Processing of polymers in short series production

A master thesis at ABB Corporate Research

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Preface

This is a master thesis project carried out at ABB Corporate Research in Västerås during the summer and autumn of 2010.

First of all I want to thank Alessandro Mattozzi and Tommaso Auletta for giving me the opportunity to do this thesis at ABB. I also want to thank everybody else I have been in contact with at ABB for their sharing of knowledge, support, understanding, and warm welcoming.

I would also like to take the opportunity to thank all external representatives I have been in contact with for showing interest, both in me personally and in the project.

Peter Ahlström
Västerås, November 2010

This is the PUBLIC VERSION of this report. Due to this, material names, supplier names, part names, some cost estimations, most drawings, and some other information have been removed or replaced. Where information has been removed, this is noted.

Abstract

Title: Processing of polymers in short series production

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Key words: Low volume production, short series production, DFMA, design for manufacturing and assembly, thermoplastics, product development, concurrent engineering, process selection

Purpose: There are three main purposes:

1. To prepare five thermoplastic body parts of a robotic tool for production by suggesting design changes, processing methods, and materials.
2. To find out if part F of this robotic tool can be produced from a thermoplastic material.
3. To evaluate methods to lower the costs of thermoplastic processing is short series.

Method: A theoretical study is made to evaluate which potential solutions should be further examined in the empirical study. The empirical study is carried out as interviews with for example thermoplastic manufacturers and polymer suppliers. Based on the information gathered an analysis is made.

Theoretical framework: It contains information of development processes and tools, thermoplastic materials, thermoplastic processes, assembly and joining processes, coating processes, and factors to consider when estimating production costs. The information is primarily gathered from handbooks, more specialized books, and articles.

Empirical results: This contains cost estimations of thermoplastic processes, design recommendations, and general information of thermoplastic processing, which are gathered by interviewing representatives from manufacturers, polymer suppliers, and mold manufacturers, steel producers, and others.

Conclusions and recommendations: All parts examined would be most economical to produce with injection molding and, in some cases, complementary machining. A few parts would benefit from a more uniform wall thickness which should be possible to create using a ribbed design. Others must be further analyzed using a simulation tool to find out if they can be produced with injection molding without too much warpage.

A design suggestion of a thermoplastic part F is presented. Based on this, a prototype can be produced. As a first step to produce this prototype, the design needs further mechanical strength analysis. If the prototypes are produced, they can be used to determine if it would be commercially possible to use a thermoplastic part F.

The result of the general study is a number of qualitative and quantitative guidelines. These should be used when developing low volume thermoplastic products to minimize future production costs.

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1 Introduction

This chapter covers the background of the project, the problem which it is trying to solve, its goal, its scope, and to whom it is written.

1.1 Background

The background of the project is here presented in a hierarchical order. First the company is introduced. Then follows a description of the function at which the project is carried out. The background ends by explaining how the product works.

1.1.1 The Company – ABB[1] [2]

ABB is a multinational power and automation corporation with headquarters in Zurich, Switzerland. It was created by a merger of the corporations ASEA, from Sweden, and Brown, Boveri & Cie, from Switzerland, in 1988.

Today the company consists of the five divisions Power Products, Power Systems, Discrete Automation and Motion, Process Automation and Low Voltage Products.[3] Power Products is responsible for the products necessary to distribute electricity. These are for example transformers, switchgears, circuit breakers, and cables. Power Systems is also in to the area of electric distribution. However, it provides entire system solutions to its customers, which partly are built with Power Products' products. The systems control electric networks and power generation in power plants.

Process Automation helps its customers to automate and optimize industrial processes. The goal is to lower the customers' costs, increase their performance and reduce their environmental impact. The customers are for example companies within oil and gas, power, pulp and paper, and pharmaceutical industries. Discrete Automation and Motion instead provides automation solutions to discrete manufacturing companies, such as car manufacturers. It is also into renewable energy sources and the rail industry. Low Voltage Products produces low-voltage components to, for example, buildings. Together, these five divisions are able to provide complete and integrated solutions to most manufacturing industries.

By taking a look at ABB today, a few trends can be noted. Even during the recent economical crisis, ABB has increased its R&D budget by five percent, to $1.3 billion. This is because it considers discovering new technologies as a part of its core business. It is, however, trying to reduce costs in other ways. For instance purchase more of standard products from a reduced number of suppliers and spreading best practice examples among its manufacturing facilities. Finally, the crisis has also increased ABB's focus on emerging markets, since these are growing faster than the rest of the world. [4]

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[1] http://www.abb.com/cawp/abbzh252/a92797a76354298bc1256aea00487bdb.aspx. ABB's corporate homepage, Our businesses. 2010-06-04.

[2] http://www.reuters.com/finance/stocks/overview?symbol=ABB. Reuters Finance info on ABB LTD. 2010-06-04.

[3] Contradictions in sources! More info in the chapter Contradictions in sources

[4] *The ABB Group*, Annual Report 2009

1.1.2 The Function – ABB Corporate Research and Development[5]

Corporate Research and Development in Västerås is ABB's largest corporate research and development center. Its over 200 employees are developing new technologies to the divisions Process Automation and Power Systems.

1.1.3 The Product – Robotic Tool

Unfortunately the product must be maintained a secret, since this is the public version of this report.

1.2 Problem

There are two problems attended to in this thesis. The first is in regard to the robotic tool described above and the second to the issue of producing thermoplastic parts in short series economically.

1.2.1 The New Robotic Tool

The robotic tool is a low volume product. This has caused problems in the production of its parts, and especially its thermoplastic body cover. The body is presently machined from thermoplastic semi-products at high costs. To be able to produce these parts, large semi-products with thick walls must be used. These are especially expensive to purchase since thick-walled thermoplastic parts cool very slowly. Furthermore, the wastage costs are high since only a cover for the part is needed. So the first problem with the robotic tool is that the production costs for the present robotic tool body are very high.

