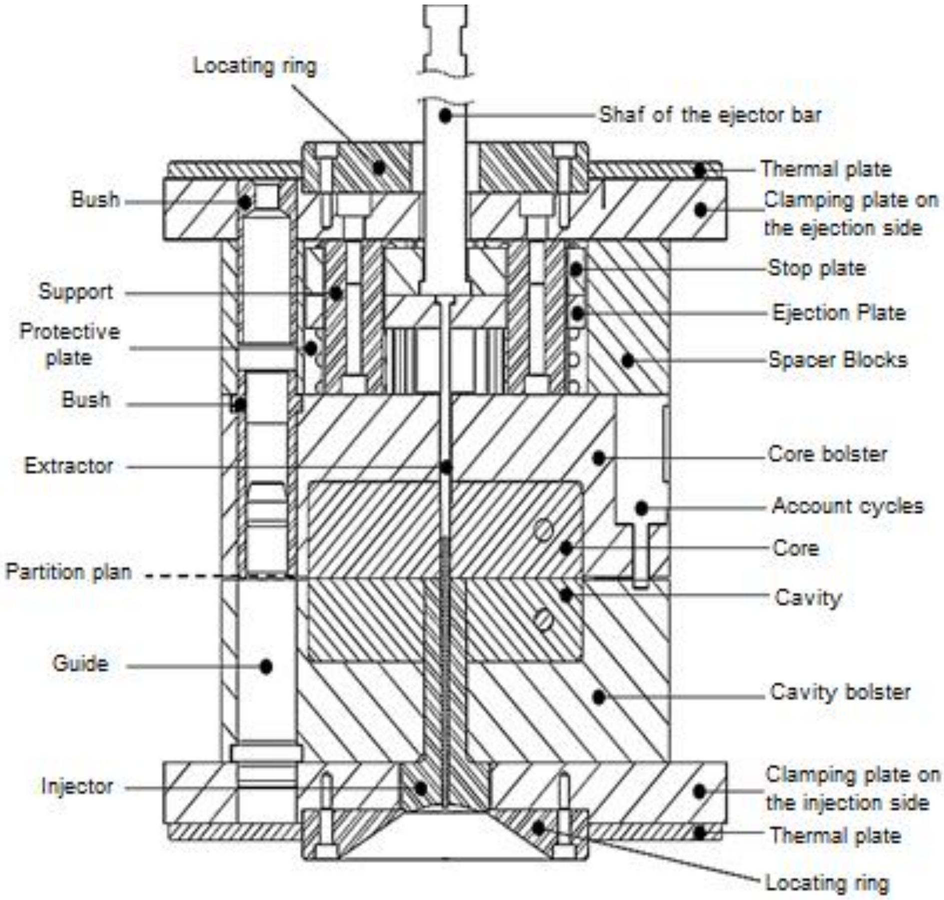

Figure 4 – Mould elements [Taken from the Automoldes inside library].

Injection moulds can be classified as [19]:

• **Cold sprue moulds** – the material injection is done directly on unheated channels since it left the machine nozzle until reaching the moulding zones. As a result, is obtained the parts and the feeding system;

• **Hot runner moulds** – this type of moulds has a manifold that keeps the material warm from the machine nozzle until the moulding zones. Usually, the result is just the plastic part;

• Two plate moulds - moulds with only one opening;

•**Three plates moulds** - moulds with a pre-opening, usually to separate the feeding systems from the parts. Thus, there is an early separation of the two components in the machine.

Currently, market demand forces more and more to have parts quickly, as complex as possible, and in the fewest number of operations. For this reason, several strands have emerged, such as multi-material moulding, a technique that combines two or more materials in just one component, made in just one mould [1].

2.5 Multi-material moulding

Multi-material moulding is the name given to the technique that uses two or more materials whose purpose is to produce components with a variety of functionalities, colours, materials or designs different from the usual [12].

The demand for getting a ready-to-use piece from an injection mould is steadily increasing. Therefore, more and more companies are upgrading their injection moulding technology as well as machining techniques [20].

The parts made by this process can have both economic performance and aesthetic advantages. Thus, can be produced from components based on flexible/rigid combinations of components with high degrees of freedom in colour. It is also frequent to obtain cheaper products using this method because it is not necessary to make finishing operations [12].

Multi-material products have several beneficial qualities over traditionally moulded products, such as [21]:

- Innovation of the aesthetic multicolour appearance;
- Skin/core configurations;
- Assembly of components inside the mould, which allows a cheaper product;
- Ergonomic components.

There is an infinity of equipment when it's about multi-material moulding. Some examples of the different machines used nowadays are illustrated in Figure 5. As evidenced, two or more injection units can be used to inject material into the same mould. These machines can be injectors or even extruders [12]:

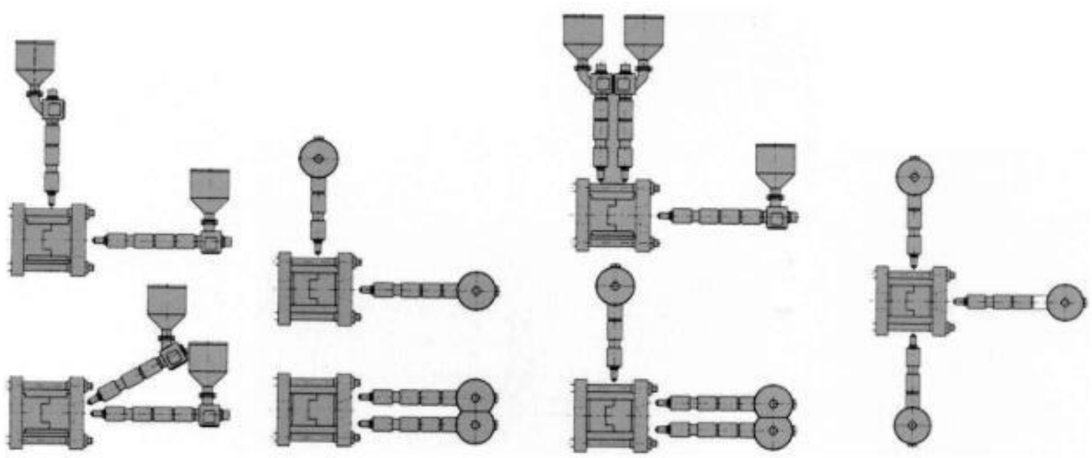

Figure 5 – Different multi-material moulding equipment [12].

Multi-material moulding technique can be divided into three large groups: multi-component, multi-shot and over-moulding, as shown in Figure 6 [1,22]:

- **Multi-component moulding**: In multi-component moulding, plastics are injected into one mould simultaneously or in sequence, as opposed to placing one material as an additional layer relative to another;
- **Multi-shot moulding:** Multi-shot moulding refers to inject materials into the mould in a specific sequence, one after another, creating a layering effect between materials;
- **Over-moulding:** Over-moulding refers to the use of a material heated above the glass transition temperature to add additional layers of shape to an existing component, already placed on the mould.

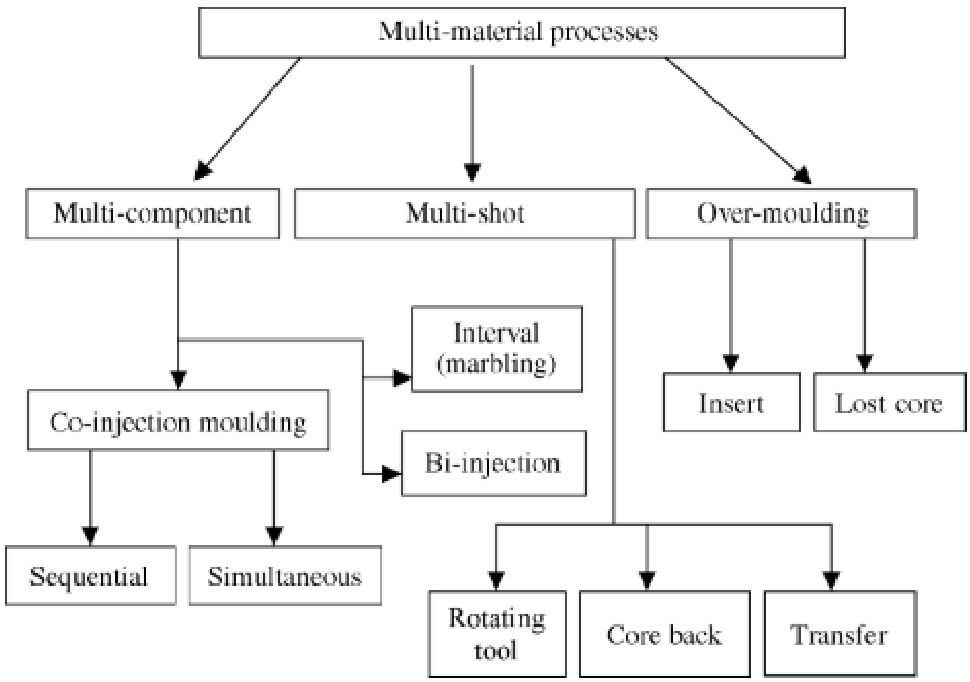

Figure 6 – Multi material moulding strands [1].

As already explained, this dissertation describes the core back technology, for this reason, between all the technologies, multi-shot processes are studied in further detail.

2.6 Multi-Shot Moulding

Multi-Shot Moulding is the name given to the technique that applies distinct multiple material shots to produce a single final part [1].

There are three fundamental strands: rotating tool, transfer process and core back, these processes are frequently chosen when the volume of annual productions is high [1].

2.6.1 Rotating Tool

The rotating tool consists on a mould of two cavities that is able to rotate through 180º for a two-shot part or 120º for a three-shot part. Generally, the sequences of operations are as follow: first the material is injected, then the mould opens, and the ejection side rotates to transfer the pre-form to a second cavity. After closing the mould, the injection of the second material is given upon the pre-form and, at the same time, the first material is injected in the pre-form cavity. When the final component, already a bi-material part, is ejected, the mould rotates again to transfer the pre-form to the second cavity. This process is represented in Figure 7 [1,12].

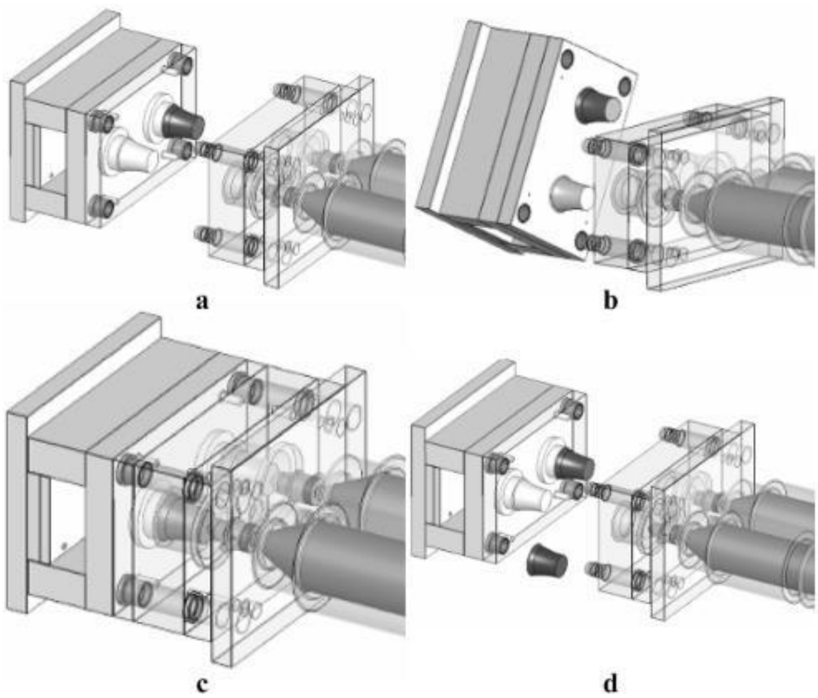

Figure 7 – Rotating tool process [12].

2.6.2 Transfer Process

Transfer process is mainly used when moulded parts must be over moulded. The first pre-form, after being injected, is transferred, with the help of a robot, to a second core of the same mould, where is injected the second part. Both materials are injected simultaneously in all cavities, which reduces the cycle time [23]. This technique is generally used with simple geometry components and with big dimensions, since rotating the entire mould is too difficult [12]. Figure 8 exemplifies how this process works.

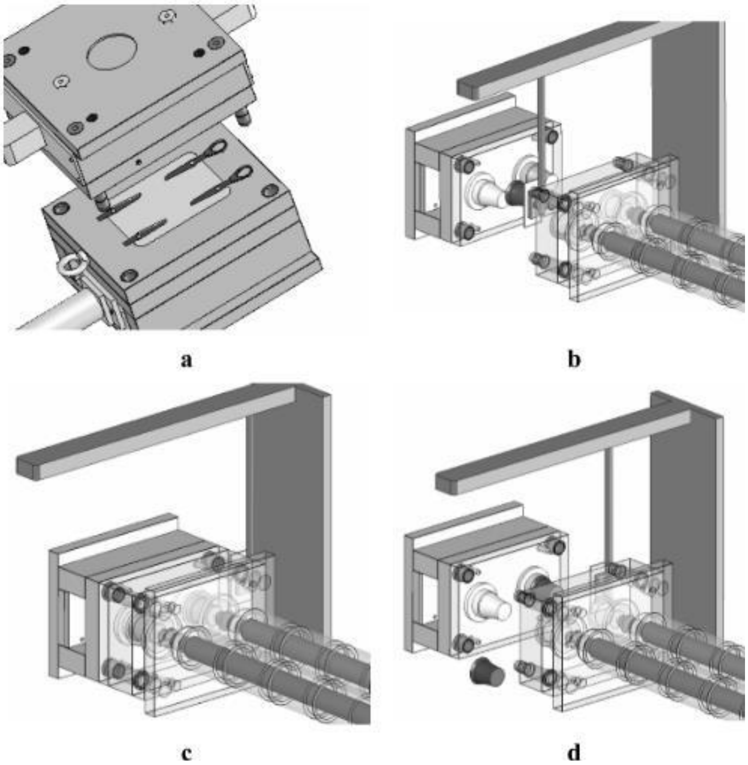

Figure 8 – Transfer process [12].

2.6.3 Core Back Moulds

In this process the first material is injected, then, the second material is impressed after a physical movement in the moulding zone. The movement occurs without opening the mould and it's only viable for parts with simple geometry, normally it's a rigid part with some elastomer applications [12]. Figure 9 depicts the core back moulding process.

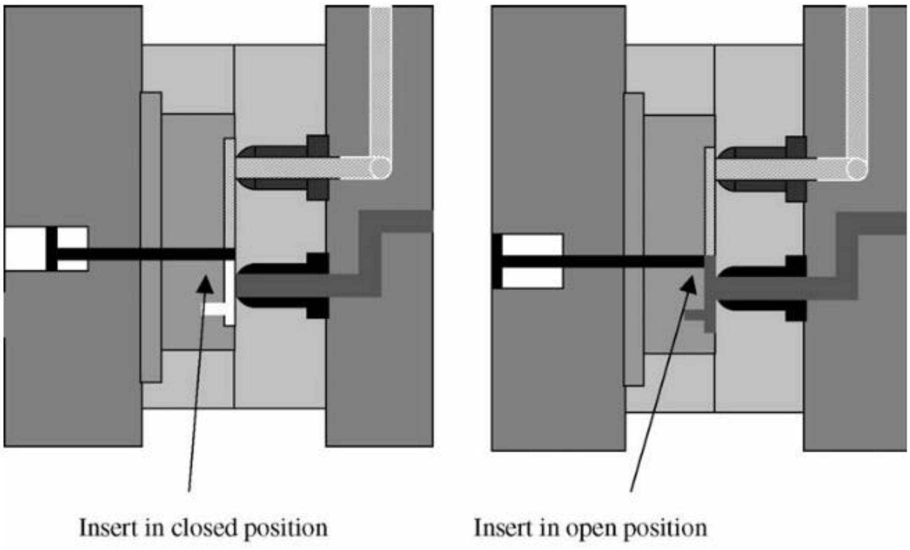

Figure 9 – Core back moulding process [1].

As illustrated in Figure 9, when the insert is in closed position the first material is injected, then the insert opens, and the second material is injected.

2.7 Core Back Moulding

Core back moulding is a relatively recent technique, with a sequential cycle, especially suitable for simple geometry parts. The cavity is extended by pulling up and down a slide and a second component is injected, the movement of the slides is usually hydraulic. By shifting the cores inside the mould, hollow spaces can first close off and subsequently reopen [1].

In this technology, the number of mould cavities coincides with the number of parts produced by cycle, and the process is done sequentially, not parallel as in other multi-shot methods [1].

Core-back moulding has the capability to add more material with low weight to components, making it an ideal choice for many types of applications where sealing is desired. Some of the advantages and disadvantages of core back technique are [2,4,24]:

Advantages:

- Parts can be produced without the need of intermediate opening of the mould and further transport of the pre-moulded part;
- Compact tool size;
- Simple, cost-effective mould technology.

Disadvantages:

- Longer cycle times, because it requires injection of one component after another and two separate cooling cycles;
- Only applied if the cavity for the second component can be opened and closed by axial movements of slides;
- The complexity of the parts is limited because the pre-forms are not demoulded but released only partially;
- Increasing the number of components beyond two to be produced by cycle increase the cost of tooling due to the complexity required.

In components whose design lends it to more than one technique, a detailed analysis of the economic implications of the process may be required to determine the most appropriate method of production. This could be due to either: tooling costs, especially on large parts; or to the nature of the material; for example, robotic transfer of a very flexible material may be difficult. The cooling times may be very short on a thin moulding; in these cases, a core back tooling system may be the best option. Due to the low tool cost, but higher cycle time, this method is primarily used for small series [1,4,14].

As in all injection moulding techniques, some requirements must be met in order to make the technology efficient and avoid problems in the process. It is necessary to make sure that the first shot cavity has support against the second-shot cavity pressure, therefore, ribs or undercuts may be necessary to hold the first shot in place to prevent flash and deformation. Also, hydraulic cylinders actuating on the cores must be robust enough to resist the cavity plastic pressure, otherwise, the processing window will be very restricted, because less injection pressure will be required. The injection machine must have the necessary means to activate all the slides in the tooling to make this method efficient [1,2]. Furthermore, Heim [2] affirms that the design on the ejection side needs to be restricted because additional space must be provided by means of an axial movement of the slides.

Some applications of the core back mould technique are automotive components with a sealing lip with a combination of PP/TPE, represented in Figure 10.

Figure 10 – Sealing components [25].

Flip-top closures are other example of applications. Figure 11 illustrates flip-tops with identical polypropylene materials but in different colours.

Figure 11 – Flip-top closures [25].

2.8 Material Selection for Multi-Material Moulds

Since one type of polymer does not possess all the physical and mechanical properties desired in a finished product, it is used two or more polymers in order to meet requirements. By blending different polymers, several properties can be improved, while retaining some of the original properties [26].

In multi-material moulds it is possible to combine both compatible and incompatible materials. Material selection should be done according to the application of the final component. The combination of incompatible polymers is useful when it's intended to produce parts with movements, since in this way, assembly post-operations are avoided. Combining compatible polymers into the mould is also interesting because weld post-operations are not necessary [1,12].

The combination of compatible polymers is the most frequent method. However, adhesion between materials is not always an easy process since all processing parameters, material effects and basic conditions either directly or indirectly affect the interface [1].