Injection molding has been suggested as a new manufacturing process due to the high production costs. However, the initial costs for the molds used for injection molding are high. Because of this, injection molding is often used as a process to produce high volume products. Since the robotic tool is a low volume product, there are not many parts to spread the costs on to. The second problem is the high cost molds of injection molding.

There is also another, more specific, problem which is attended to. Part F of the robotic tool is one of the most crucial parts of it. Part F is the external name for one of the parts of the robotic tool. It is today produced in aluminum by using machining processes. Even though aluminum is a light weight material, it would be good if it could be even lighter, with a decrease of weight and costs as a result.

1.2.2 Short Series Production of Thermoplastics

This issue is of a more general nature. Most of the products in ABB's portfolio are low volume products, and many of them have thermoplastic parts. Because of this, these products face the same problem as the robotic tool; the high initial costs of especially injection molding.

1.3 Purpose

The purpose of this thesis can be divided into two parts; one to attend to each generic problem. The first is presented as case study of a new product development of a new robotic tool, and the second is in regard to the problem of producing short series of thermoplastic parts economically.

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[5] http://www.abb.com/cawp/seabb361/d2763491a6c93e61c1256ab800248c8f.aspx, ABB Research and Development Västerås, 2010-06-07

1.3.1 The New Robotic Tool

The new product development of the new robotic tool began before this project. The case study presented in this thesis is therefore based on a preliminary design and suggested materials. The purpose of the case study is to take part in the development of the body of the new product, and be responsible for increasing its manufacturability. This is to be done by:

- Evaluating the capabilities and the economy of applicable manufacturing processes.
- Suggesting materials based on cost, availability, manufacturability, and product specifications.
- Making design suggestions with the aim of decreasing the total cost of production.

The work is to be carried out in collaboration with the design team, which also has market-related knowledge of the product, and with people with expertise knowledge of materials.

During the task described above is a related project going to be carried out. The purpose of this project is to evaluate the possibility to produce a thermoplastic part F. The reason of this attempt is to produce a less expensive and lightweight part F, with similar or better performance as the existing products. The process suggested to produce the product is injection molding, but other processes should also be considered.

To improve the wear resistance of this thermoplastic part F, it should also be investigated whether or not it would be possible to apply some hard coating on it. If so, suggestions of company-specific coatings should be given.

1.3.2 Short Series Production of Thermoplastics

When producing parts with injection molding, the initial costs are very high. Due to this, the second purpose of the thesis is to investigate if the cost per product can be lowered in some way. It should be emphasized that it is not only the initial cost which is under investigation, but the total production cost of a product. However, it is most often the initial cost which seems to cause the largest problem.

When preparing a product for production and selection manufacturing processes, there is a risk that the analysis only is made on a part by part basis. The risk is that the production cost of individual parts is sub-optimized, and no consideration is taken to the product as a whole. The result of this may be that for example assembly costs are much higher than they would have to be. With this in consideration, the analysis of the economy of short series production is to be carried out with focus on the entire product, and not on the production of individual parts.

The questions which are to be examined are the following:

- Can the initial cost be lowered?
- Can alternative processes with lower initial and/or total costs be used?
- Can the total cost be lowered by designing the product and its parts differently?

1.4 Scope

The scope of the two sub-projects is presented below.

1.4.1 The New Robotic Tool

The scope of the case study of the robotic tool can be divided into parts, design, production, and material related matters.

There are five body parts which should be analyzed. These are referred to as part A, B, C, D, and E. The sixth part which should be analyzed is the thermoplastic part F. No other parts of the robotic tool should be considered.

The initial design of the body parts is to be accepted as it is. This means that no major changes are to be made of the structure of parts or the interaction between them. However, minor changes of parts should be suggested to improve the manufacturability of them. Joining alternatives should also be suggested and evaluated based on initial design of the parts.

The design of the thermoplastic part F had not begun by the start of the project. It is therefore within the scope of this thesis to evaluate the present design, and suggest appropriate design changes. The interaction with other parts, however, should not be changed, and the suggested design should not interfere with other parts.

Since the product is going to be produced in the near future, it is only commercially available manufacturing processes which are to be examined. If a process is in a testing phase, and soon is to be available on the market an exception can be made. However, if this is done, alternative processes should be evaluated and recommended in the case that the process in question is not yet available when the production of the product is to begin.

Material alternatives for external body parts, this means parts which are visible when the robotic tool is assembled, have been established. The materials in question are MATERIAL A and MATERIAL B. MATERIAL A and MATERIAL B are the external names of the thermoplastics discussed in this report. Both are chemically resistant materials which during the project are tested further to determine whether or not they are applicable. Due to this it can be discovered that one of the materials cannot be used after this project is finished. Therefore it is important that both materials are evaluated from a manufacturing point of view.

For internal body parts which are to be analyzed, the material selection is more open. Since these parts are not exposed to the chemicals, other materials than those which are considered for the external parts can be used. However, it is not within the scope of this thesis to determine or suggest materials which can be used for the production of internal parts, even though a general discussion of materials can be made. For manufacturing evaluation purposes MATERIAL A and MATERIAL B can be used for internal parts as well.

The situation is the same for part F as for the external body part. Materials which have been established here are MATERIAL B and MATERIAL C. MATERIAL C is the external name of a other thermoplastic discussed. The only difference is here that MATERIAL C is definitely able to withstand all the chemicals which the robotic tool endures.

1.4.2 Short Series Production of Thermoplastics

The scope of the general study of short series production of thermoplastics can be divided into material and process scope. The materials considered are most thermoplastics. No special analysis is made for any individual thermoplastic. The processes which are investigated are the same as those which are investigated in the robotic tool case study.

1.5 Target Group

The target group for the case study of the robotic tool is primarily the people who are involved in the development and, later on, the production of it. Since the people involved have wide backgrounds, such as representatives from design, market, and business functions, the information given in especially the theoretical study may be too basic for some. However, the purpose of the thesis is that it is supposed to be understood by all involved.