Table 1 shows adhesion compatibility of various material combinations.

Table 1 - Polymer adhesion [1].

	ABS	ASA	EVA	PA6	PA66	PBT	PC	PE-HD	PE-LD	PET	PMMA	POM	PP	PPOmod	PS-GP	PS-HI	SAN	TPU
ABS	+	+	+			+	+	-	-	+	+	-	-	-	*	*	+	+
ASA	+	+	+			+	+	-	-	+	+	-	-	-	*	-	+	+
EVA	+	+	+					+	+				+		+	+	+	
PA6				+	+	*	*	*	*			-	*	-	-	-	+	+
PA66				+	+	*	*	*	*			-	-	-	-	-	+	+
PBT	+	+		*	*	+	+	-	-	+	-	-	-	-	-	-	+	+
PC	+	+		*	*	+	+	-	-	+		-	-	-	-	-	+	+
PE-HD	-	-	+	*	*	-	-	+	+	-	*	*	-	-	-	-	-	-
PE-LD	-	-	+	*	*	-	-	+	+	-	*	*	+	-	*	-	-	-
PET	+	+				+	+	-	-	+	-	-		-	-	-		+
PMMA	+	+				-		*	*	-	+		*	-	-	-	+	
POM	-	-		-	-	-	-	*	*	-		+	-	-	-	-	-	
PP	-	-	+	*	-	-	-	-	+		*	-	+	-	-	-	-	-
PPO mod	-	-		-	-	-	-	-	-	-	-	-	-	+	+	+	*	-
PS-GP	*	*	+	-	-	-	-	-	*	-	-	-	-	+	+	+	-	-
PS-HI	*	-	+	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-
SAN	+	+	+	+	+	+	+	-	-		+	-	-	*	-	-	+	+
TPU	+	+		+	+	+	+	-	-	+			-	-	-	-	+	+
- No adhesion, * Poor adhesion, + Good adhesion																		

Using polymer combinations with different hardness sometimes is useful, such as rigid/flexible combinations.

In multi-material injection moulding, there are some problems usually associated like shrinkage, warpage and adhesion problems. When it comes to components made of different hardness materials, these problems are more frequent because the process is more complex [1].

2.9 Materials Adhesion in Multi-Material Moulds

When there is the need to combine different materials in multi-material moulds, attention must be paid to their adhesion properties. This adhesion can be produced by chemical or mechanical bonding. Chemical bonding is done owning to the reaction between the molecules, while mechanical bonding happens when there is intermolecular diffusion at the interface, when the temperature of both polymers is above their glass transition temperature [27,28].

According to Pötsch and Michaeli [3] determining the bond strength is a big challenge and it is impossible to predict regarding to the limited knowledge about the numerous factors that influence adhesion.

Interface quality of the component is then influenced by a lot of parameters, the more important are: interface compatibility, interface temperature and interface stress (Figure 12) [2].

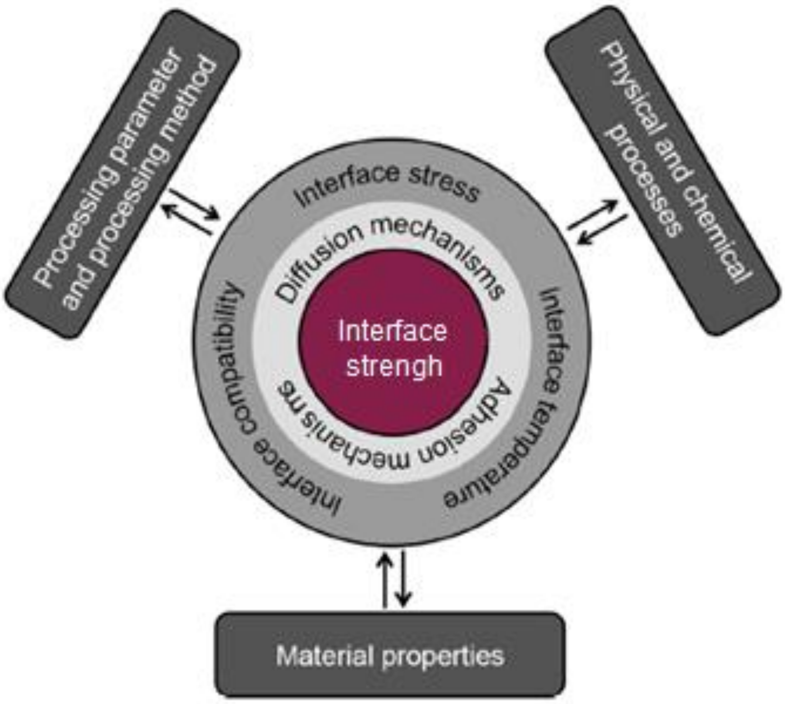

Figure 12 – Influencing parameters in interface strength. Adapted from: [2].

2.9.1 Interface compatibility

Interface compatibility depends on the materials used and the adhesion between them, which is dependent on several factors like polarity, surface tension, crystallinity, molecular weight, molecular orientation, thermodynamic compatibility and surface pre-treatment [2].

- **Polarity**

Adhesion is usually given more easily when combining two polar polymers, so the presence of functional groups in the polymers is generally a good indication relatively to the adhesion. However, too high polarity induces, as a rule, lower molecular mobility and, thus, inhibits diffusion processes, which has a negative influence on the adhesion process [2,29].

- **Surface tension**

Usually, the lower is the difference between the surface tensions of both components, the higher will be the diffusion and adhesion processes, consequently, composite strength is improved [2].

Also, the surface tension is related to the polarity. Thus, typically, when the polarity of the polymers is high, molecular forces increase, what causes a decrease of the surface tension and consequently better adhesion [29].

- **Crystallinity**

The degree of crystallinity influences the adhesion of the materials. The crystalline areas negatively affect the molecular chain mobility, and, consequently, the strength of the bi-material part is compromised [2].

Therefore, adhesion in parts with semi-crystalline polymers may have more problems. For that reason, the injection temperature of the second material must be high enough to melt the contact area and promote diffusion, because this one is injected beside the spherulites formed due to the cooling of the first material [2].

- **Molecular weight**

The molecular weight has two opposite effects on the adhesion of the materials. On the one hand, the molecular chain mobility decreases with the increase of the molecular weight, which is not an advantageous factor for adhesion. On the other hand, the possibility to diffuse entire molecules tangles increases. Therefore, there is a critical molecular weight that depends on the polymers. The correlation between molecular weight and part adhesion is represented in Figure 13 [2].

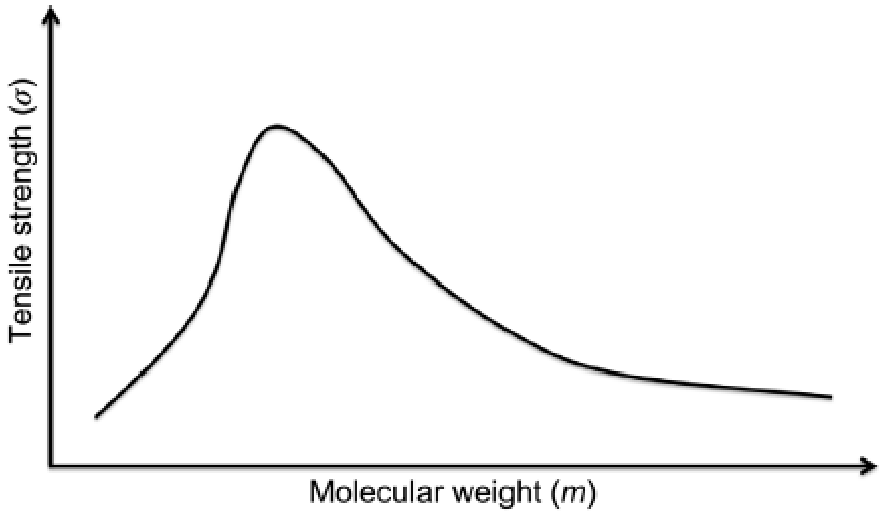

Figure 13 - Relation between tensile strength and molecular weight [2].

- **Molecular orientation**

Adhesion is improved when the orientation degree in the molecular chains, which are parallel to the interface, is high. So, the higher the orientation, the higher the elastic deformation of the molecules, and diffusion is promoted [2].

- **Miscibility**

Miscibility is the penetration of molecules during diffusion processes. Therefore, the higher the miscibility the higher the diffusion. In the case of semi-crystalline polymers, miscibility is reduced because mixing is only possible in the amorphous areas [2].

- **Surface pre-treatment**

Surface pre-treatment eliminates interface tensions, which promotes adhesion. There are some methods of pre-treatment usually applied, such as primers, flaming, or corona and they can be integrated in the injection process by rotary disks or handling system. These methods regularly consist in introduce polar groups to the surface, what improves the surface energy and adhesion. They are mainly used to promote adhesion in material combinations with zero adhesion [2,29].

2.9.2 Interface temperature

The longer a high interface temperature persists, the higher will be the degree of molecular mobility, and the tendency for diffusion processes will occur [2]. Interface temperature depends on several factors, such as:

- **Mass temperature/Injection sequence**

The ideal temperature for a composite interface depends on the materials used, however it is possible to make good adhesion predictions with the temperatures used. It is known that when two polymers are heated above their glass transition temperatures, the polymer chain mobility increases, allowing a strong bond [29].

For the first material, the effects of the injection temperature are irrelevant, however, cooling influences the adhesion of the materials. On the one hand, the material should not be overly cooled, because it can lead to poor adhesion, even if the materials are compatible. On the other hand, the first material should be sufficiently cooled because it can deform with the input of the second material [2].

For the second material, injection temperature can't be too high to not deform the first material. Thus, the ideal temperature for amorphous polymers is a temperature slightly higher than the glass transition, and, for semi-crystalline polymers, slightly higher than the melting temperature [2].

- **Mould temperature**

High mould temperatures generally are recommended because they increase the interface temperature, what promotes molecular diffusion and entanglement rate at the bond interface, consequently, adhesion is better [2,30].

On the other hand, Heim [2] affirms that even low temperatures can promote adhesion because they prevent the formation of spherulites, and, as stated above, less crystallinity promotes the strength of the joint.

- **Intermediate cooling time**

The intermediate cooling time is the period between the end of the first material injection and the beginning of the second material injection. This should be relatively short, in order to maintain a high interface temperature and keep the cycle time short [2]. Though, a study of Islam et al [30] unveil that if it is set to an insufficient value it has a negative effect on the adhesion of the bonding area.

- **Holding time / Contact time**

The contact time improves the composite strength until a certain value, after that, no more effects are added, like demonstrated in the graphic of Figure 14. Therefore, it is important to ensure that the contact time is enough, but if it is set to high values, the cycle time will increase with no benefits [2,30].

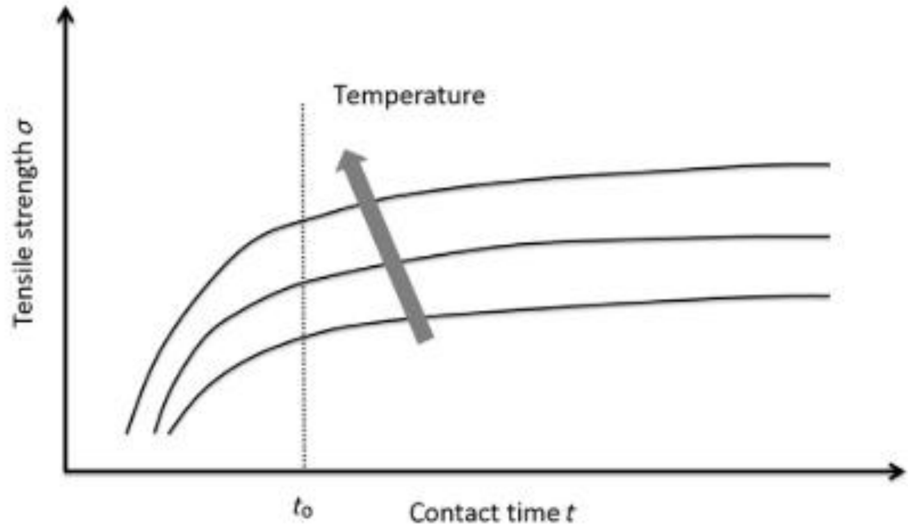

Figure 14 – Contact time effects on the tensile strength [2].

2.9.3 Interface stress

Usually, tensions influence negatively the part strength. Interface stress depends on the following factors [2].

- **Shrinkage**

Shrinkage is influenced by numerous processing parameters and it has a bad influence on the bonding strength. Since the two materials have different shrinkage, it leads to stresses in the interface and, consequently, to poor adhesion. The second melted material, which has a higher temperature, when getting in contact with the first component that is colder, can lead to different shrinkage, creating stresses [2].

- **Connection design/ Interface Geometry**

The design of the parts may influence the composite strength. In order to improve adhesion, some undercuts and perforations should be made in the components, to mechanically supports the connection. Moreover, interface geometry affects the molecular orientation, when the molecules orientation is parallel to the interface the diffusion processes increase, and, subsequently, adhesion also increases [2,31]. Some researches show that certain complex geometric interfaces perform better adhesion strength comparing with flat bonded interfaces [21].

- **Surface Roughness**

Surface roughness is a controversial subject concerning to adhesion. According to Islam et al. [30] the rough surface increases the mechanical interlocking of the materials and the interfacial contact area, what promotes the heat transfer and a bigger area for mechanical interactions. A study of Fetecau et al.[28] also demonstrates that increasing roughness promotes adhesion due to the penetration of the second material in the first material injected. Nevertheless, Heim [2] has two different perspectives: on the one hand, adhesion is improved with the larger contact surface, on the other hand, since the surface size is bigger, it can lead to higher heat dissipation and, consequently, a lower temperature on the interface. Besides, the rough can enable air or dirt to enter the contact area, which is not favourable.

In addition, previous studies have proven that surface roughness has no influence on adhesive strength [29,31].

- **Mould Design**

There are some determining factors in mould design to consider when it's intended to promote adhesion between materials [2], namely:

- Elimination of air is recommended in order to avoid air pockets that lead to poor adhesion;
- In semi-crystalline polymers, the wall thickness of the part should be thin because it prevents the formation of spherulites, which, as stated above, make it difficult to form a strong interface;
- The temperature in the boundary area, the pressure, and the contact time are recommended to be high enough to promote adhesion;

- **Thermal Expansion Behaviour**

Varying degrees of thermal expansion in the components can lead to tensions in the interface and, as already stated, stresses negatively affect the part adhesion. Consequently, heat contractions in both components should be similar, to improve the quality of the interface [2].

- **Injection and Holding Pressure**

The processing pressures usually affect the molecular orientation, and, consequently, the interface adhesion. Thus, injection and holding pressures are recommended to be high because, as was already seen, the higher is the level of molecular orientation, the stronger will be the interface [2].

When the holding pressure is high, the mechanical locking of the second-shot polymer melt at the interface is greater and makes the interface stronger [2]. However, a study made by Bex et al. [32] suggest that increasing too much the values of holding pressure will not bring additional advantages in the adhesion strength. Also affirms that the holding pressure only affects negatively the adhesion strength when it is too low, or if the holding time is too short.

- **Injection Speed**

Injection speed affects interfacial adhesion. Usually, increasing injection speed has a positive effect on the bonding of two materials [2].

The higher is the injection speed, the higher will be the melt temperature due to the friction generated and lower will be the melt viscosity. Similar to holding pressure, the mechanical locking is increased with the injection speed increase. However, it is also possible for a higher molecular orientation to cause shrinkage-induced stress in the contact area, which, in turn, can inhibit bonding. Thus, this subject generates some controversy [2].

According to the results of the study made by Bex et al.[32] the increase of the injection speed had not a big positive influence in the adhesion strength.

2.10 Material Adhesion in Core Back Moulds

As in all multi-material injection, attention must be paid to the compatibility of the melts. In the core back technique, strong adhesion between materials is guaranteed comparing with the other techniques, because the time between injection of the first material and the second can be optimized, yet it is necessary to take into account that the second material should not be injected until the first is sufficiently cooled and already in a solid state. Also, some of the stated conditions for improving adhesion are respected, as the geometry of the parts designed to adjust both materials [1,14,31].

Core back moulds are frequently used when it is intended to promote a good chemical adhesion between materials. This occurs because materials are injected sequentially without opening the mould [33].

According to Heim [2] the succession of the injection steps is quick, the first injected component does not cool off as much, what promotes higher interface temperature and hence adhesion in the joining area is achieved. He also claims that, regarding to interface stresses, better conditions are expected.

2.11 Rigid/flexible materials combinations

Multi-material moulding allows using combinations of polymers with different hardness. These can be rigid/flexible combinations or even combinations which one of the materials is a reinforced polymer. In most cases, rigid/flexible combinations consist of a thermoplastic and an elastomer or a TPE (thermoplastic elastomer) [1,27].

A thermoplastic is a material that is rigid when it is cold, and, when subjected to high temperatures, turns liquid. These materials can be subjected to the heating and melting process several times, so it has the advantage of being easily remoulded and recycled with an insignificant loss of properties [34].

An elastomer is a material that presents elastic properties and can handle major deformations before the rupture. These materials are regularly called “rubbers” [35].

A TPE is a rubbery material with the characteristics of a thermoplastic and the performance properties of thermoset rubber. The following commercial TPE families are represented in Figure 15 [36].

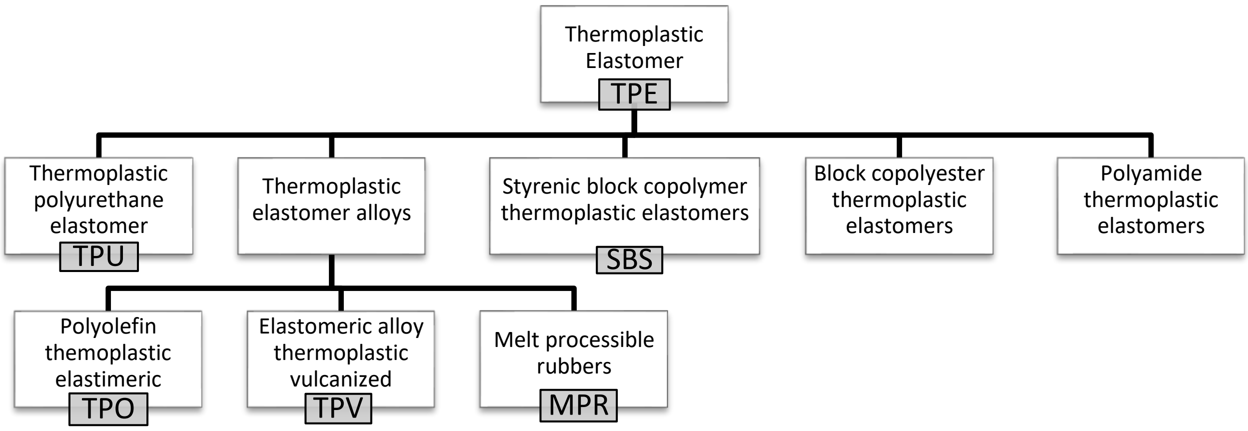

Figure 15- TPE family.

There are a lot of possible rigid/flexible combinations, Ethylene Propylene Diene Monomer (EPDM), a type of elastomer, and other polyolefin polymers like Polypropylene (PP) are one of the most common. There has been a large improvement in the production of EPDM and PP combination. Although they are usually immiscible with each other, there exists some degree of mutual compatibility between them [37].

Another convenient rigid/flexible combination is Liquid Silicone Rubber (LSR) and another thermoplastic. Sometimes it is even more advantageous than combinations with TPE's because these have some limitations concerning to high temperatures, chemical resistance, mechanical strain, among others. LSR is thermally more stable, which allows it to be processed at high temperatures [1,31].

2.11.1 Hardness

When combining rigid/flexible materials, it is important to know that they have different hardness values. Hardness can be defined as the resistance of the material to indentation. There are different scales to measure hardness like Brinell, Rockwell, Meyer, Shore, etc… For polymers, Shore is the scale commonly used [1].

TPE's tend to be rated on a Shore A scale. The softest materials with values around 3 Shore A, and the hardest with 95 Shore A. Thermoplastics are measured on the Shore D scale and elastomers on the Shore A. Figure 16 exemplify this variation of hardness [1].

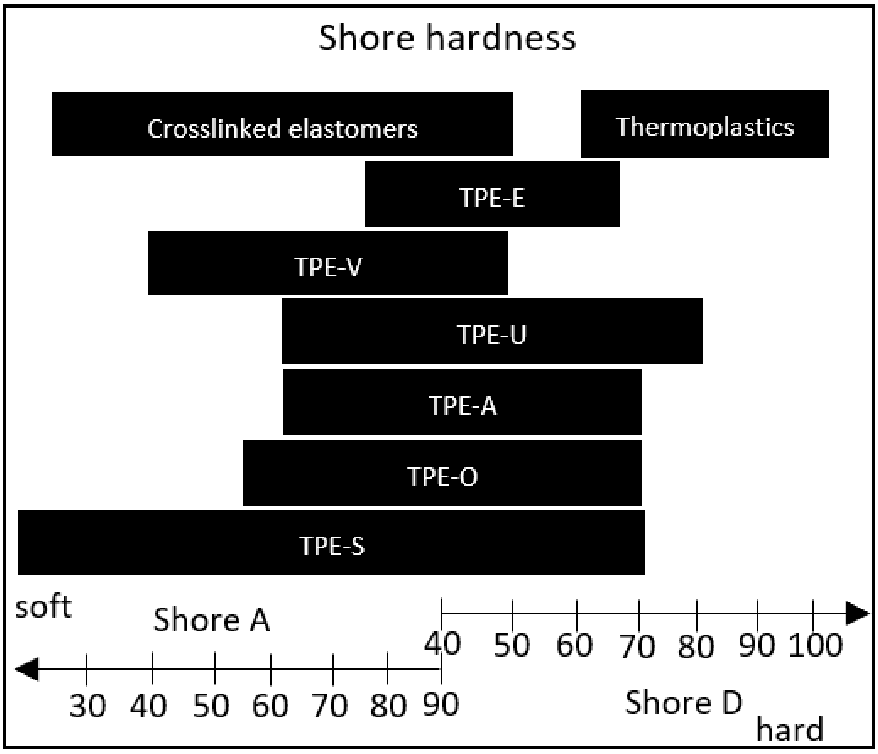

Figure 16- Shore hardness. Adapted from [38].

2.11.2 Injection sequence

When it is intended to make a component with an elastomer or a TPE and a rigid material, the injection sequence is important. If the flexible material is injected before the rigid, it is not possible to obtain a good product because the elastomeric material can't mechanically resist to the required pressures to inject the rigid material. This problem happens even if the flexible material is completely cured before the rigid material is injected [1].

To obtain a quality component, the first material to be injected must be the rigid one. The injection of the elastomeric material must be sufficiently delayed so that the rigid material doesn't deform with the necessary injection pressures. This way it is ensured a strong connection between the elastomeric and the rigid material. However, if the first material totally solidifies before the injection of the second material, bonded processes will be compromised. [1,39].

2.12 Effects of the processing conditions on the adhesion

As was seen in point 2.9, processing conditions are one in several aspects that influence the adhesion of a multi-material part. Adhesion is influenced by almost every processing parameters involved in the injection process, however, the most relevant are [30,40]:

- Melt temperature of the second material;
- Mould temperature;
- Injection pressure;
- Holding pressure;
- Injection speed;
- Holding time;
- Cooling time.

Some researches indicate that melt and mould temperatures are the processing conditions that have bigger influence in the bond strength. Besides, they demonstrate that when these parameters increase, bond strength also increase [28,30,32,40]. Stan et al. [40] suggest that increasing too much the values of these parameters can lead to a poor adhesion. Furthermore, at higher mould temperatures, the adhesion strength slightly decreases when the melt temperature is increased.

As per Bex et al. [32] holding pressure is the parameter that has less influence on the process.

2.13 Evaluation of the adhesion strength

In order to evaluate the interface adhesion there are some experimental tests that can be performed, such as tensile tests, shear stress tests and peel tests. They measure the force required to break, tear or delaminate the interface of the bi-material part. These tests are the most frequent and they are used mostly to check the adhesion quality and to make sure that the values are within defined limits [29,36].

To carry out these tests it is necessary to cut a part of the bi-material component in the shape of test specimens. Figure 17 represents some examples of specimens shapes used in the respective tests [41].

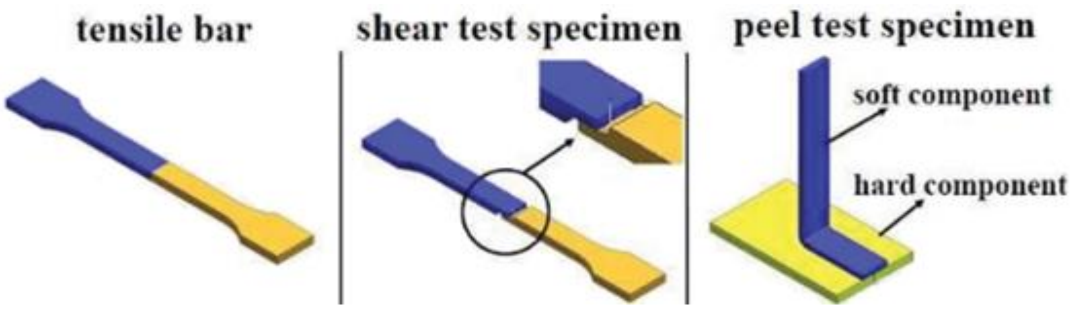

Figure 17 -Test specimens [41].

- **Tensile testing:**

The test specimen is placed between two clamps in a tensile tester and the clamps are pulled apart to apply tension until the sample breaks. With the test is obtained the stress-strain graph, in which it is possible to analyse the behaviour of the material and some properties like: ultimate tensile strength, breaking strength, and maximum elongation and [36].

Figure 18 shows a scheme of a tensile testing machine.

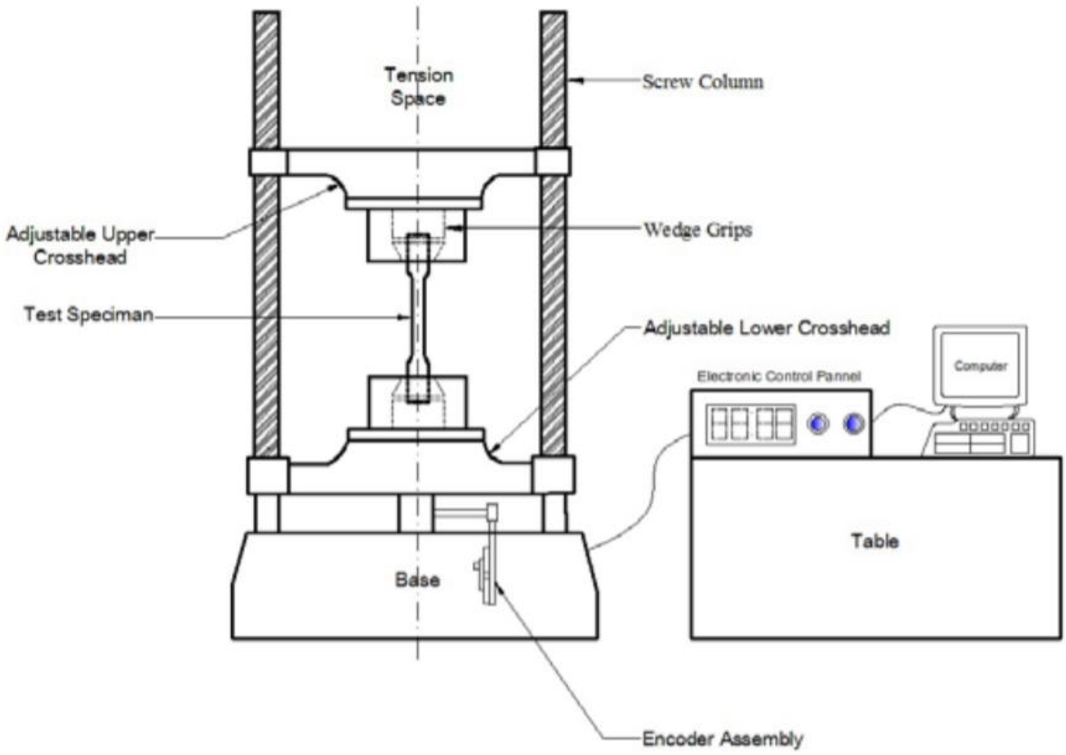

Figure 18- Tensile test [42].

- **Shear stress testing:**

Shear stress testing differ from the tensile testes because forces are applied in a parallel direction to the contact surface of the two materials, while in tensile tests the forces applied are perpendicular to the interface. In shear stress testing one surface of a material move in one direction and the other surface to move in the opposite direction so that the material is stressed in a sliding motion, as represented in Figure 19 [36].

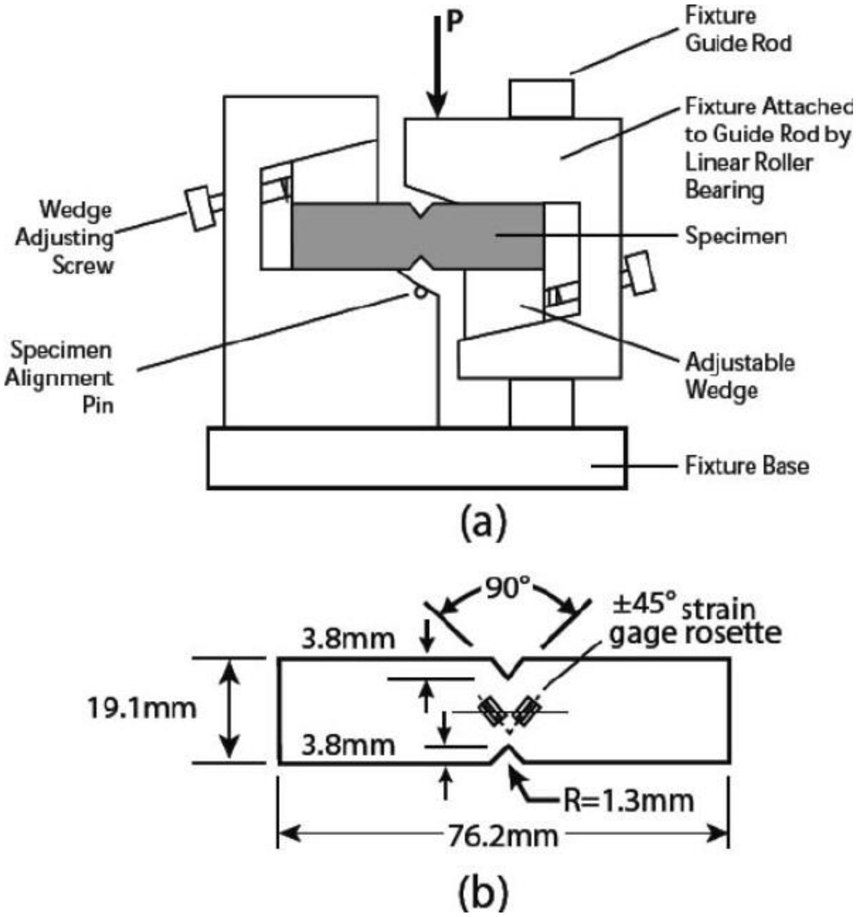

Figure 19 - Shear stress test [43].

- **Peel testing:**

In a peeling test the rigid material is fixed and the flexible material is pulled by a clamp usually with an 180º angle, measuring the strength of the materials interface, as represented in Figure 20. This test is only viable if one of the materials is flexible enough so that it can fold back on itself [36].

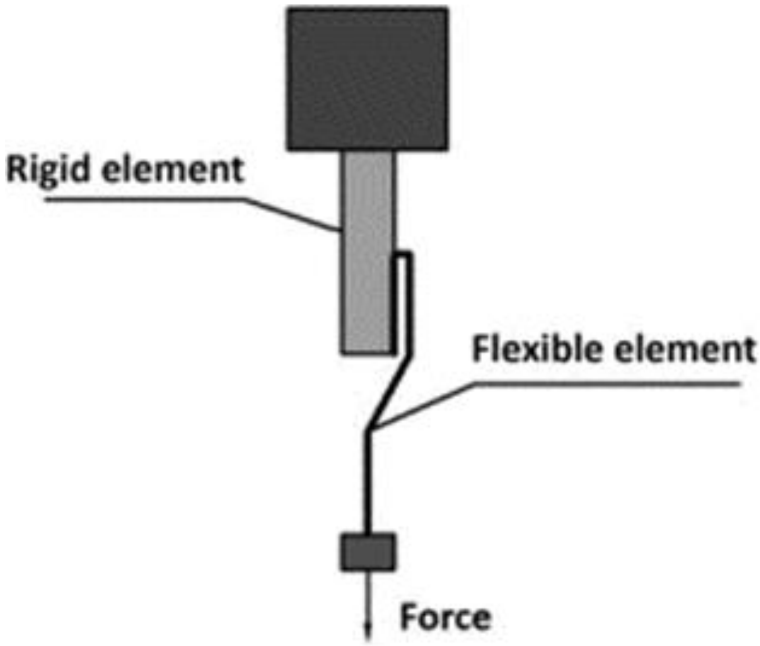

Figure 20 - Peeling test [44].

These tests are preformed and chosen according to the part, more specifically, according to the geometry and the materials in question. Usually tensile tests are widely used for testing the bonds strength and they are applied in several geometries, however, shear stress tests are better for two rigid components and peel tests works better for components that have one of the materials very flexible [36].

According to Kunstsoffe [38] it is of an extreme importance to ensure that materials can be deformed at a defined angle in a peel test, that's because if the material has increased hardness, cracking and premature failure may occur.

Haberstroh and Ronnewinkel [31] affirm that tensile tests and peel tests can show different results even using the same material combination because sometimes it becomes too difficult in peel tests to separate the two materials while in tensile tests it is relatively easy.

After choosing the most suitable test to be performed, the results must be analysed and check if they are within the range limits of values imposed by the costumer.

2.14 Design of Experiments (DOE)

Design of Experiments (DOE) is an efficient method that simultaneously investigates multiple process factors, using a minimal number of experiments. It has been used in several industrial applications in order to optimize manufacturing processes. This method is a branch of applied statistics focused on using the scientific method for planning, conducting, analysing and interpreting data from controlled tests or experiments [45,46].

This method allows evaluating multiple variables or inputs to a process, their interactions with each other and their impact on the output. In addition, if performed properly, is possible to determine which variables have the most and least impact on the output, so the process can meet quality requirements and satisfies customer needs [46].

Briefly, to apply DOE it is essential to define the objective and select the characteristics that have influence on the process. It is also necessary to define the levels of the factors in question. Then, starts the statistic phase, that consists in combining the process parameters in orthogonal arrays to plan the experiments. After that, the experiments are made and, when they finish, the results can be analysed. According to the results, changes can be made to enhance the process [47,48]. The steps of DOE methodology steps are represented in Figure 21.

By properly using DOE methodology, the number of tests can be greatly reduced, and it is possible to save project time.

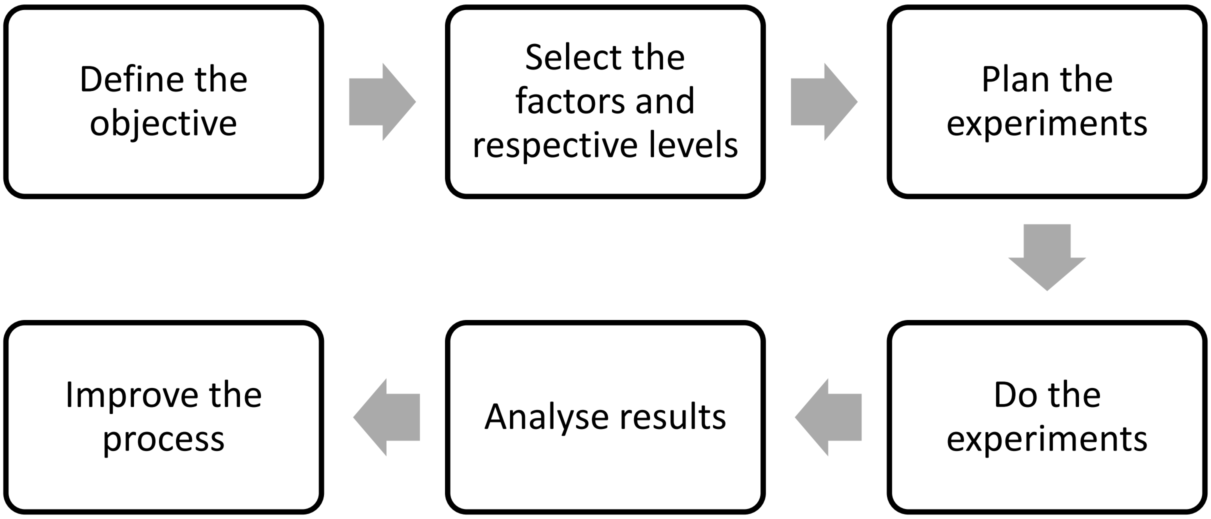

Figure 21- DOE methodology.

The application of DOE requires careful planning, prudent layout of the experiment, and expert analysis of results. Based on years of research and applications Dr. Genechi Taguchi has standardized methods for DOE application steps. Thus, DOE using the Taguchi approach has become a much more attractive tool to practicing engineers and scientists [49].

2.14.1 Taguchi method

Taguchi method is one of the design of experiments methods and it is one of the most used since it is a simple method that helps to produce high-quality products at a low cost. Various industries have employed this method over the years to improve their processes. This is a fractional factorial design of experiments method, which means that only a fraction of the total number of combinations of the input variables is performed. For this, orthogonal arrays are realized in order to define the tests to be made [45,49].

In order to apply this technique, it is important to define the typical elements of the process, illustrate on the diagram of the Figure 22.