It is also written to those whom are going to be responsible for the development future and other robotic tools. The purpose here is that these people also should be able to read this report and see potential for improvement.

The general study of short series production of thermoplastics is written to help other product development teams, which develop products with thermoplastic parts, to lower the production costs of the products they are developing.

2 Method

This chapter is divided into two parts; one for the new robotic tool case and one for the general survey of short series production of thermoplastics.

2.1 The New Robotic Tool

Due to the complexity of a case project like this, it is hard to strictly follow a predefined process. However, an iterative step-by-step process is used as a general guideline. The steps used are the following:

1. Information gathering of the product and literature study
2. Empirical study with interviews
3. Analysis including cost calculations and design suggestions
4. Conclusion

The three first things which need to be done are to understand the product, to perform a literature study to examine the capabilities and limits of different processes, and to understand procedures which can be used to prepare a product for production. The goal of this, the first step, is to get a broad understanding of the context of the problem and to discover potential solutions to be further investigated. The literature study is performed by the use of handbooks of respective fields, more specialized books in fields which are found especially applicable, and articles in the subjects. The information gathering of the product is performed by interviews of people with experience from the product and by the use of internal educational documents of the product family robotic tools.

The second step is to further examine potential solutions by doing an empirical study. This is mainly carried out as interviews with the design team to understand the limits of the design, and with companies which use processes found interesting. To minimize the risk that the entire design gets into the hands of one stakeholder, only two or three parts are discussed with each external company. However, it also is important to make sure that the information gathered is accurate. Because of this, almost every part and subject is discussed with at least two companies. Examples of companies which are contacted are steel manufacturers, injection molding mold manufacturers, manufacturers, and polymer suppliers.

Based on the findings in the theoretical and empirical study, an analysis is made. The analysis includes material selection considerations, design change suggestions, manufacturing considerations and cost estimations, and other aspects necessary to make a manufacturing decision. The analysis is then summarized in the conclusion where recommendations also can be found.

As mentioned, this is only the general guideline of how this project is carried out. In many cases iterative steps are necessary to properly investigate solutions and potential problems.

2.2 Short Series Production of Thermoplastics

The methodology used in the more generic case of short series production of thermoplastics is very similar to the one which is used in the robotic tool case study. A fundamental theoretical study is performed to serve as a springboard to the empirical study. Furthermore, since much of the information gathered in a special case, such as the robotic tool, also can be used in a general case, many facts are reused in the analysis of this subject. However, because of the general nature of this study, the theoretical framework is wider than what had been necessary for only a case study. Some information in the theoretical study may not even be used in the analysis, but only serve as background information to what is possible.

A general analysis is then made of each of the processes investigated.

3 Theoretical Framework

In this chapter the theoretical framework is presented.

3.1 Concurrent Engineering

Traditionally, products have been developed in a sequential manner. First customer needs were examined. This information was then sent on to design teams who designed the product and selected material. Finally, the personal responsible for manufacturing made sure that the product was produced. This was the logical way to develop a new product. However, it was wasteful of both of time and money. Because, for example, if it was discovered that the design had to be changed when the manufacturing was prepared, a lot of work had to be redone. The result would be that the project would be much more expensive than if the design was made right the first time.[6]

This wastefulness is the reason why a new product development process was created. This process was called concurrent engineering, or simultaneous engineering. Instead of a sequential process, concurrent engineering is a process where all functions of a company are involved at an early stage of development. Since representatives from all functions can have their say in the concept stage, the risk that large changes have to be made at a late stage of the development process decreases.[7]

During concurrent engineering all activities during a products life cycle should be covered. This includes everything from the examination of customer needs to the recycling of the product. To be able to achieve this, a lot of information sharing, collaboration, and communication has to be done within and between organizational functions. What also is important is that everyone involved work forward the same goals. Therefore, the market targeted and the users of the product must be elaborately defined before the development is begun.[8]

Concurrent engineering is usually illustrated with five phases and four or five aspects. An illustration can be seen in Figure 1. Sometimes the sustainability aspect is integrated into the others[9]. The marketing aspect makes sure that the product developed fulfills customer needs, and that the product is in line with marketing strategies. The design team is responsible for everything that has to do with product design. People with knowledge of manufacturing make sure that the cost of for example design is not sub-optimized, but that the costs of future manufacturing also are considered. It is also their responsibility to make sure that the quality level desired can be achieved with the selected manufacturing process, and to keep track other manufacturing related criteria. Business and environmental requirements are controlled by representatives from these functions. Each of these aspects is supposed to be considered during each of the phases of development.

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[6] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[7] Ibid.

[8] Ibid.

[9] Ståhl, Jan-Eric (2009) *Industriella Tillverkningssystem del II*. Industriell Produktion vid Lunds Tekniska Högskola. Second Edition. Lund.

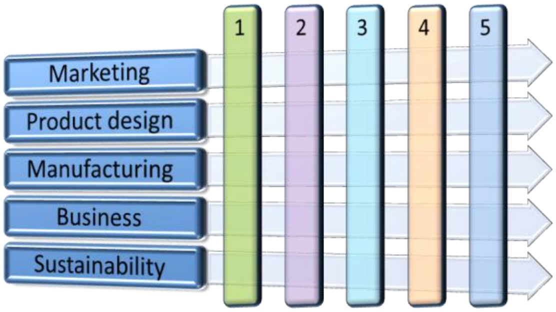

Figure 1 Illustration of concurrent engineering.

There are five phases involved in this process. Each step takes the customer needs closer to being a finished product. In the first phase ideas of products, which potentially could satisfy the targeted customers, are generated. The ideas are then furthered developed into concept sketches in phase two. These concepts are evaluated, and the ones which pass this evaluation go on to phase three. During phase three the first complete product design is established and functional prototypes are created. The manufacturability of the design is then improved during phase four. The product is after this taken into production. The only thing left to do after this is systematic improvement of the production facility. This is to be done during phase five.