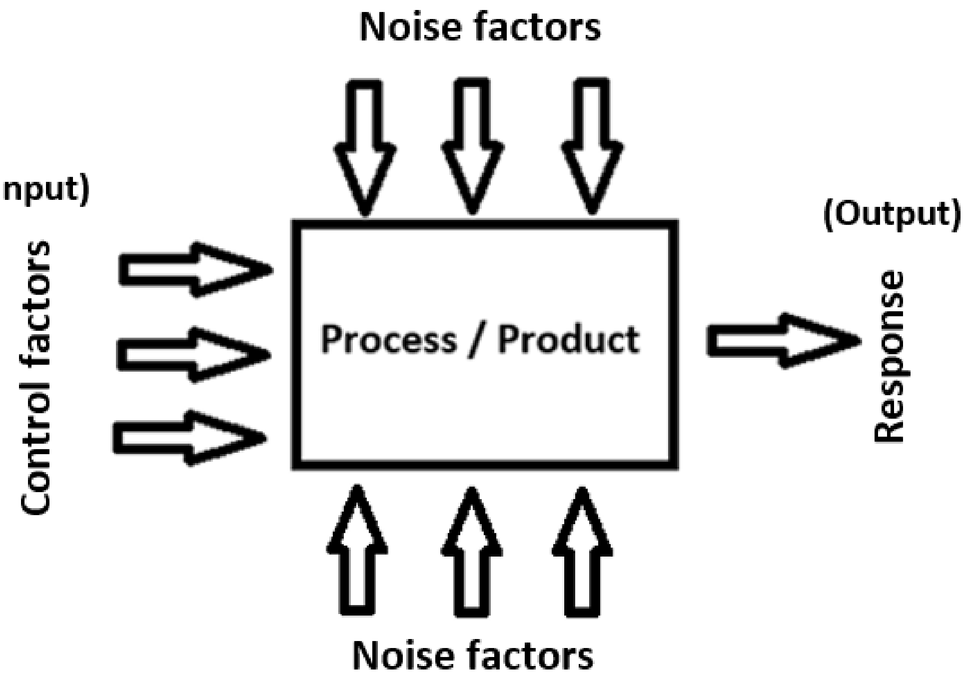

Figure 22 - Typical DOE factors. Adapted from: [49].

- **Control factors (inputs):** Variables that influence significantly a certain characteristic of the process/product. These are independent variables and must be easily controlled.
- **Response (outputs):** Measurable characteristic of the product quality.
- **Noise factors:** Uncontrolled factors that affect the process/product.

Regarding noise factors, they can be internal or external. They are classified as internal noise factors if they are for example the material or the operator, otherwise, if they are for example contaminations or humidity, they are external noise factors [49,50].

When the objective is the optimization of an industrial process, usually the control factors are parameters of the machine, such as values of temperature or pressure. It is important to consider that the higher the number of control factors, the longer it takes to complete the testing and, subsequently, higher will be the cost. Also, concerning the interactions between the factors, this method is more efficient when the number of factors is reduced.

After identifying the control factors, is necessary to define their levels, in other words, the values of the factors in the experiments. To represent these levels some typical symbols are used, ex: (+) and (-), or 1 and 2. This way, it is possible to construct a designed experience that proves all combinations of factors or levels [50].

In order to combine all the factors, it is necessary to create an orthogonal array that shows all possible combinations of high and low levels for each input factor.

As described, it is possible to study some different factors, so the array will be as bigger as the number of factors to study. The array to be used is chosen according to the levels and number of factors to be studied, knowing that the higher the number of factors to be studied, the less accurate the results [50].

In the Table 2 is represented an example of an orthogonal array $L_4(2^3)$, this means $L_{\text{experiments}}(\text{levels}^{\text{factors}})$.

Table 2 - L4 matrix example for DOE.

Exp.	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

An L4 table have the following characteristics:

- Number of factors: 3 (A, B, C)
- Number of experiments: 4 (1, 2, 3, 4)
- Levels: 2 (1 and 2)

If this array were not applied, it would be necessary to make 8 experiments to reproduce the same result, which means that the use of Taguchi method, in this case, would halve the number of experiments.

Depending on the goal, a certain orthogonal array is used, varying the number of factors and the number of levels. Table 3 exemplifies some of the current types of arrays.

Table 3 - Some types of arrays. Applied from: [49].

Array	Number of factors	Number of levels
$L_4(2^3)$	3	2
$L_8(2^7)$	7	2
$L_{12}(2^{11})$	11	2
$L_{16}(2^{15})$	15	2
$L_{32}(2^{31})$	31	2
$L_9(2^4)$	4	2
Etc..	Etc..	Etc..

After all the experiments are done, it is necessary to make an analysis of the results, calculating the interactions effect and comparing the relevance of each factor on the process. For that, the average of the levels influence in each factor is made [51,52].

A lot of studies confirm that Taguchi method is a simple and efficient methodology when the aim is to improve some industrial process or product [17,45,51,53]. Moreover, investigations made by Athreya and Venkatesh [51] evince that this method allows less number of experimentations comparing with full factorial methods and generate similar results. Besides that, it can be applied for analysing numerous types of problems.

According to Antony and Jiju Antony [48] Taguchi method is essential to reduce scrap rates, rework costs and manufacturing costs due to excessive variability in processes.

3. MOULD DEVELOPMENT

In order to meet the objectives of developing and testing the mould, described in the point 1.2, a set of operations have been undertaken. They are described as follow:

1. The part model set by the costumer was analysed to define all aspects of mould design.

2. A 3D design of the mould, including all its systems (injection, cooling, ejection, gas trap, etc) was made.

3. Validation of 3D mould design by the costumer (all the information is gathered and sent to the costumer for validation)

4. Mould machining and assembling: the mould machining went through several procedures as conventional machining; CNC machining; EDM machining and wire cut. Then, the mould was adjusted and assembled with the standards components and the injection system. If it is the case, that is also purchased as a standard part.

5. Mould testing: In the first test some of the best theoretical processing conditions were used just to test the mechanical functionality of the mould. These conditions result from the state of the art.

6. Definition of DOE, test and analysis: The orthogonal array was defined according to the results of the mould testing applied. Then the set of tests were performed, and the results of the DOE analysed.

7. Mechanical testing of the final parts: Parts were obtained using the mould just developed. Then specimens were cut and the mechanical tests performed. These data allowed to study the influence of the processing conditions on the adhesion between both materials.

3.1 Part design

The component under study is an anti-recycling partition of the motor and has the functionality of conducting air for systems dedicated to engine cooling, called radiators. It is placed between the engine section and the front of radiators, and it helps the hot air to escape and prevents the recycling of hot air, since it could return to the radiators again.

This part is very important for the car since the correct functioning of the radiator prevent the engine from overheating due to combustion, consequently, impair its performance.

Two different parts are produced per cycle, since the mould has two cavities, as represented in Figure 23. Their design is slightly different from each other, despite both having the same functionality.

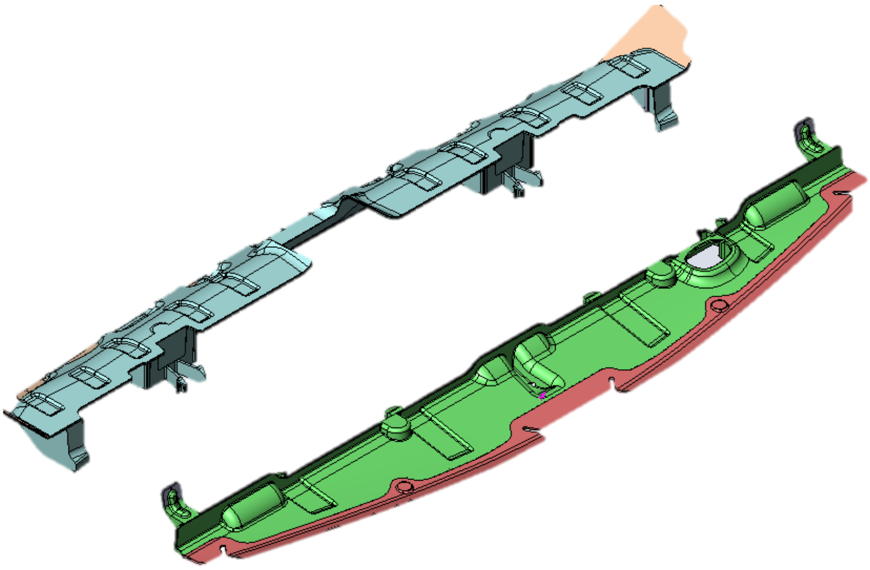

Figure 23 – 3D part design.

The part consists in a rigid component that is involved by a flexible one. The materials used are specifically a PP TD20 (PP with 20% talc filler) involved by an EPDM. Detailed description of the materials is presented in the point 3.3.1 The joining of materials is very convenient since the thermoplastic is responsible for the air conduct and the elastomer acts as a seal.

This part is very complex in terms of details, due to the different shapes. Despite of that it does not imply the use of transference of the part from one position to another on the mould neither a rotative plate. It can be made just by the action of a mechanism that allow the injection of the first material, its cooling and then the injection of the second one. This simplifies greatly the construction of the mould, being a positive point for the use of a core back mould.

In order to improve adhesion, the design of the mould was made so that roughness would be created at the surface of the part when the first material was injected. In that way the second material could be anchored more easily and adhesion between the two materials improved.

3.2 Core back mould design, technology and its functional systems

Once determined the technology, a 3D project of a core back mould was made. For this particular case, the costumer asked for a mould that produced two different parts for the same project just for the sake of costs, so the mould has two cavities (two different parts), as illustrated in Figure 24.

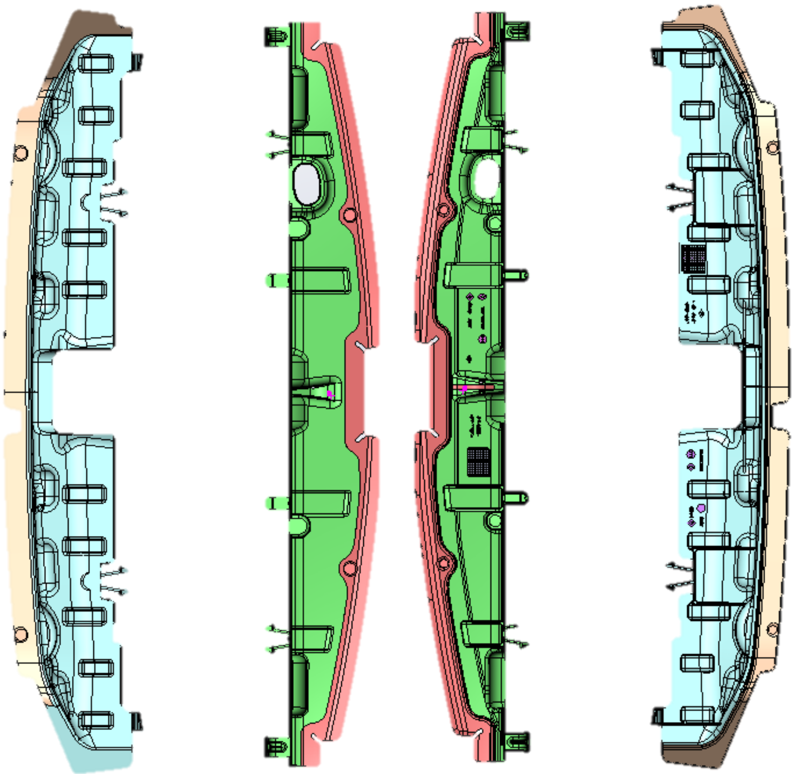

Figure 24 – 3D part design.

The overall picture of the mould is shown in Figure 25.

As already describe in the point 2.7, the core back moulds have a particular technology that differentiates that kind of moulds from all others. With this technology it is possible to inject a 2K (2 material) part in the same mould without opening the mold between the injection of the first and second material.

It is possible using a mechanical system of sliding inserts triggered by a hydraulic system.

The 3D design of the mould includes the principal systems of the mould: injection, cooling, ejection and exhaust gas systems. In order to further detail Annex C shows the 2D mould design.

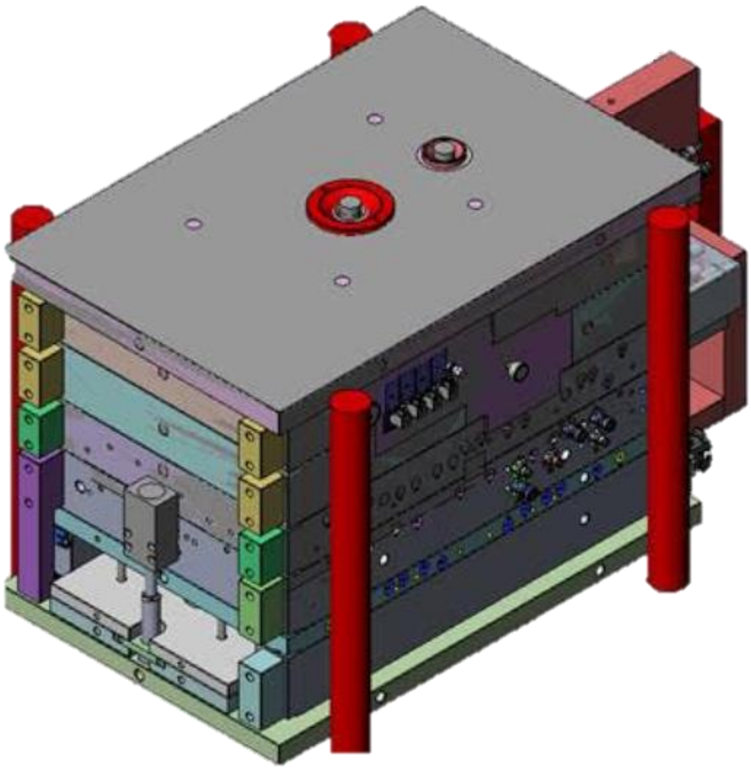

Figure 25 – Mould 3D design.

3.2.1 Core back technology

As described before in the point 2.7 the core back technology, consists on a hydraulic system that activates a mechanical linear system that share the cavity of the part. So if the system is activated it is only possible to inject the rigid part (partial filling of the cavity), and once that part is injected and cooled the system is “disactivated” or retreated, and it is then possible to inject the rest of the part, with the flexible material. Figure 26 exemplifies the system operation of core back mould. The number 1 represents the hydraulic cylinders that when actuated, move the guide bars horizontally and make the cores to move vertically, as indicated by number 2. This movement of the cores is what allows or prevents material from being injected.

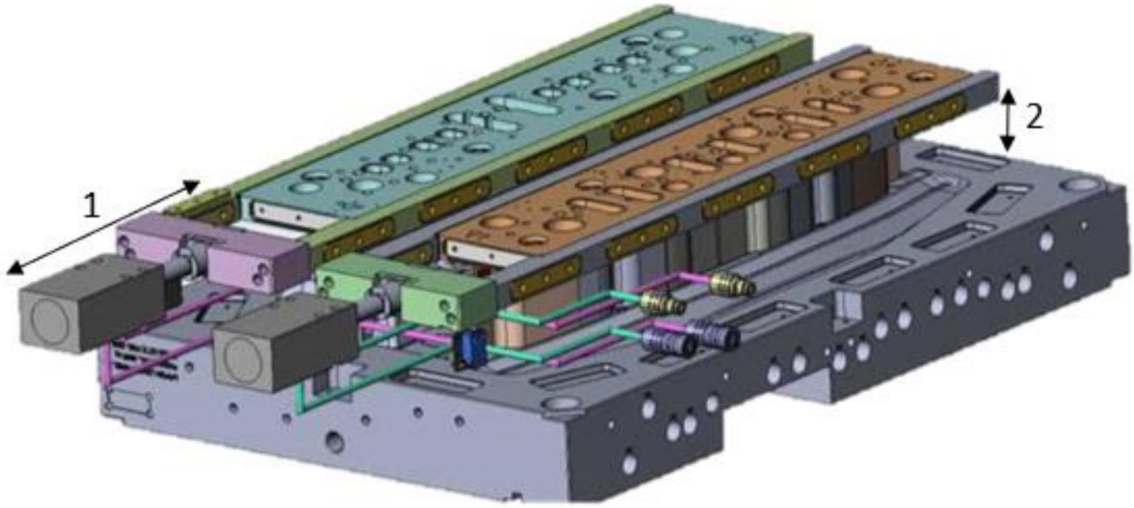

Figure 26 – Core back system.

The cores need to move 3mm according to the direction represented with the number 2 in order to make the correct filling of the second material. Since the plates are arranged at an angle of 2° in order to allow the movement of the cores, the hydraulic system needs to perform a movement of approximately 86mm.

3.2.2 Injection system

The parts have two injection points to inject the first material and another two points to inject the second material, as represented in Figure 27. This is a hot runner system, where the material is kept in the molten state from the machine nozzle until the entrance channel in the mould part. Besides, this kind of injection system allows to obtain parts with the best finishing and without the waste of a cold runner.

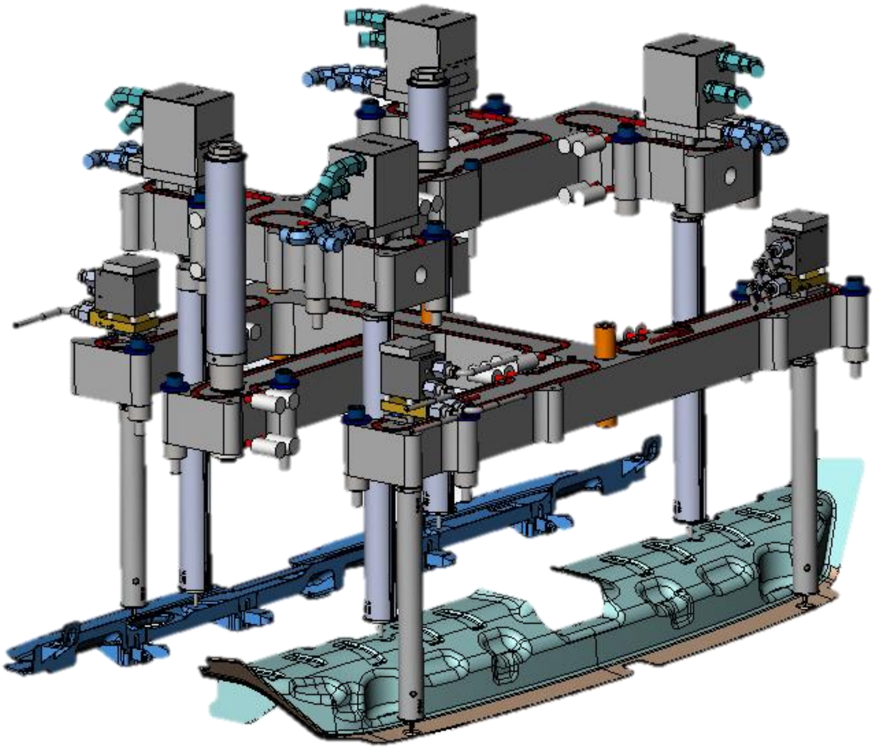

Figure 27 – Injection system.

3.2.3 Cooling system

The cooling phase is very important for the good mould functioning, and for having good parts produced. During this phase shrinkage of the materials occur and ideally it should be equal in all zones of the part. In other words, it should be given likewise in all directions in order to avoid warpage. Consequently, the cooling system was created to ensures effective cooling of the parts, as represented in Figure 28. As illustrated, different designs of cooling circuits were chosen for each side of the mould, according to what was more favourable, and avoiding the collision of the cooling circuits with other components of the mould. For better understanding, each circuit was represented with a different colour.