3.1.1 Customer Needs and Product Specifications[10]

A development process of a new product should start with the gathering of customer statements regarding previous and similar products. These statements are then translated into customer needs by the development team. This is done to transform the statements into something that fits in the case of the product and the development process at hand. It is also done to enable gathering and organizing of the statements. In a theoretical example, the following statements from customers have been gathered during the development of a new screw driver, named SD:

- "I need to screw fast, faster than by hand."
- "I like the magnetized tip."

These statements can be translated into the following customer needs:

- "The SD drives screws faster than by hand."
- "The SD tip retains the screw before it is driven."

Note how the customer needs are more generic in nature, and does therefore not purpose a solution but rather illustrates a need.

To be able to grade the product proposals, and to compare them with existing products, the needs relative importance should be determined and metrics should be associated with the need. The need is translated into a product specification. It can sometimes be hard to set a metric related with a need, for example if it has to with esthetics, but it all cases possible it should be done.

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[10] Ulrich, K. & Eppinger, S. (2007) *Product Design and Development*. McGraw Hill Education. Fourth Edition.

3.1.2 Design for Manufacturing and Assembly (DFMA)

Between 70 and 80 percent of the cost of a product's development and future manufacturing is determined in the initial design stage of the development of a new product. Therefore it is very important to take activities such as manufacturing and assembly into consideration as soon as possible. By increasing the effort made at the early stage, designers are able to make a huge impact on the total future cost of a product. However, of course costs should not be minimized at any price. The developers should always take consideration to customer needs via the product specifications. [11]

The two main reasons why not more companies are using DFMA are that developers often lack the knowledge needed to make this type of analysis and are geographically located far from production facilities. It makes harder to find a solution since many companies outsource all, or a part of their production. Such decisions increase the physical and intangible distance between the activities.[12]

What is needed is that the designers have some fundamental knowledge about manufacturing processes and their capabilities. Examples of the type of information they need is which processes can be used given a specific material and geometry, which surface requirements can be achieved, which tolerances can be used, cycle times, and processing cost. However, designer must not only have knowledge of manufacturing processes, but also of assembly and joining methods. This is important because a product which might be cheap to manufacture might be expensive to assemble. So to avoid sub-optimization, designers must have knowledge of which geometries are easy o assemble, and the pros and cons of joining methods, such as welding, brazing, and mechanical joining.[13]

One of the main concepts of DFMA is to reduce the number of parts of the product. This can be achieved by asking three questions when adding a new part to the assembly. The goal of this is to integrate as many parts as possible. The questions are: [14]

- When the product is used, does the part analyzed move relative to the rest of the assembly?
- Must the material of the part be of another type than the material of the parts assembled?
- Must the part added to the assembly be separate by reasons of assembly or disassembly?

It is easy to fall in to the trap to just answer yes to the questions above. However, they should be analyzed properly. For example, when the first question is analyzed, only the type of movement that could not be achieved by elastic deformation should be considered. When thinking of the second question, only reasons which are given by strict material specification and material properties should be accepted. Finally, the third question should also be analyzed properly, and really be thought through if it

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[11] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[12] Ståhl, Jan-Eric (2009) *Industriella Tillverkningssystem del II*. Industriell Produktion vid Lunds Tekniska Högskola. Second Edition. Lund

[13] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[14] Boothroyd, Geoffrey (1994) *Product design for manufacture and assembly*. Computer-Aided Design. Volume 26, Issue 7. Page 505-520

otherwise would be impossible to assemble or disassemble the product without the use of an extra part. The next step is to identify parts which are essential to the product with these questions.

Before the design is further examined, the design team should assess assembly times for adding the different parts to the assembly. These times can then be transformed into costs by multiplying them with the salary of the assembler. This information can then be used by the team to evaluate the improvement of the design. After this, it is up to the creativity of the persons involved to try to integrate parts into each other to reduce part count.

The analysis described is the first step in DFMA analysis, and it is called design for assembly, DFA. It is supposed to be used as an iterative step, which is repeated until no further development can be made. The entire process can be seen in Figure 2.[15]

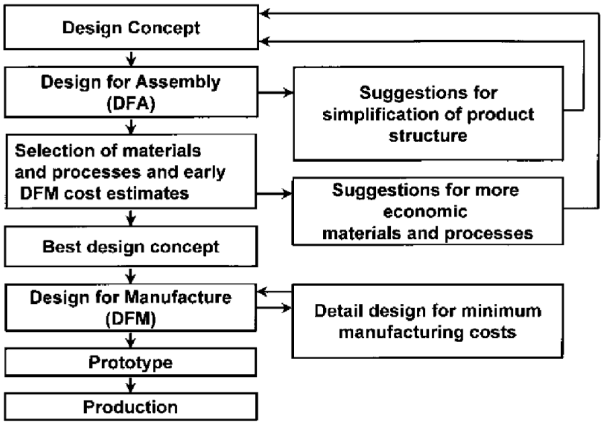

Figure 2 Typical steps taken in the use of DFMA.

When the design concept is finished, the design team should start by gathering material and process specifications. This information is needed in the screening and selection of materials and manufacturing processes. This is also an iterative step, and should lead back to the first design concept. This is because a change of material or process could lead to another more economic design with this in consideration.

The output of this process is the best design concept, which is to be further developed by minor changes to adapt it to the manufacturing process selected. However, since the basic design is established, no major costs can be saved in this stage. The last stage is to create a prototype to make sure that the design, material and manufacturing process, can live up the product specification before full scale production has begun.

It has been explained how DFMA can cut costs in both assembly and manufacturing, but there are other benefits as well. One of them is decreased time to market (TTM)[16]. In an increasingly competitive business environment this can be just as important as cutting costs. The earlier a product can reach the market, the larger market share can be obtained and the sooner the company can start to cover its

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[15] Ibid.
[16] Ibid.

expenses[17]. Shorter TTM is achieved by putting down more effort in the initial stage of the product development, see Figure 3. By doing so, problems can be identified and handled earlier. Thereby, large costs and extra time for redesign in the later stages can be avoided. Another benefit has to do with quality. In a famous case from Motorola, the number of defects in a product was traced as the assembly efficiency of the product was increased during several runs of DFMA analysis. What was discovered was a strong correlation between the two. As the efficiency went up, the number of defects went down.