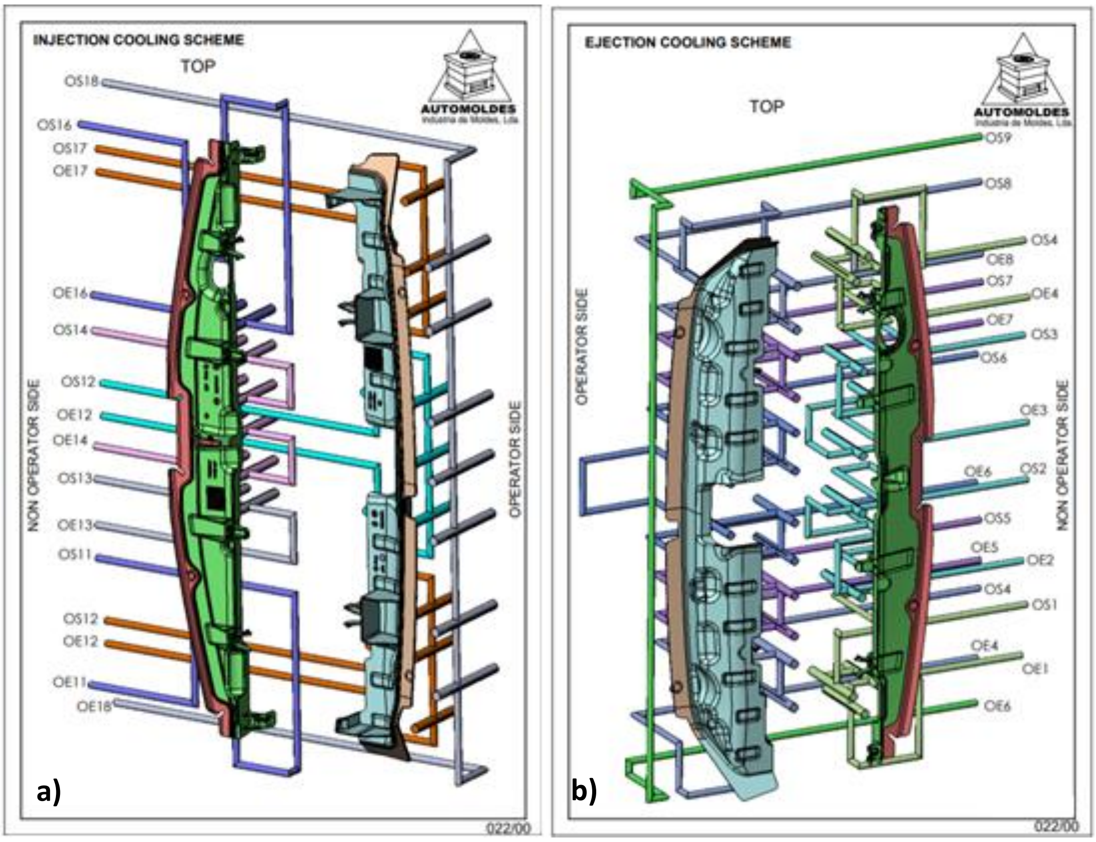

Figure 28 – a) Injection side cooling scheme; b) Ejection side cooling scheme.

3.2.4 Ejection system

The ejection system of the mould was actioned by a hydraulic system because of the dimension and weight of the mould and plates. The hydraulic system consists in a hydraulic cylinder that move the ejection plates, which, consequently, make ejectors move forward and eject the parts off the mould.

The ejectors have different diameters, as big as possible keeping a logical scheme, and they were uniformly distributed through the part. The ones which have the smallest diameter were applied on the snap fits, the most critical zones to be ejected, due to the risk to get stuck on the core.

Figure 29 shows on the left side all the ejection system, and, on the right side the zones where the ejectors will act.

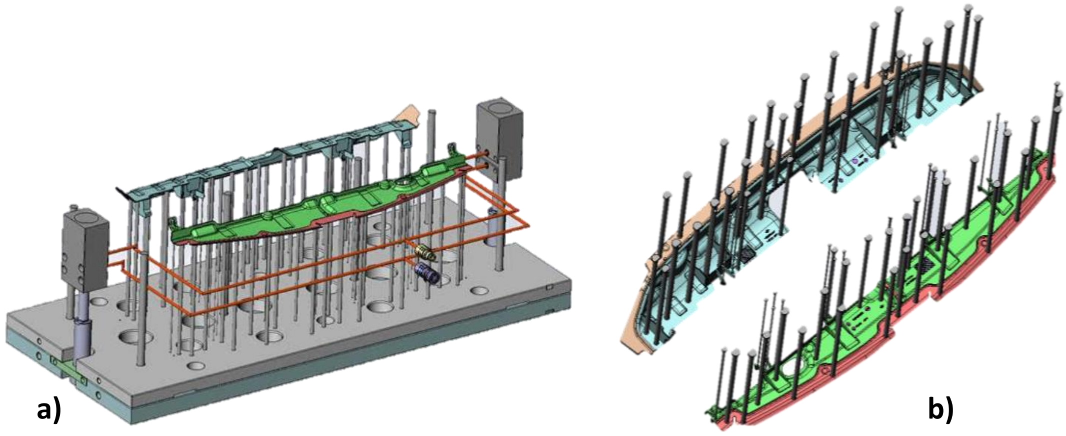

Figure 29 – a) ejection system; b) extractor areas.

3.2.5 Gas trap system

When the molten material is filling the cavity, the air trapped in the cavity must move to a suitable exhaust, otherwise, the air trapped can be pressurized causing both incomplete filling of the part and also burn marks. These defects are very frequent in plastic parts. Preventively it was projected a gas trap as illustrated with the red circles in Figure 30. Besides, the ejectors at the end of the part also help this effect.

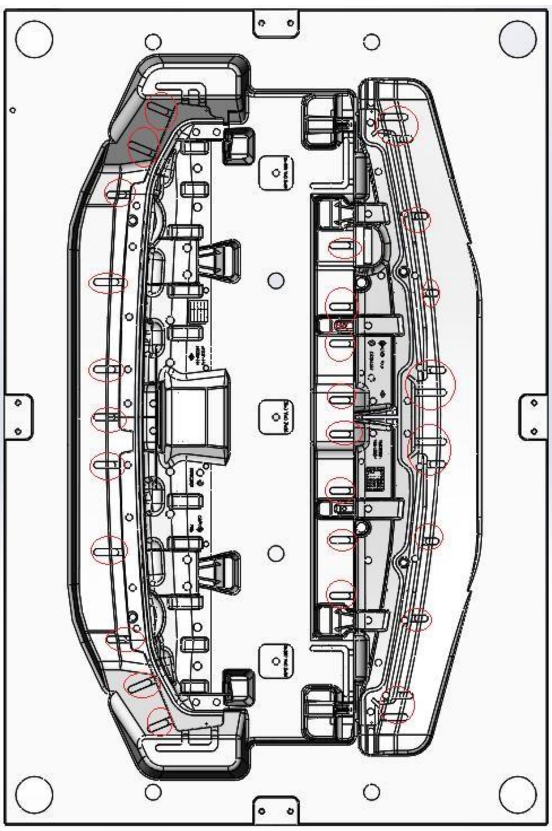

Figure 30 – Gas trap system.

Besides the principle systems that was explained above, the mould has also some accessories such as:

- **Magnetic plates:** It allows the mould to clamp in the injection machine with a high force. This is a big advantage because it simplifies operations, reducing the time needed for assembly the mould in the machine and assures the security of the operators.
- **Feeding sensor:** assures the injection phases commutation between the first and the second material to be injected.
- **Microswitch on the core back system:** assures the forward and backward of the core back system.
- **Microswitch on the ejection system:** assures that the ejection plates are well retreated before start the new injection cycle.
- **Interlocks:** helps the guidance and adjustment of the mould, ensuring the precision of the mould closing.

3.2.6 Mould machining, assembly and testing

After 3D design, the mould went through several phases until it was completely ready. At first, the components were milling by CNC. Figure 31 represents an example of a mould plate being milling by this method.

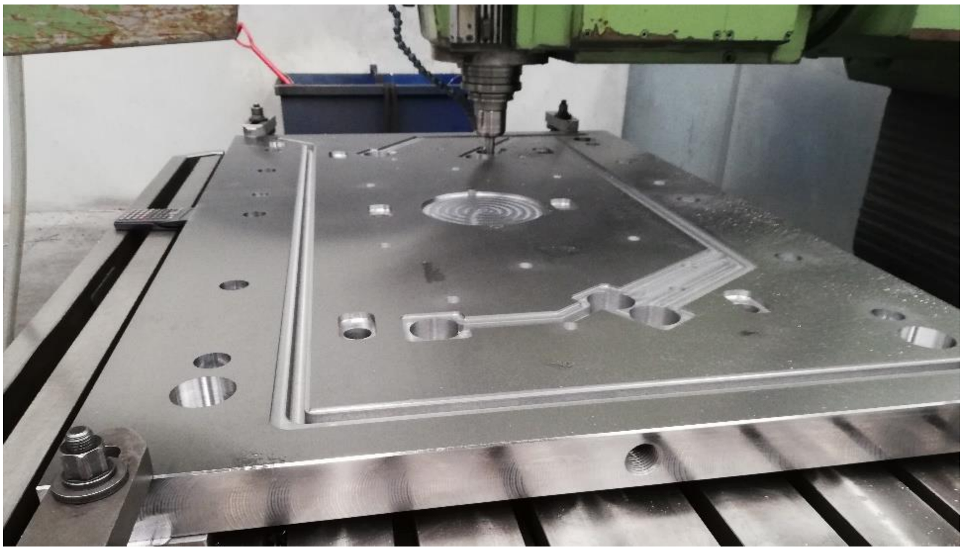

Figure 31 – CNC milling.

The CNC is not able to mill complex shapes with tiny details, when this occurs EDM was adopted. The EDM consists in an electric erosion of the steel, it is done by a negative form from the final part, and need to be performed in a conductive material (graphite in that case) to allow the electric current to pass from the machine to the steel.

Annex B shows the areas where it was necessary to apply EDM for concluding the milling of the mould plate.

After defining the areas to be made by EDM, it was necessary to design the electrodes (negative forms) which were milled in graphite. The EDM could then be done on the mould plate.

After the milling phases, the mould was adjusted to ensure a part without defects (like burrs). Finally, the mould was assembled with all components, including the standard ones. These two phases are illustrated in Figure 32.

Figure 32 – a) mould adjustment; b) mould assembly.

Once the mould is ready, the mould is tested for the first time according to the customer requests, namely the machine size and processing conditions. No details are allowed to be given regarding this part. The mould was tested successfully, and no further adjustments were needed for the mould.

3.3 Experimental work

3.3.1 Materials

The materials used for producing the bi-material part were: PP with 20% of talc filled, whose commercial name is PP compound 15T1020 provided by SABIC; and the second one was an EPDM, whose commercial name is EPDM 245, also provided by SABIC. These materials are generally used in multi-material moulds. Table 4 and

Table 5 shows some properties of PP and EPDM, respectively. These properties are given by the technical datasheet presented in Annex D and Annex E, respectively.

Table 4 – PP Properties.

Properties	Values	Method	Unit
Melt flow rate (at 230ºC and 2.16kg)	7	ISO 1133	dg/min
Density	1040	ISO 1183	Kg/m³
Mould shrinkage (24 hours after injection moulding)	1.2	Sabic mathod	%

Table 5 – EPDM.

Properties	Values	Method	Unit
Mooney viscosity (ML 1+4, 125 ºC)	25	ASTM D1646	MU
Ethylene Content	50	ASTM D3900	wt%
Ethylidene Norbornene (ENB) Content	**4.5**	**ASTM D6047**	**wt%**

3.3.2 DOE

In order to make the study about the influence of the injection parameters in the adhesion between both materials a DOE method was applicated, namely the Taguchi method.

This methodology defines the number of experiments to do according to the variables chosen to study. Based to the theoretical study (stated in the point 2.12) some of the processing conditions that most influence the adhesion of the materials are:

- Injection temperature of the second material;
- Mould temperature;
- Injection pressure.

It was chosen to study only three variables with the purpose of having a more detailed information about the interactions. Table 6 shows the values chosen for the variables.

It is important to note that the window of processing conditions for these materials is very restricted, so it was not possible to make a higher variation of the level values.

Table 6 – Variables and respective levels.

Variables	Level 1	Level 2	Units
A - Injection temperature of the second material	195	200	(ºC)
B - Mould temperature	35	40	(ºC)
C - Injection pressure	75	80	bar

Table 7 illustrates the experiences plan to be performed, more specifically, corresponding to a L_4 array. The number 1 corresponds to the lower level and number 2 corresponds to the high level.

Table 7 – Experiences plan.

Exp.	Injection temperature of second material - A	Mould temperature - B	Injection pressure - C
1	Level 1	Level 1	Level 1
2	Level 1	Level 2	Level 2
3	Level 2	Level 1	Level 2
4	Level 2	Level 2	Level 1

3.3.3 Injection moulding

The injection of the parts needs to be done in a 2K machine, more specifically, in a machine capable to inject two different materials at the same time or with just some seconds of delay. This information was also considered for the mould design.

At the beginning of the project the costumer knows already that a bi-material machine is necessary and provides one of their machines to this project.

Thus, due to the need to place the both entrances for the two materials, the injection of the parts took place in a bi-material machine Sumitomo DEMAG 550T, represented in the Annex F. This machine is characterized by having the two injection units positioned horizontally.

The process conditions used was the ones already explained in Table 6 and Table 7.

3.3.4 Specimen preparation

After the injection of the parts, it was necessary to prepare the specimens for tensile tests. The specimens were cut in different regions of the part, as shown in the Figure 33. This was made with the aim of obtaining the mechanical properties of the joined parts and evaluate the adhesion between the materials and the uniformity of the adhesion along the part. Each specimen was identified with the respective number as it can see in the Figure 33.

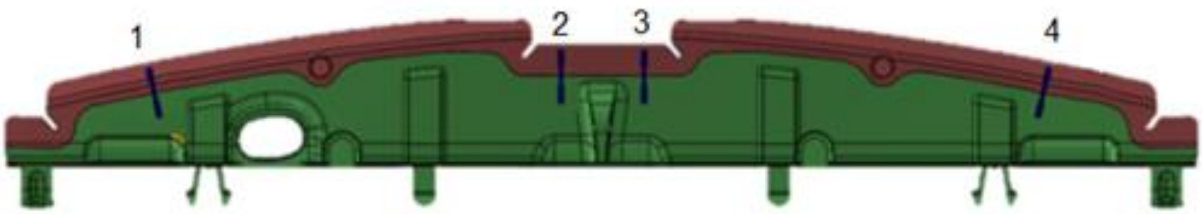

Figure 33 – Cutting areas of the specimens.

The dimensions of the specimens were established respecting the standard specimens' dimensions for mechanical tests and the useful area of the part. Combining both aspects, the specimens used have the dimensions shown in the Figure 34.

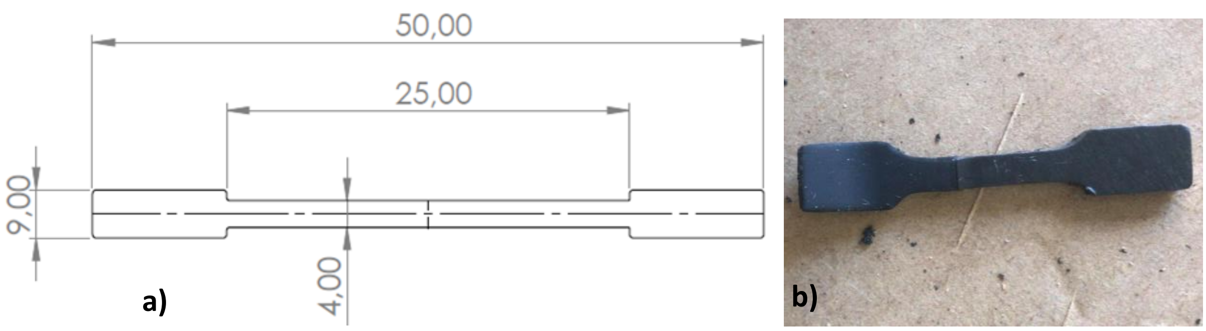

Figure 34 – a) Specimens dimensions; b) Real specimen.

The specimens were obtained by cut a small area of the part with help of a press equipped with a sharp with the dimensions of the final specimen. For better understanding Annex G presents an image of the specimen's preparation. It was cut four specimens in each part.

For this propose, it was used the press Geo E Moore & Son (Bham), whose image is presented in Annex H.

Once having the specimens well cut and identified, the mechanical tests could be performed.

3.3.5 Mechanical testing

Tensile tests were chosen for the mechanical testing of the part because they are the most appropriate tests given the nature of materials (both rigid and flexible) and the geometry of the part.

These tests can predict the material behaviour as shown in Figure 35.

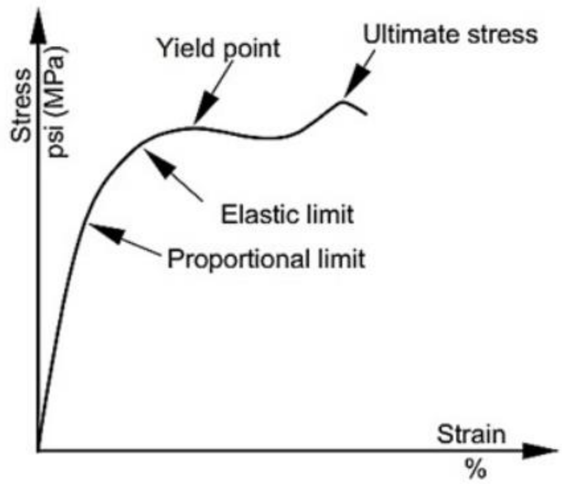

Figure 35 – Tensile–deformation of a polymeric material [54].

As illustrated, polymers typically have an elastic and a plastic region. In the elastic region, when the efforts acting on the part are removed, it returns to its original shape. However, when achieved the limit, there is no recover to the original shape, thus, under these conditions the material is in the plastic region.

The first inflection point refers to the yield strength, that's when the material changes the elastic behaviour to the plastic behaviour. The value of the maximum stress is called the breaking strength, in other words, is the tensile when the material breaks.

Another important parameter is the elastic modulus, that provides a measure of the stiffness of a material. It is possible to determine by drawing a line tangent to the curve. The point of tangency provides the modulus value.

The tests were performed in the tensile machine INSTRON model number 2663-901, illustrated in Annex I. The tests were done with a speed of 50mm/min. The tensile-deformation graphics of the experiments are illustrated in Annex J. It was performed according to the ASTM D638-03 standard.

4. PRESENTATION AND DISCUSSION OF TENSILE TEST RESULTS

Figure 36 presents the sequence of deformation of PP/EPDM during the tensile mechanical testing. As expected only the EPDM material suffers deformation during the test, while the rigid party (PP) is undeformed. The specimens broke at the joining area, meaning that this region is the most vulnerable on the parts.

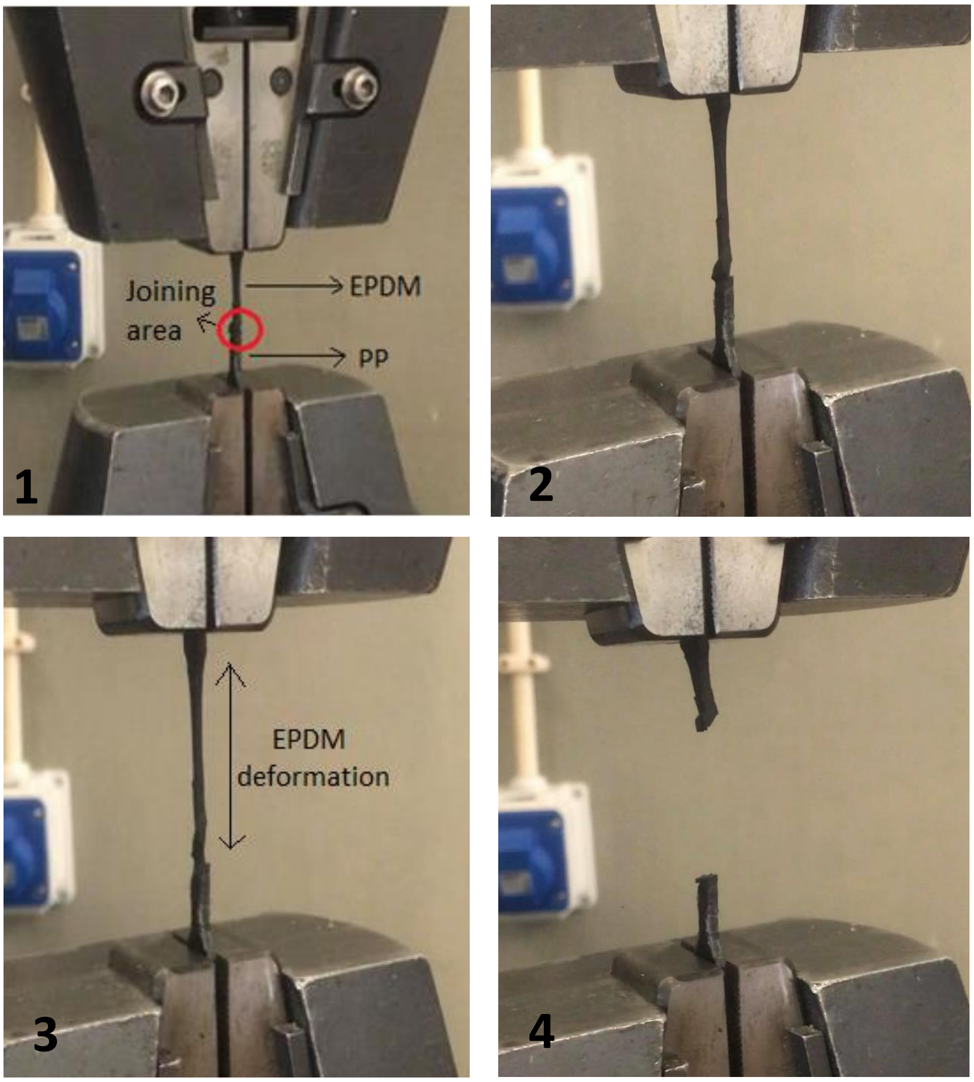

Figure 36 – Sequence deformation of PP/EPDM.

An example of the stress strain curve is depicted on Figure 37 for the experiment 1, with the processing conditions indicated below in Table 8, whereas in Annex J all the results are presented. The curves are typical of a ductile material. However, the maximum tensile stress and the deformation at break are very low.

The maximum stress of PP is typically around 37MPa, value taken from the technical file (Annex D), and the maximum stress of EPDM is around 10MPa, information given by the costumer. The results from the tensile tests show that all the samples have a maximum stress between 2,4-3MPa, these values are too far from the values of the materials used.

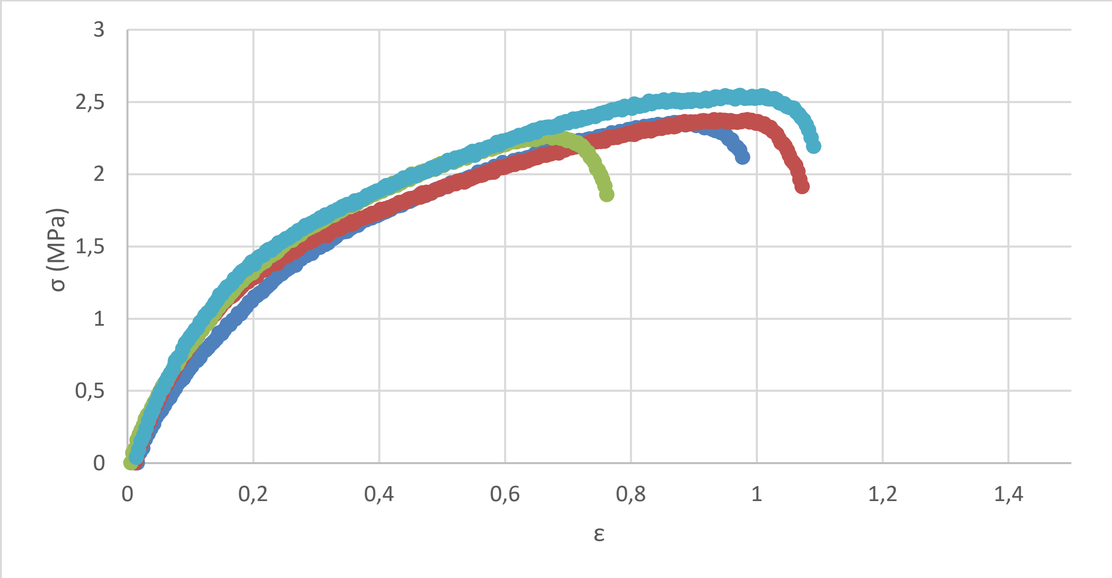

Figure 37 – Stress strain curve of experiment 1.

Table 8 and Table 10 summarizes the tensile behaviour of the part, according to the DOE plan of experiments made. The values presented refer to the maximum stress and deformation at break obtained in each experiment, respectively. The average and standard deviation is then presented.

The maximum stress of the specimens was evaluated because that determines the maximum load that the material can support before breaking, This information is detrimental to the performance of the part when it is functioning in the vehicle, since the joining area is the most vulnerable one. Recall that one of the roles of the part is to act like a seal.

Table 8 – Maximum stress (MPa) obtained for each set of experiments.

Exp.	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average	Standard deviation
1	2,38	2,27	2,55	2,36	**2,39**	0,10
2	2,58	2,53	2,52	2,75	**2,60**	0,09
3	2,76	3,06	2,52	3,04	**2,85**	0,22
4	3,39	2,91	2,87	3,01	**3,04**	0,21

Table 9 shows the results obtained by the tensile tests and the respective effects for each experiment. Also displays the interactions between the factors, determined considering the level of each factor in interaction. For the interaction calculation, if the variables have the same level the interaction is defined by 2, on the other hand if the variables have the different levels the interaction is defined by 1.

Table 9 – Response Table for Maximum Tensile Stress (MPa).

Exp.	A	B	C	AxB	AxC	BxC	Results (MPa)
1	Level 1	Level 1	Level 1	Level 2	Level 2	Level 2	**2,39**
2	Level 1	Level 2	Level 2	Level 1	Level 1	Level 2	**2,60**
3	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	**2,85**
4	Level 2	Level 2	Level 1	Level 2	Level 1	Level 1	**3,04**
Avarage (level 1) MPa	2,50	2,62	2,72	2,73	2,82	2,95	
Avarage (level 2) MPa	2,95	2,82	2,73	2,72	2,62	2,50	
Effect	0,45	0,20	0,01	-0,01	-0,20	-0,45	

According to these results, the injection temperature (A) of the second material is the variable that has the biggest influence on the mechanical performance of the joined part (region of adhesion between both materials). The value is marked in red at the table.

The next variable is the mould temperature (B), marked in green at the table.

The injection pressure (C) proved to be almost irrelevant to the process, marked in blue at the table.

Figure 38 shows the maximum stress results of each experience. With the graphic analysis is possible to note that the experience 4 was the one that showed the maximum stress, followed by the experience 3.

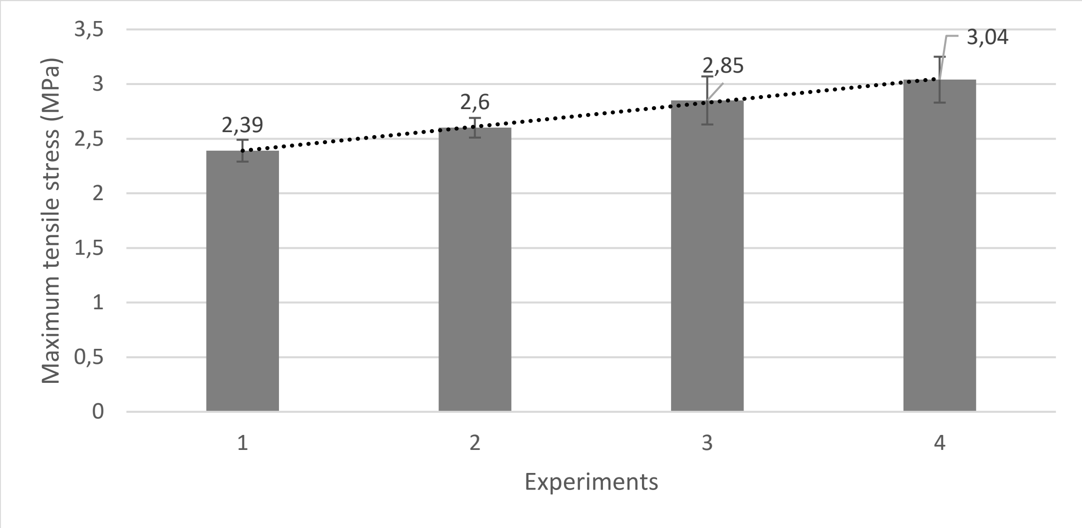

Figure 38 – Maximum stress at joining of PP/EPDM.

It is also pertinent to carry out a comparison of the deformation suffered between each experience. These results are depicted in Table 10 and Figure 39. The results show that all the samples are deforming between 1-1,4 mm/mm and the conditions applied in Experiment 4 are the ones most favourable for the slight increase of deformation at break.

The maximum deformation of PP is typically around 0,50mm/mm and around 0,2mm/mm for the EPDM. This means that comparing with the deformation results, the specimens broke down in the joining area, the most fragile area in the part, since the results from the tensile tests are lower than these values.

Table 10 - Deformation values (mm/mm) obtained for each set of experiments.

Deformation (mm/mm)						
Exp.	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Specimen 4**	**Average**	**Standard deviation**
1	1,07	0,76	0,98	1,09	**0,98**	0,13
2	1,43	0,93	1,47	1,24	**1,27**	0,21
3	1,27	0,93	1,24	1,16	**1,12**	0,12
4	1,54	1,25	1,34	1,50	**1,41**	0,12

For better understanding the results interpretation Figure 39 illustrates a graphic of the deformation of each experience.

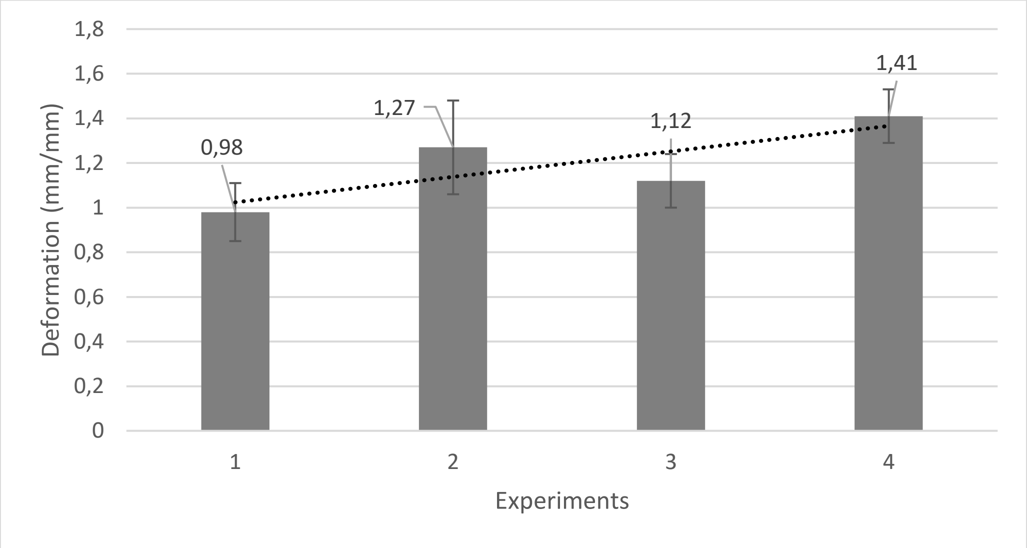

Figure 39 – Deformation results.

In general, the experience with the highest result for maximum stress (experience 4) has also the highest deformation value. The same is true for the lowest values (experience 1)

Regarding to the variables effects, Figure 40 displays a graphic that illustrates the effect of each one in the process.

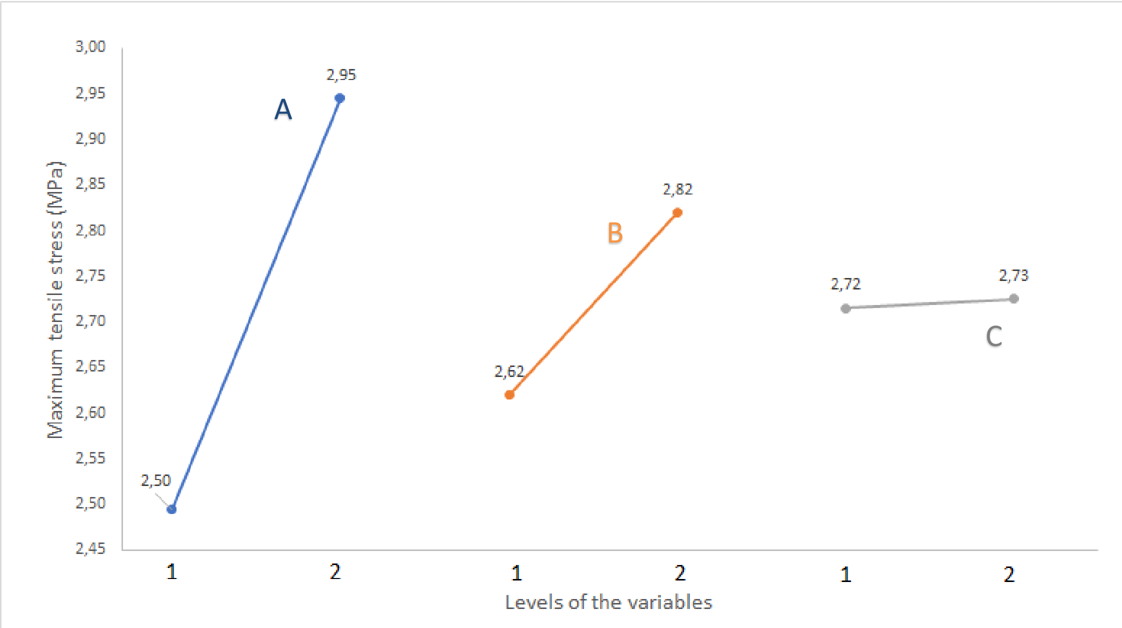

Figure 40 – Variables effect.

It is possible to note that the maximum stress increases with the increase of the injection temperature of the second material (A), therefore, the adhesion strength is better. This result was expected once that a high temperature on the interface provided a high degree of the molecular mobility and, consequently, the diffusion was also high, what promoted adhesion [2]. This variable had an effect of 0,45 on the process, what means that there was an increase of 0,45MPa in the tensile stress for the specimens with a temperature of 200ºC.

Also, it is noticed that the maximum stress increases with the increase of the mould temperature (B), because it presented better tensile stress values for the specimens with mould temperature values. It has an effect of 0,20 on the process, hence, the tensile stress increased 0,20MPa for the specimens with 40ºC. As was already stated, high mould temperatures can have two opposite effects, both increase and decrease the adhesion strength. The negative effect is due to the formation of spherulites that has a bad influence in adhesion. The positive effect promotes molecular diffusion and hence better improves adhesion [2]. In this case, since increasing the mould temperature caused an increase in the maximum tensile strength, probably the effect of the molecular diffusion was bigger than the effect of the spherulites formation.

Regarding to the injection pressure (C), it was noticed an increased in the maximum stress almost imperceptible with the maximum value of this variable (80bar), as demonstrated in the graphic, having just an effect of 0,01. Consequently, the tensile stress has an increase of 0,01MPa for an injection pressure of 80bar. The result was not what was expected because according to the research high injection pressures promote a higher level of molecular orientation and, consequently, higher adhesion [2]. However, this result was similar to other researches done, as has also been described.

The interactions between the factors is depicted in Figure 41.

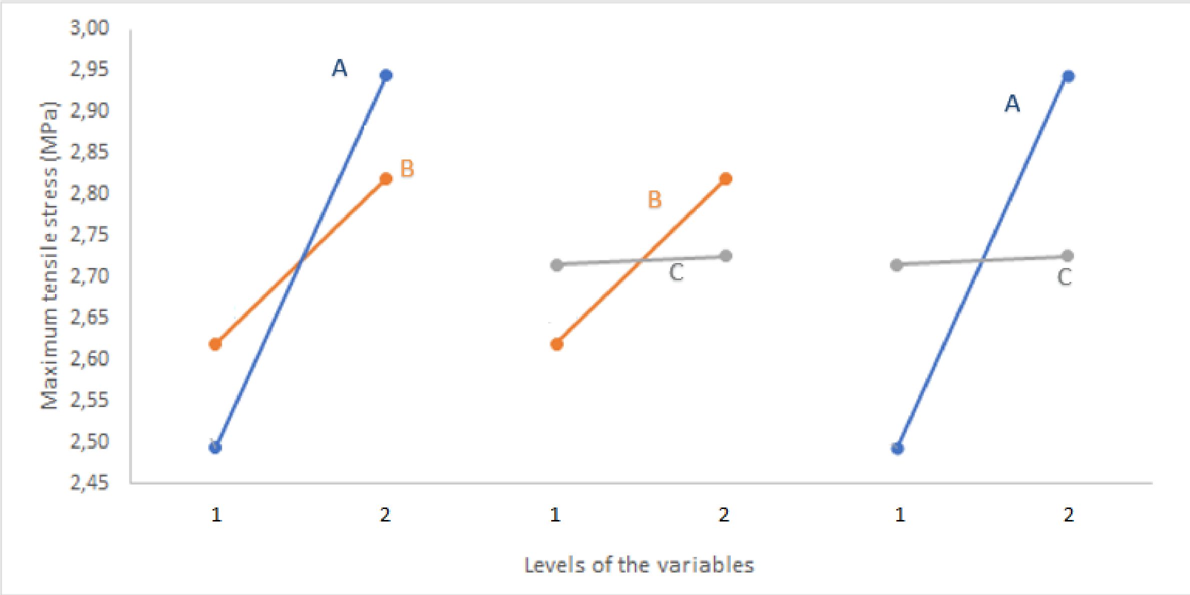

Figure 41 – Interaction between parameters.

As it can be seen in the graphic of the Figure 41 there is an interaction between the injection temperature of the second material (A) and the mould temperature (B), which means that they are dependent from each other, otherwise, the lines would be parallel. According to the graphic, it is recommended to have high temperatures in both factors because their interaction suggest that there is no negative interaction when the parameters are increased at the same time. In other words, the slopes are different, but they have the same effect.

Also suggests that there is an interaction between the mould temperature (B) and the injection pressure (C). In this case, the effect of the interaction is bigger, because the slopes are even more different, and the crossing of the lines becomes more evident. As in the previous case, it shows that is good to keep the parameters in question with high values.

It is also possible to note that there is a strong interaction between the injection temperature of the second material (A) and the injection pressure (C) due to the different slopes. This means that, as in the other cases, the values should be high because it provides the increase of the maximum stress, and, consequently, a better adhesion.