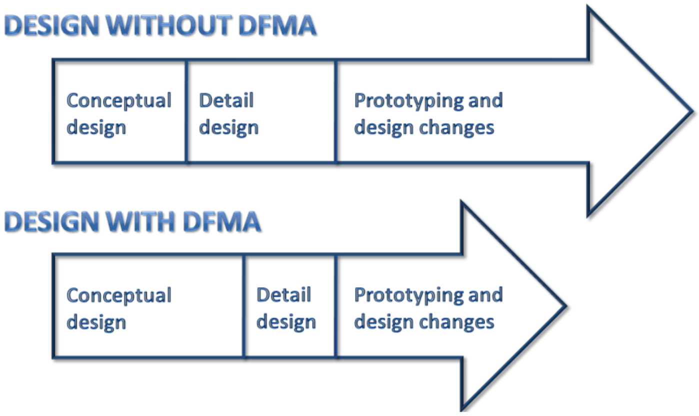

Figure 3 Time to market with and without DFMA.

The method described above is highly quantitative. The design team is supposed to count the number of parts and calculate assembly times and costs. Some of those whom research DFMA say that more qualitative guidelines only do harm. The reason given is that, qualitative guidelines increase the risk that the design team only simplifies parts of the final product and not overall design, see Figure 4. Even though the individual parts would be cheaper to manufacture this way, the cost of assembly often outweigh these savings. [18]

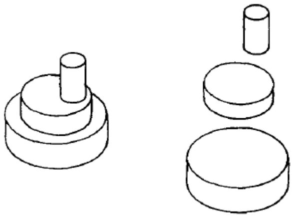

Figure 4 Simplify overall design vs. simplify individual parts.

At least one other researcher states that a combination of qualitative and quantitative guidelines is a good solution[19]. The reason given is that the use of qualitative guidelines is a way to make knowledge of the practice of design explicit. This knowledge can be derived from past experiences of design teams and are therefore proven guiding principles. However, it should be noted that since these guidelines have

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[17] Bergman, B. & Klefsjö, B. (2009) *Kvalitet från behov till användning*. Studentlitteratur AB. Fourth Edition. Lund.

[18] Boothroyd, Geoffrey (1994) *Product design for manufacture and assembly*. Computer-Aided Design. Volume 26, Issue 7. Page 505-520

[19] Edwards, K.L. (2002) *Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering*. Materials & Design. Volume 23, Issue 7. Page 651-657.

been taken out of their original context, there is some risk that some information is lost. The main concepts though, are kept. Below are some guidelines. These have in no way been altered from their original text. However, the order which the guidelines appear has been changed and some guidelines have been removed. In some cases, the guideline would fit as an assembly guideline and a manufacturing guideline. In these cases this guideline is sorted under design for assembly guidelines[20]

Design for assembly guidelines:[21]

- Keep the number of components and assemblies to a minimum.
- The most obvious way in which the assembly process can be facilitated at the design stage is by reducing the number of different components to a minimum.
- Minimise production steps.
- Standard sizes and components should be used wherever possible.
- Standardise and reduce the number of materials and components.
- Use standard components, processes and procedures whenever possible.
- Do consider using stock items when you need only a small quantity of components.
- Materials and methods of fabrication must be the cheapest acceptable.
- Manual processes should be reduced to a minimum.
- It is always necessary in automatic assembly to have a base component on which the assembly can be built.
- Design a base component to reduce the need for jigs and fixtures.
- Design a stacked product in order to achieve simpler assemblies.
- It should be pointed out that components that are easy to handle automatically will also be easy to handle manually.
- The introduction of automation may result in a cheaper product but one that is quite uneconomical to repair.
- Interchange ability of components should be arranged.
- Minimise tolerance and surface finish demands on components so that production costs are reduced.
- Do consider the use of economical order quantities.
- Aim at simplicity and economy of construction including interchangeable components.
- Design for the most suitable production process with economic assembly as a goal.
- Redesign to simply assembly.
- Design components to serve more than one function.
- Eliminate high precision fits whenever possible.
- A reduction in the number of components in a product or assembly should be the first objective of a designer wishing to reduce assembly costs.
- Sharp corners must be removed from components so that they are guided into their correct position during assembly.

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[20] Ibid.
[21] Ibid.

- Simplify handling of components.
- Apart from product simplification, great improvements can often be made by the introduction of guides and tapers which directly facilitate assembly.
- Avoid component features that induce tangling or nesting.
- Follow symmetrical layouts.
- Make components symmetrical.
- Attempt to make components symmetrical to avoid the need for extra orienting.
- If symmetry cannot be achieved, exaggerate asymmetry features to facilitate orienting.
- Avoid expensive and time consuming fastening operations.
- Do not specify material that is available only on special order purchase unless there is no alternative.
- To achieve a high level of reliability the designer must consider the use of well tried and tested components and materials, rather then [sic!] new and uncertain ones.
- Introduce datum systems whenever a high degree of accuracy is necessary in the location of interchangeable components.
- Will one spanner fit all clamp bolts and nuts?
- Designs should be made for ease of packing.
- Avoid sharp edges and angles.
- Make sure disassembly is equally practicable as assembly.

Design for manufacturing guidelines:[22]

- Insure maximum simplicity in overall design.
- The designer must be aware of the capabilities of his/her workshop, sub-contractors and materials suppliers.
- Design castings so as to minimise the cost of flash removal.
- Provide just sufficient material at all points where machining is required to permit machining within the limits specified.
- Avoid the use of undercuts where possible.
- Avoid slow processes and design for high speed continuous processes.
- Eliminate expensive operations not really needed to achieve function and simplify design details.
- Design the component so that the number and duration of machining operations required are minimised.
- Design the component so that it can be machined with a minimum number of tools and with standard tools unless special ones effect economies.
- Select materials to suit each processing operation best.
- Select materials for suitability as well as lowest cost and availability.
- Put a price on every tolerance and finish.
- Use the widest possible tolerances and finishes on components.

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[22] Ibid.

- The best way to achieve true reliability is by simplicity.
- Design to fit the manufacturing processes and reduce costs.
- Design castings so that they will combine as many components as permitted and still avoid undue complexity and excessive costs.
- See that all sections are of uniform thickness.
- Fillets should be used at corners wherever possible avoiding sharp corners but not so large to produce heavy cross-sections.
- It is not desirable to design structures with abrupt changes in section.
- Aim to make castings as simple in structure as conditions permit.
- Employ ribs to help avoid warping or are needed for extra stiffness and can be used to lower weight.
- Depth of draw should be kept as small as conditions permit if cost is to be minimised.
- Gauge of stock should be as light as conditions permit.
- If a component is one normally exposed to view, make sure that its appearance is as pleasing as due economy in production permits.
- Avoid square bottom holes when a hole made with a standard drill will meet the requirements.
- Unless removal of burrs is necessary, do not stipulate.
- Develop the design to contain as many identical components as possible.
- The designer will nearly always be able to reduce the number of components by combining two or more functions in a single component.
- Ensure changes of section are gradual.
- Allow for the effect of thermal stresses.
- Aim at uniform wall thickness and cross-sections and at gradual changes of cross-section.
- Use standards and codes wherever possible.
- Manufacturing processes favour objects with planes at right angles to each other and those that can be turned on a lathe.

When it comes to processing of plastics there are some more specific manufacturing guidelines since most of these processes share some characteristics, like for example heating, cooling, flowing of material, and high cost molds. This makes it possible to apply the following common guidelines: [23]

- When designing the parts, the design team should be thinking of the direction of opening and closing the mold and the parting surfaces.
- The flow of material through the mold shall go smoothly. Therefore reduce the number of sharp corners and heavy variation of wall thickness.
- Cooling, and therefore solidification, goes quicker if the thickness of the final part is kept as thin as possible. This results in lower cycle time and lower production cost.
- Try to keep the amount of moving parts in the mold as low as possible. Complex geometry may for example require moving side cores or extra ejection pins.

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[23] Poli, Corrado (2001) *Design for Manufacturing*. Elsevier Inc. First Edition.

3.1.2.1 Design for manual assembly[24]

First of all; it is important to differ between automatic, semi-automatic, and manual assembly. These types differ a lot in character and therefore in design recommendations as well. This chapter will cover the basics in design for manual assembly.

The process of assembling a product can be divided into two sections. First the parts which are to be assembled needs to be handled and oriented, and secondly the parts are to be inserted into each other to be fastened. There are many guidelines for assembly, and some of these have already been coved on page 13. However, the guidelines covered here are guidelines which are specific to manual assembly.

In order to be able to handle and orient the parts, they should preferably have an end-to-end rotational symmetry about the axis of insertion. If symmetry cannot be achieved the parts should be made apparently unsymmetrical to ease orientation. To avoid jamming of stacked items, the design should have features that prevent this. In some cases the parts are going to be transported in boxes, they should be designed so that they do not tangle. For graphic examples of these guidelines see Figure 5. Furthermore, parts should not be sharp, be so small that they are hard to handle, long and flexible so that they may nestle, or slippery.

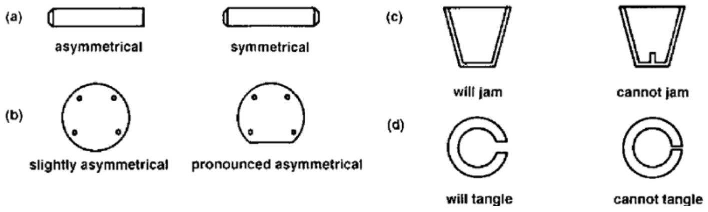

Figure 5 Design for manual assembly handling guidelines.

After the part has been handled it is time to insert and fasten it. To be able to insert the part, generous clearance should be given so that the part does not get stuck. It is also important to makes sure to avoid geometries which could jam during insertion. For example see Figure 6.

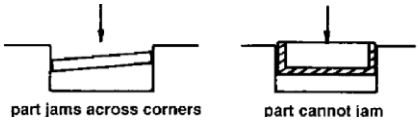

Figure 6 Jamming and non-jamming parts.

If pins are going to be inserted into blind holes, air-relief passages should be created to ease insertion. See Figure 7 for an example.

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[24] Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

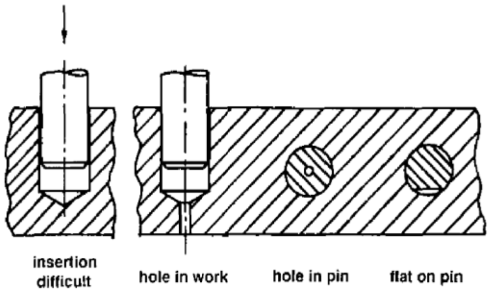

Figure 7 Insertion into blind holes.

For an example of how chamfers can be used to ease insertion, see Figure 8. The same figure also illustrates the importance of step-by-step insertion.

Figure 8 Use of chamfers and step-by-step insertion.

The cost of assembly is equivalent to the time it takes to assemble a product. The time needed is in turn dependant on the type of fastening method. In Figure 9, four fastening methods can be seen. The snap-fit solution to the left takes least time and is therefore the least expensive to use in assembly purposes, and the screw solution to the right takes the most time to use and is therefore the most expensive. The plastic bending and riveting solutions are in between.

Figure 9 Common fastening methods.

As mentioned earlier, there are a large amount of guidelines. However, they are insufficient in themselves. Without quantitative methods it is impossible to rank different assembly alternatives. Therefore are there elaborate methods for estimating time to assemble based on part symmetry, weight, size, et cetera.