After the analysis of all situations, it is found that the best process parameters used were the parameters of the experience 4, because it showed the higher value of maximum stress. However, accordingly to the results, the process can even be improved if all the parameters are at the maximum level, since all the conditions proved to achieve better results when they are increased. Therefore, the optimal process conditions are the ones represented in Table 11.

Table 11 – Optimal process conditions.

Process conditions	**Injection temperature of the second material (A)**	**Mould temperature (B)**	**Injection pressure (C)**
Levels	2	2	2
Values	200ºC	40ºC	80bar

It is also important to study the mechanical performance along the part, in the positions referred in Figure 33. The aim is to understand whether the mould is meeting the requirements, such as good filling and cooling performance. Table 12 shows the maximum stress along the part.

The variables used for each experiment setup (Table 7) were different and affect slightly the stress obtained. Even so, all of these results were joined so that a representative value of the stress at each position of the part would be acquired. These results are depicted in Table 12 and summarized in Figure 42.

Table 12 – Maximum stress along the part.

	Part 1	Part 2	Part 3	Part 4	Average	Standard deviation
Specimen 1	2,38	2,58	2,76	3,39	**2,78**	0,38
Specimen 2	2,27	2,53	3,06	2,87	**2,68**	0,30
Specimen 3	2,55	2,52	2,52	2,91	**2,63**	0,17
Specimen 4	2,36	2,75	3,04	3,01	**2,79**	0,27

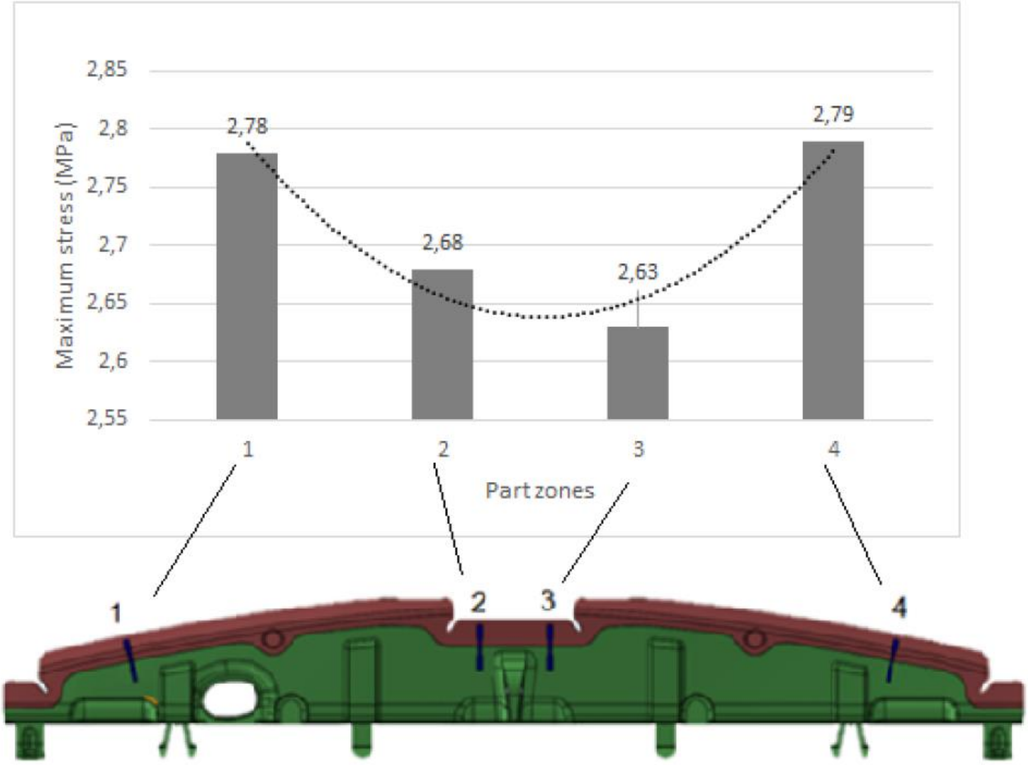

Figure 42 – Maximum stress along the part.

It is possible to note that in the part extremities the maximum stress is high, what means that the adhesion is more efficient in these zones comparing to the centre zones. That happens because the injection points are located closer to the zones 1 and 4, and the shorter is the distance from the injection point, the shorter will be the flow path of the material during the part filling, what brings advantages in terms of adhesion. If the distance from the injection point is too large it can cause the premature cooling of the material, lowering the temperature at which the adhesion between materials is made.

Moreover, there is an area reduction just by the side of position 2 and 3, as it is represented in Figure 43, which may lead to the premature cooling of that region and the accumulation of residual stresses. Both effects affect negatively the adhesion between both materials.

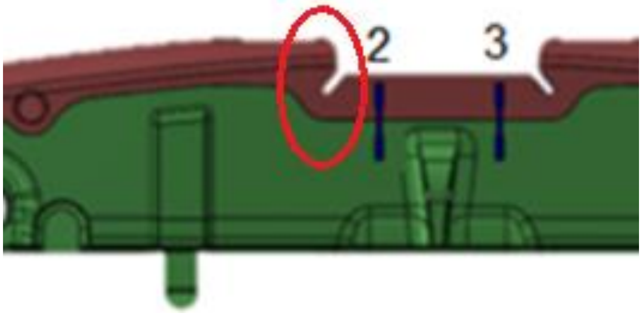

Figure 43 – Reduction of area in the part.

5. CONCLUSIONS

5.1 Conclusions

The theorical and practical research presented in this dissertation was carried out with the aim of design and building a mould able to produce a biomaterial part made of a rigid/flexible material; and to understand the process variables that most influence the adhesion between the materials and that can optimize the mechanical performance of the part on the joint region.

The development of a core back mould was a very complex process which must take into consideration various details such as the location of the injection points and the design of the water channels so that there is a good mould filling and uniform cooling so as not to hinder the adhesion process.

A design of experiments was used to optimize the processing conditions that could improve mechanical strength of the joined parts. From the tensile tests realized it was concluded that the variable that showed the biggest influence was the injection temperature of the second material, followed by the mould temperature. The injection pressure had no significant influence on the process. However, the study also showed that the interation between those variables result in the increase of maximum tensile stress. For that all the variables have to be used at their maximum level. Therefore, the optimal process conditions obtained from the DOE, in order to optimize the adhesion in the joining area was 200ºC for the injection temperature of the second material, 40ºC for the mould temperature and 80bar for the injection pressure.

The results also show a difference between the mechanical strength of the joints along the part. The joint strength is affected by the geometry of the part and by the positioning of the injection gates. Therefore, far from the gate there is the tendency for cooling the flow front that in turn reduces the adhesion strength between materials.

Finally, this study shows that a mould with a core back technique is reliable to produce parts of good quality and has some advantages comparing with other multi material techniques, such as being economical and having a compact tool size.

5.2 Prospect for Future Work

For future work it would be interesting to test the optimal set of factors obtained from the DOE to make sure that these variables actually bring improvements to the process. Unfortunately it was not possible to carry out this verification, because due to the COVID 19 situation, the mould had to be export to the final customer in advance without having the possibility of carrying out any further tests.

It would also be interesting to test the variables with a large process window so, in this way, the results could be more conclusive. However, the processing possible window cannot be too large due to the problem of the part quality. If the difference between the low and high level is too elevated, in low levels it is impossible to inject due to the melt flow index of the material. In high levels, the second material promotes the fusion of the first one when both interacts, and, in this case, the part would not have an acceptable quality.

Another suggestion is to test other operative variables such as holding pressure, injection speed, holding time and cooling time, in order to analyse their real influence.

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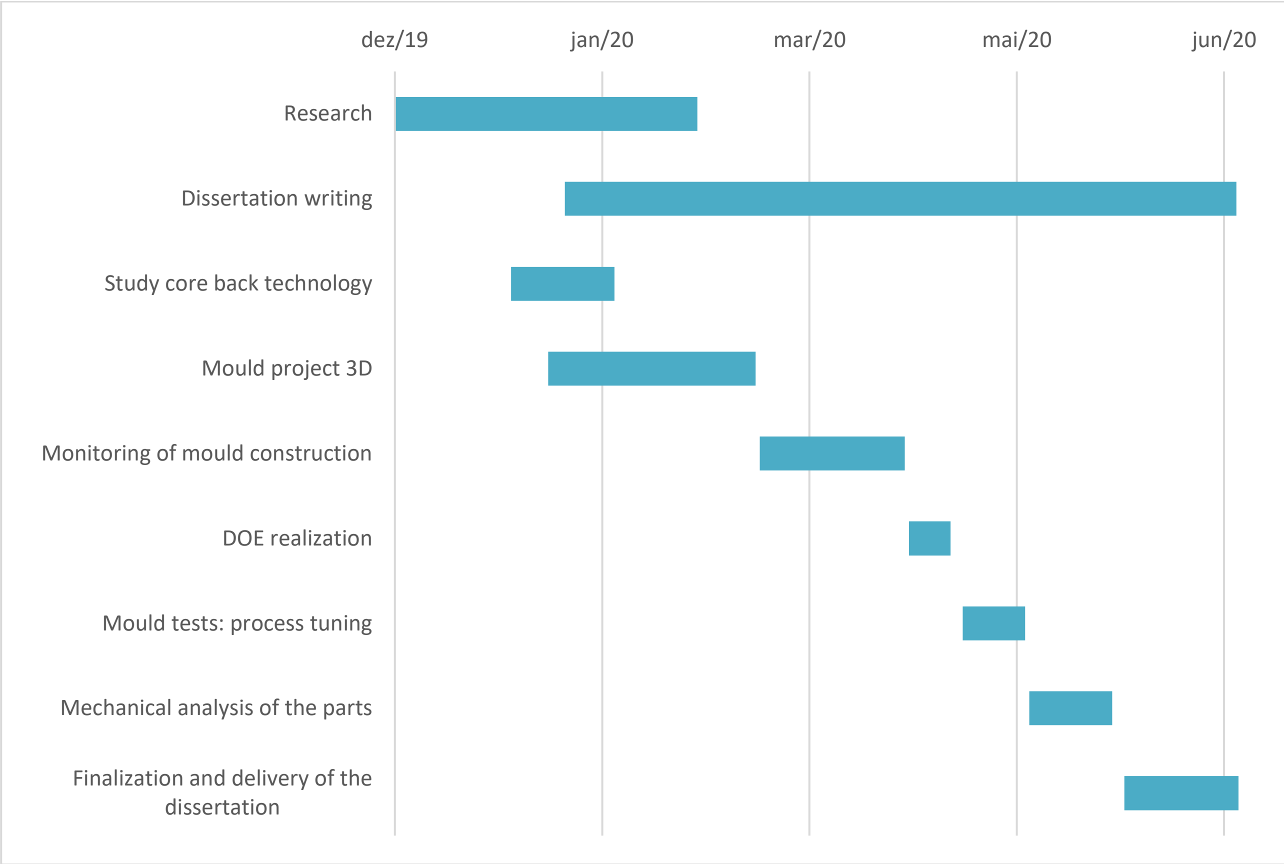
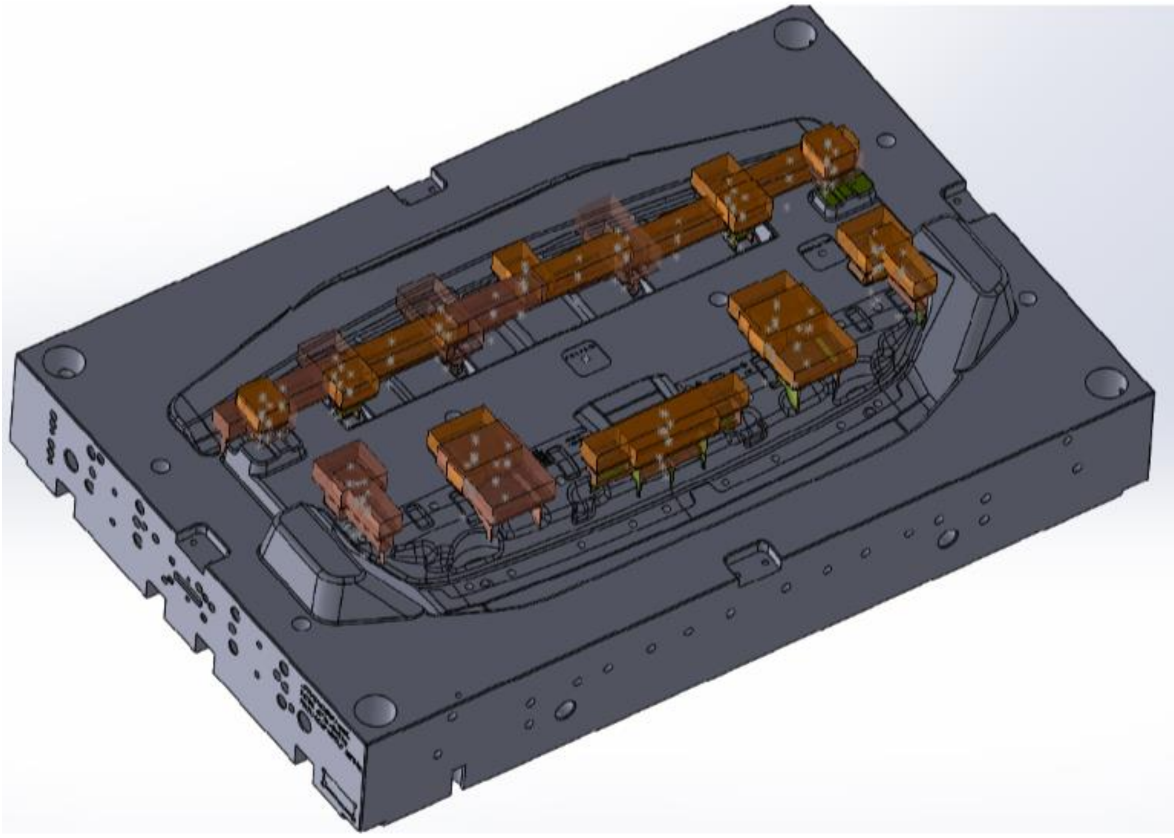
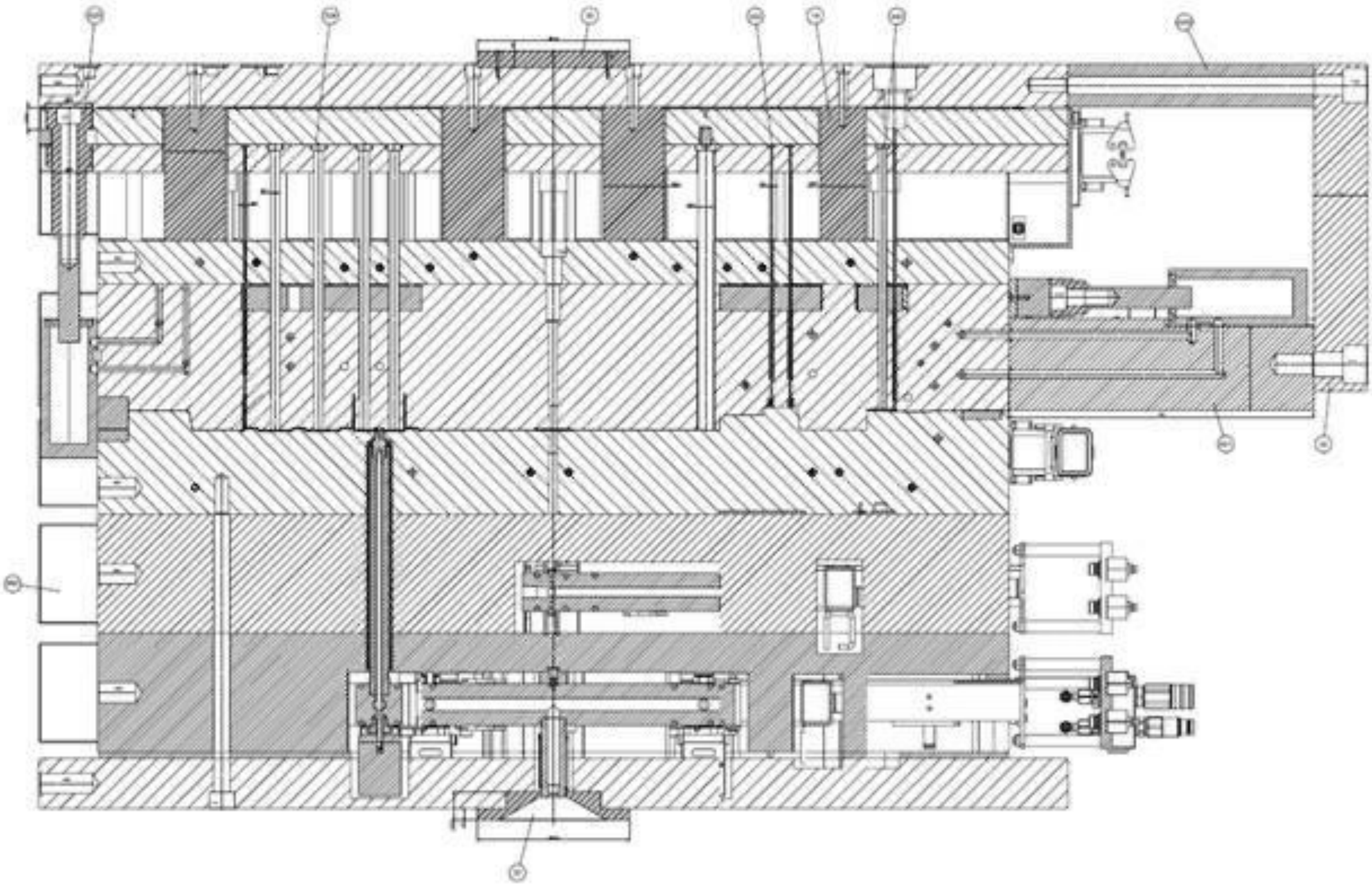
Annex A – PROJECT SCHEDULE

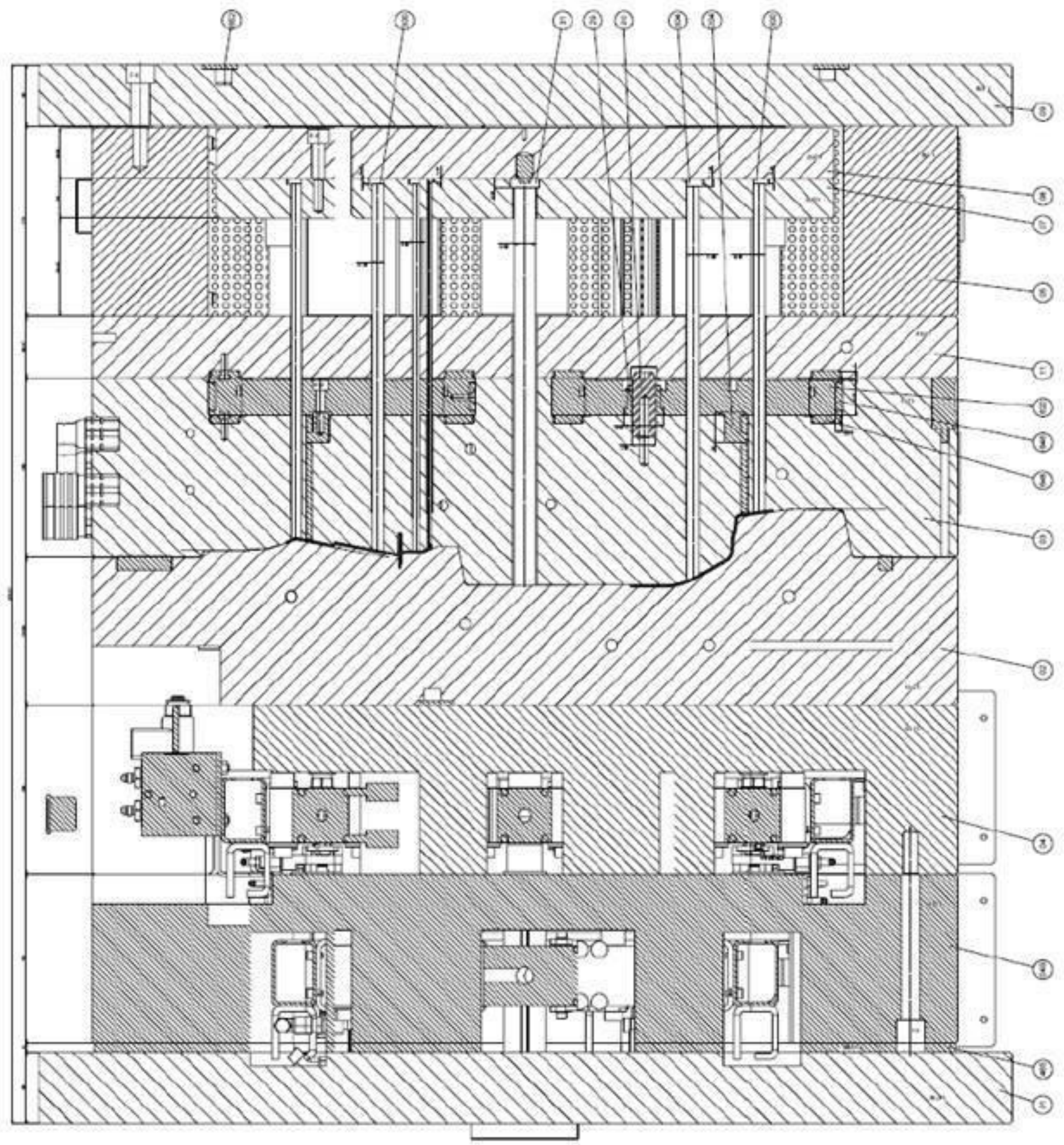


Annex B – ELECTRODE ZONES



Annex C – 2D Mould Design





Annex D – TECHNICAL DATA PP15T1020

SABIC® PPCOMPOUND 15T1020

PP COMPOUND MINERAL FILLED

DESCRIPTION

SABIC® PPcompound 15T1020 is a 20% talc-filled polypropylene homopolymer. The material's high modulus and good thermal stabilization makes it suited for applications under the bonnet such as heating, ventilation and air conditioning housings.