3.1.2.2 Critique against DFMA[25]

DFMA often gets critique for putting down to much effort into DFA, instead of DFM. Since manufacturing stands for the largest part of the cost, it may feel strange that the emphasis should be put on assembly. It is true that the DFMA process starts with and focuses on DFA. This can be seen in Figure 2.

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[25] Boothroyd, G. ,Dewhurst, P. , & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

It is also true that manufacturing often involves higher costs than assembly. However, it has been shown that by starting with DFA and putting down a lot of effort into this part, the costs of manufacturing can be reduced drastically thanks to lowering part count and product complexity.

DFMA is critiqued for taking too much time. The time needed in the initial stage of product development, to properly carry out the analysis, is considered to be too long. According to the theory of DFMA, though, the time spent in the initial stage of the development is later on recovered, see the principle in Figure 3 on page 12.

Another type of resistance that DFMA meets has to do with human psychology. Often is new processes forced upon the employees from management. This is most often the case with DFMA as well. However, to be working properly, it needs to be developed within the design function by people how has seen the possible gain. Otherwise there is a risk that it is received as just another new technique. However, once the philosophy has been implemented new obstacles occur. Telling a designer that his or hers design can be improved is much like telling a mother her child is ugly. Therefore it is extra important that the willingness to adapt DFMA comes from within and that the design team has seen the benefit. It could also be a good idea to introduce some kind of incentive for creating better designs.

A common view is that is only worth to carry out a DFMA analysis when the production volume is going to be large. Therefore no analysis is usually performed when to volume is going to be low. However, since no effort at all is made in these cases, the marginal gain can be much larger.

The most focus of DFMA is set on assembly. Some critics state that lowering the part count to make assemble easier, makes it more difficult to disassemble and serve the products. However, experts state that this is not true. For example, lowering the amount of screws by taking away the unnecessary also lower the time needed to disassemble.

One claim often heard when someone asks a company about DFMA is that their company has been working with design for producibility for a long time. What this usually means is that they use design rules which simplify individual parts instead of overall structure. In order to use DFMA properly the design team must have costs associated with decision alternatives. This means either just quantitative or quantitative and qualitative, as discussed earlier.

The final form of critique covered here is that DFMA is only one of many techniques. The others mentioned are for example design for competiveness (DFC), design for performance (DFP), and design for quality (DFQ). The response given is that the others are important as well. However, manufacturing and assembly activities have been neglected for a long time. Meanwhile, designing products for competiveness and performance is something that always has been done. When it comes to DFQ, it is already mentioned that quality can be increased using DFMA.

All in all, DFMA is a tool which some say may make companies products lack differentiation[26], resulting in price wars[27]. Others state it can be used as a competitive weapon, which is extra important to use in the initial stage of product development[28]. Independent of which, there are many examples of how the cost of producing a product has been lowered, along with other benefits[29].

3.1.2.3 Design for X[30]

Design for X, or DFX, have two meanings. The first is that the X stands for any aspect of the products lifecycle which is impacted by the design. Examples of this are logistics, quality, service, recycling, fixturing, marketing, and the environment[31]. The second meaning is that the X stands for excellence. Either way, DFX is a way to take several factors into consideration during the design stage. This is done by having multifunctional teams, with representatives from each of the considered areas.

One of the problems which could occur when using DFX is that only one aspect is considered at the time, and thus neglecting the purpose of the methodology. The solution is to try to handle several issues and aspects at the time. This can be done by the use of functional measurement systems together with the usual functionality grading of product specification. This ensures that the functions are considered as internal customers.

Another important way of improving the product development process is to share knowledge between downstream and upstream activities so that the development teams get feedback on their performances to ensure learning.

Recently, the amount of research of DFX has increased.

3.1.3 Selecting Material, Manufacturing Process, and Joining Process for a New Product

The selection of material and manufacturing process for a new product are tightly linked. By selecting a material, the amount of processes which can be used is greatly reduced. For example, if aluminum is selected as material, all processes which only are used to process plastics are no longer an option. Therefore, it could be dangerous to select material without taking manufacturing into consideration. If the aluminum product in the example above is going to be produced in large quantities, it might have been beneficial to select a thermoplastic material instead. Because then the parts could have been produced using injection molding, which is a process perfect for mass production. [32]

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[26] Burkett, Michael (2008) *Keep it Simple - But Not Too Simple*. Supply Chain Management Review. Volume 12, Issue 7. Page 12-14.

[27] Johnson, G. & Scholes, K. (2002) *Exploring Corporate Strategy*. Financial Times Prentice Hall. Sixth Edition. Madrid.

[28] Redford, M., Sawicki, J., Subramaniam, P., Hou, C., Zorian, Y. & Michaels, K. (2009) *DFM—Don't care or competitive weapon?*. 2009 46th ACM/IEEE Design Automation Conference. Page 296-297.

[29] Boothroyd, G. ,Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

[30] Sheu, D.D. & Chen, D.R. (2007) *Backward design and cross-functional design management*. Computers and Industrial Engineering. Volume 53. Page 1-17.

[31] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[32] Ibid.