SABIC® PPcompound 15T1020 is a designated automotive grade.

IMDS ID: 16486973

TYPICAL PROPERTY VALUES

Revision 20190718

PROPERTIES	TYPICAL VALUES	UNITS	TEST METHODS
POLYMER PROPERTIES			
Melt Flow Rate			
at 230 °C and 2.16 kg	7	dg/min	ISO 1133
Density (1)	1040	kg/m³	ISO 1183
Filler content	20	%	SABIC method
Mould shrinkage (2)			
24 hours after injection moulding	1.2	%	SABIC method
MECHANICAL PROPERTIES (1)			
Tensile			
Tensile modulus	2600	MPa	ISO 527/1A
stress at yield	37	MPa	ISO 527/1A
stress at break	29	MPa	ISO 527/1A
strain at break	50	%	ISO 527/1A
Flexural test			
Flexural modulus	2700	MPa	ISO 178/1A
Izod impact notched (3)			
at 23 °C	3.4	kJ/m²	ISO 180/1A
at 0 °C	2.7	kJ/m²	ISO 180/1A
at -20 °C	2.2	kJ/m²	ISO 180/1A
THERMAL PROPERTIES (1)			
Heat deflection temperature			
at 0.45 MPa (HDT/B)	120	°C	ISO 75
Coeff. of linear thermal expansion			
-30 °C to 100 °C	75	µm/mK	ISO 11359-2

(1) Injection molded sample ISO527-1A
(2) Injection molded plaque 65x65x3.2mm
(3) N.B.: No Break

QUALITY

SABIC is fully certified in accordance with the internationally accepted quality standard ISO 9001.

CHEMISTRY THAT MATTERS™

Annex E – TECHNICAL DATA EPDM 245

SABIC® EPDM 245

ETHYLENE PROPYLENE DIENE RUBBER

DESCRIPTION

SABIC EPDM 245 is a low mooney viscosity, low ethylene and medium ENB content grade produced by solution polymerization using metallocene catalyst. It is an amorphous polymer with medium molecular weight distribution. It can be used as a polymeric plasticizer in blends with other high viscosity polymers. This grade is available in friable bales.

TYPICAL APPLICATIONS

SABIC EPDM 245 can be used for: brake parts, precision seals, gaskets, molded foam sheets, electrical connectors, other molded articles

TYPICAL PROPERTY VALUES

Revision 20181012

PROPERTIES	TYPICAL VALUES	UNITS	TEST METHODS
POLYMER PROPERTIES			
Mooney viscosity (ML 1+4, 125 °C) (1)	25	MU	ASTM D1646
Ethylene Content	50	wt%	ASTM D3900
Ethylidene Norbornene (ENB) Content	4.5	wt%	ASTM D6047

(1) Polymer remassed at 140 ± 5° C

CHARACTERISTICS

SABIC EPDM 245 is designed for : excellent processability resulting in shorter mixing and molding times, good low temperature properties, good low temperature flexibility and compression set, fast cure rate and high cure state

STORAGE AND HANDLING

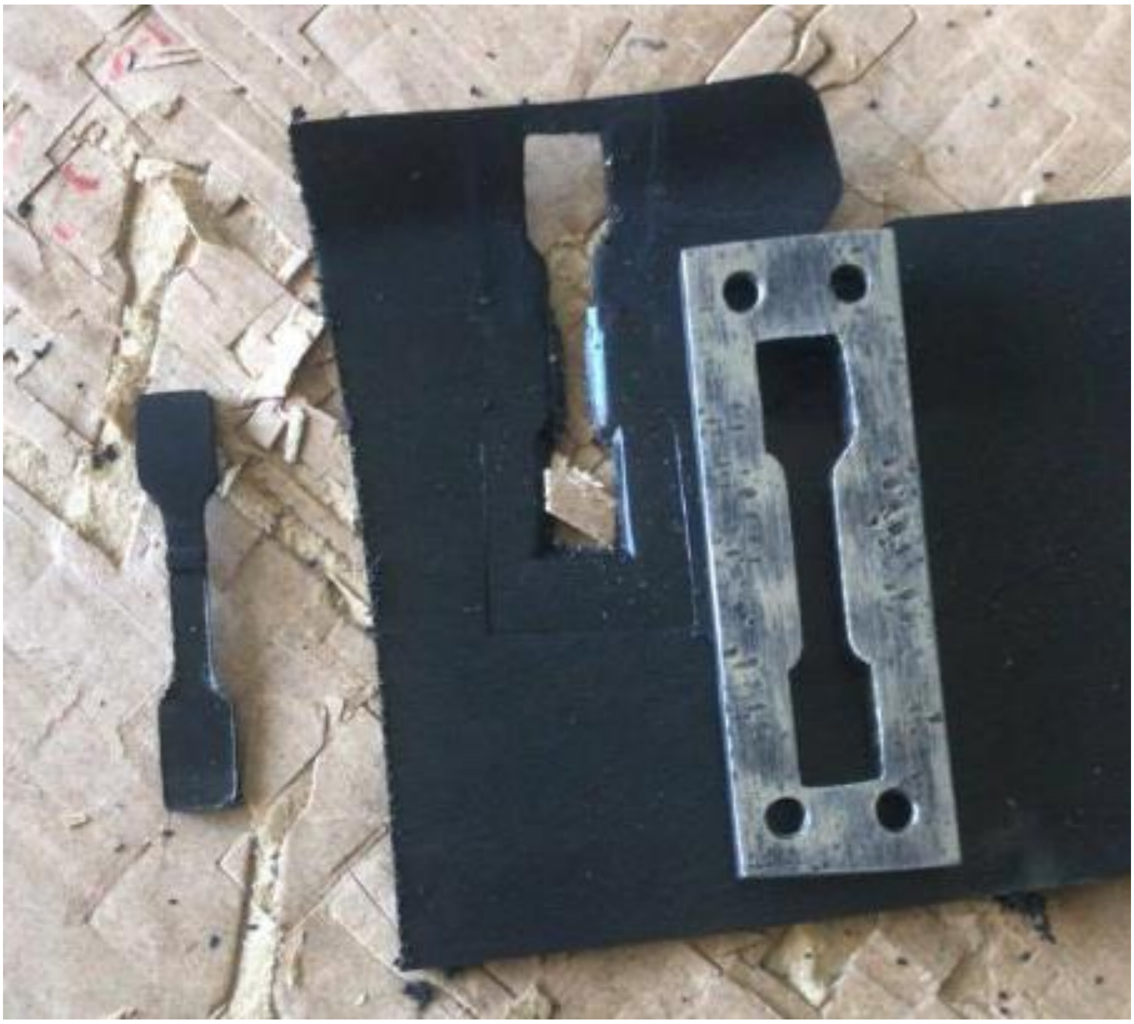
SABIC EPDM 245 should be stored in its original packing at ambient temperature in dry conditions; exposure to heat, ultraviolet light and direct sun light should be avoided. Under suitable storage conditions, the product is stable for 24 months from the date of manufacture. SABIC will not extend its warranty when storage conditions are inadequate which may lead to quality deterioration such as material hardening or color change that could result in inadequate product performance..

DISCLAIMER

CHEMISTRY THAT MATTERS™

Annex F – Injection machine

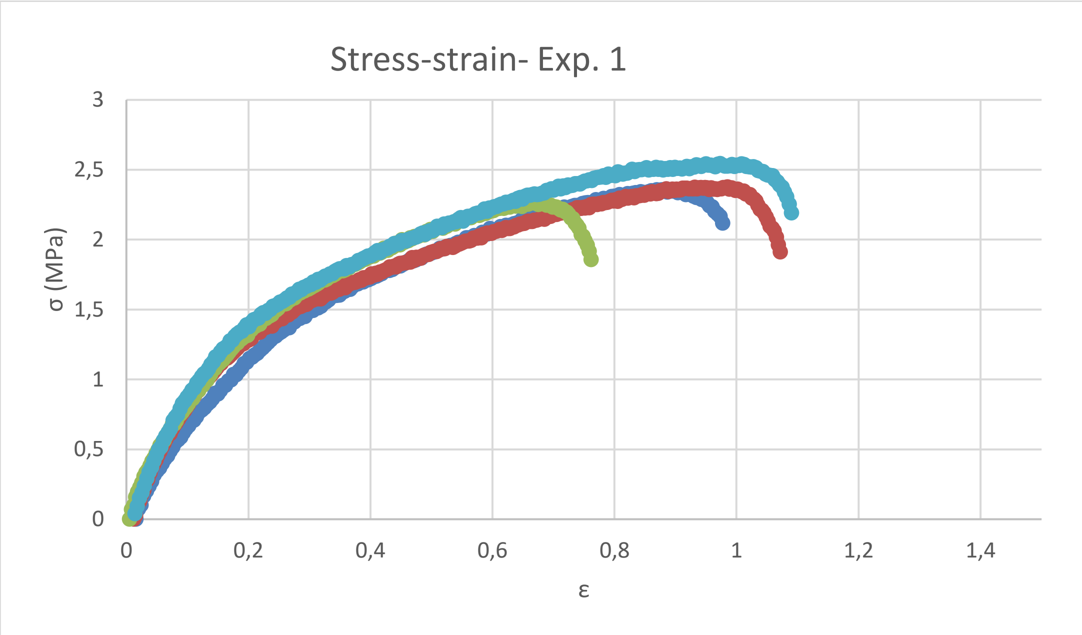
Annex G – Specimens lead up

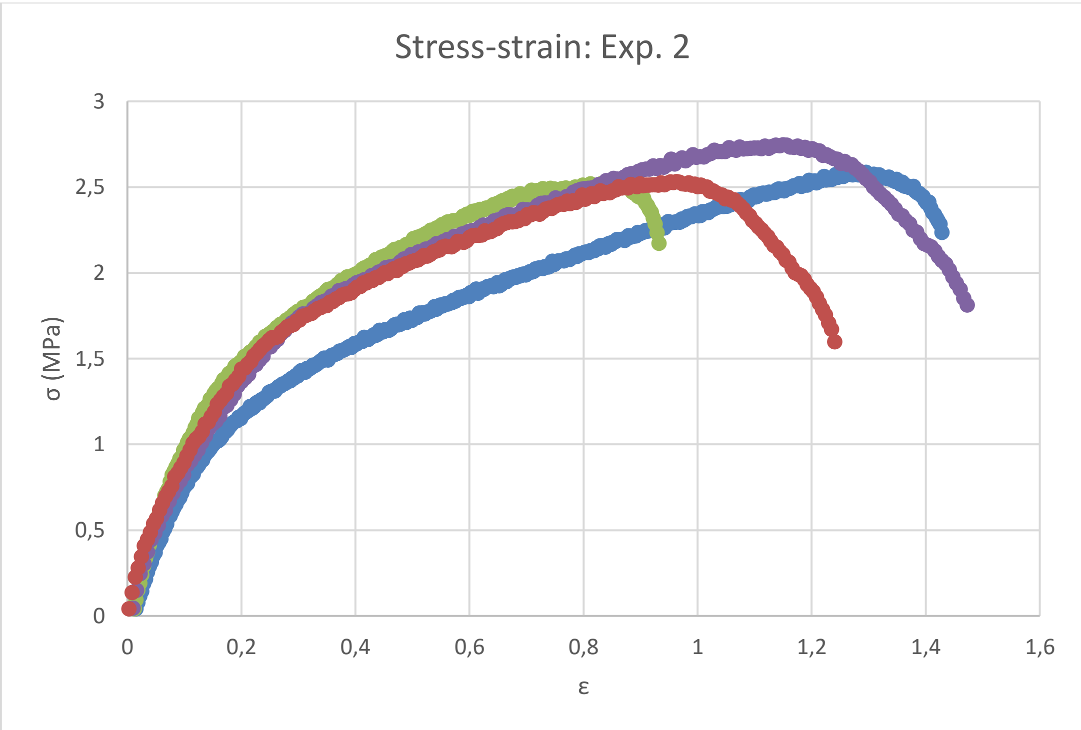


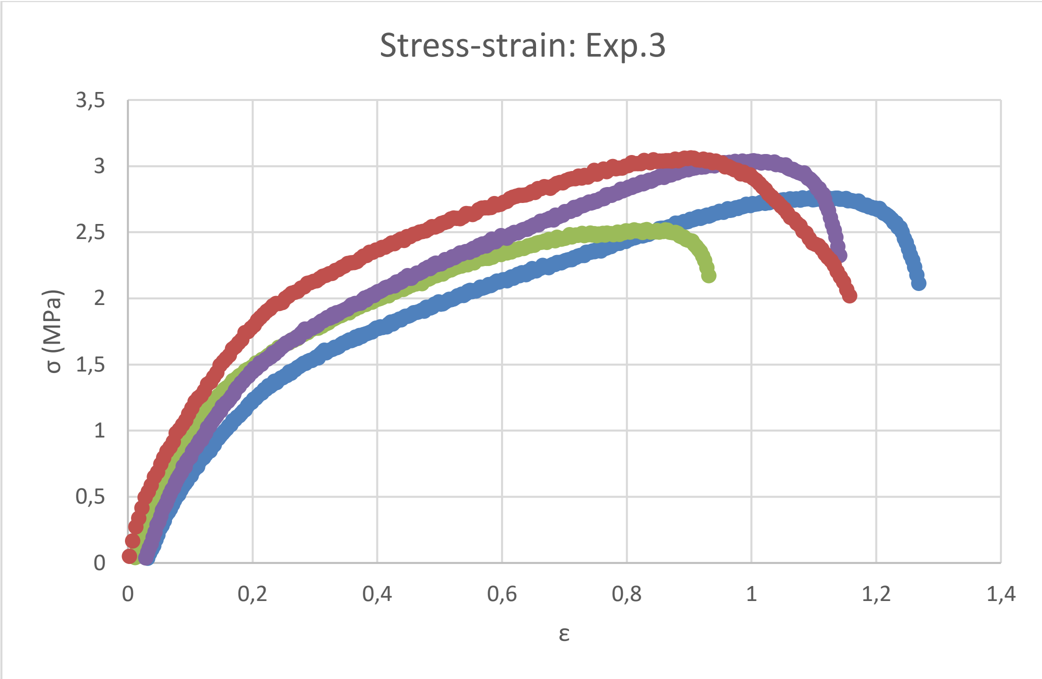
Annex H – PRESS GEO E MOORE & SON (BHAM)

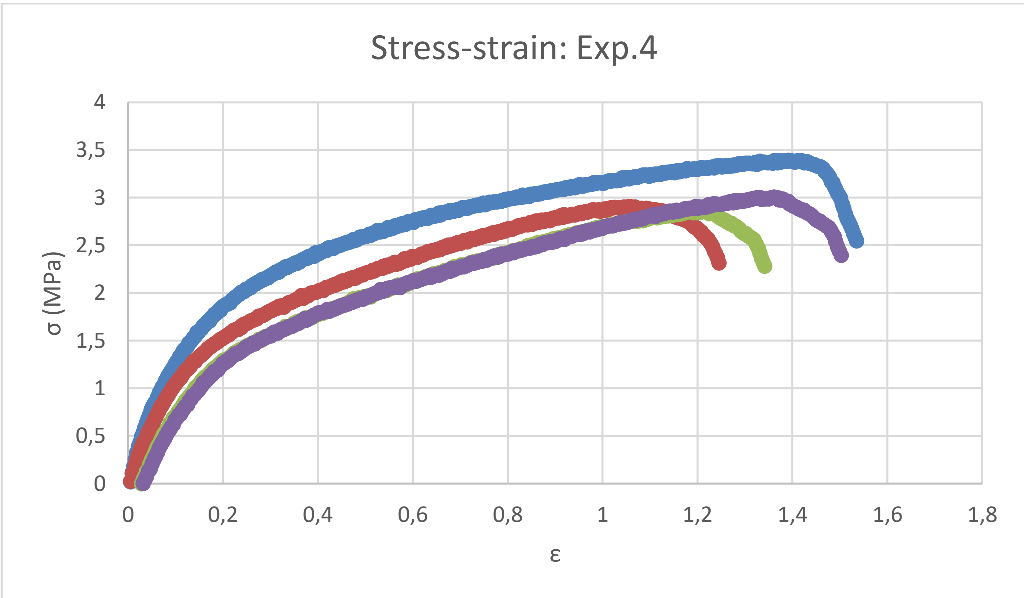
Annex I – TENSILE MACHINE INSTRON

Annex J – Stress- Strain graphics






Stress-strain: Exp.3
σ (MPa)
3,5
3
2,5
2
1,5
1
0,5
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
ε


Stress-strain: Exp.4
σ (MPa)
4
3,5
3
2,5
2
1,5
1
0,5
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
ε