There is another danger with selecting material at a too early stage in product development. The information available in this stage is limited. Perhaps it is shown at a later stage that the material selected is not at all as good of a choice as first anticipated due to newly discovered product specifications. So despite that there are many very large databases of materials which can be used to select material, it might be favorable to wait to use them until a later stage.[33]

Instead of grouping materials based on how well they suit early product specifications, the design team can group materials into categories based on which primary processes can be used to process that type of material. Primary processes are processes which are used to create the general shape of a part. By grouping the materials in this way, the design team can easily see how the selection of a material restricts the available processes. The processes still available after selection can thereafter be reviewed to figure out which geometries can be created, which tolerances can be achieved, for which volumes the process makes economical sense, which production rates can be achieved, et cetera, to makes sure that the selection of material transfers into suitable manufacturing processes.[34]

The process of selecting a material is begun by transforming customer needs into factors. These should then be analyzed in order to select a suitable material. The factors can be divided into five categories; physical, mechanical, processing and fabrication factors, life of component factors, and cost and availability. The first category, physical, handles the size and geometry of the product. Examples of which questions can be asked to analyze this category are; how complex is the shape, which tolerances must be used, and which surface requirements does the product have? These questions help the design team structure information about production specific criteria which are connected to the selected material and product geometry.[35]

The mechanical process selection factors cover the mechanical requirements which the product must fulfill. This can be done by examining the environment of the product when it is in use. The information is then transformed into specifications of which temperatures, loads, level of wear, et cetera, the product must be able to withstand.[36]

The third group of factors, processing and fabrication factors, has to do with which implications the materials has on manufacturing. It has already been mentioned that the selection of material reduces the amount of process available. However, this decision also has an impact on how effectively the different processes can be used. An example of this is the material removal rate which can be used when machining is influenced by the material. When discussing these questions it is also important to take consideration to the demand of the product and the level of quality desired. The demand determines which production rate must be achieved, and the quality level desired is vital when making sure that this level can be achieved by selecting a specific material.[37]

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[33] Ibid.

[34] Ibid.

[35] Mital, A., Desai, A., Subramanian, A. & Mital, A. (2008) Product Development: A Structured Approach to Consumer Product Development, Design, and Manufacture. Elsevier Inc. First Edition.

[36] Ibid.

[37] Ibid.

Life of component factors include all aspects of the product in use. For example, the product may corrode or oxidize. [38]

The final factors had to do with cost and availability. When the cost of selecting a material is being estimated, not only should the cost of the material itself be taken into account, but also the cost of the manufacturing alternatives still available after selecting. This is important to avoid sub-optimizing of costs. The demand of the product is of double importance when analyzing the availability of the material. First the availability needs to be examined to make sure that the demand can be fulfilled. Secondly, the availability needs to be examined to makes sure that the demand can be fulfilled given the lead times required by the customers.[39]

The choice of material and the choice of manufacturing process must be carried out more or less simultaneously since the choice of one restricts the available choices of the other. Therefore it is hard to talk about material selection processes and manufacturing selection processes as two separate processes. However, just by selecting material type, for example steel, thermoplastics, or ceramics, manufacturing processes can be evaluated. This initial evaluation is important to be able to examine different material and process selection combinations.[40]

Just as for the material selection criteria, the criteria used to select the process must be based on customers' needs. These needs can be transformed into product design specifications, PDS, which are used to select material type and later manufacturing process. A process selection process can be viewed in Figure 10.[41]

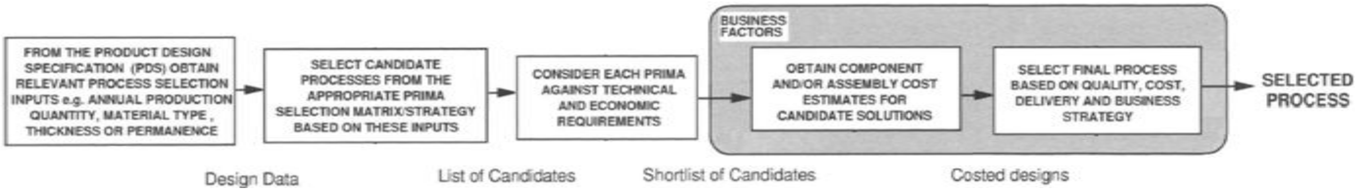

Figure 10 Manufacturing process selection.

This process begins with obtaining process selection inputs from the PDS. These inputs can for example be anticipated annual production quantity and material type. This data is then used to select manufacturing process candidates using a PRIMA selection matrix. PRIMA is short for process information maps. A copy of it can be seen in Appendix 1 – PRIMA Selection Matrix. This matrix has different materials on one axis and the production quantity on the other. Combining these two factors can give the design team an idea of which processes can be appropriate. From this a list of candidates is extracted which is further analyzed in the next stage. Here the PRIMA are evaluated using technical and economic requirements. First in the PRIMA, a general description of the process is given, and a representative part which is produced with the process is shown. There is also a list of which materials

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[38] Ibid.

[39] Ibid.

[40] Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition.

[41] Ibid.

can be used, descriptions of typical variations there are of the process, economic considerations to take into account, design opportunities and limitations, and quality issues.[42]

The result of the third stage is a shortlist of process candidates. This list is further evaluated assessing assembly and component costs for the different production alternatives. The final stage is that all other parameters, for example quality aspects, delivery reliability, and business strategy, are considered together with the costs, to make a final selection.[43]

Not everybody use the name PRIMA for information about the processes. However, even though the selection processes of some writers differ, most agree on the type of information needed to be analyzed to in the end make a correct process selection. Another example of how processes can be divided is by categorize them by which of them can create certain features. For example if the process only can create parts with uniform wall thickness, with a center axis of rotation, which have captured cavities, which are completely enclosed , with draft, or with other geometric characteristics. These groupings can then be used to determine whether a process can be used to produce a certain part. This procedure only analyzes the geometry of the part, with no regard to selected material.[44]

Furthermore, most also agree that some of the most important factors used to make the decision are annual production quantity and selected material type. Annual production quantity is so important because of the economic characteristics of manufacturing processes. Some processes have very high initial costs which need to be spread among a large amount of products. Others have lover initial costs but are instead more labor intensive, and therefore have higher variable costs. This makes some processes more appropriate for some levels of production volumes and some others for lower.[45]

At the stage when the material and the manufacturing processes have been analyzed it is time to analyze the assembly and joining alternatives available. When the design team is selecting assembly alternative, consideration need to be taken to production rate required, production quantity, and the cost of the alternative. For example if the production volume is large, maybe it would be beneficial to select an automatic assembly method. However, if the volume is low, the high initial costs of automatic systems are too high, and a manual system must be selected.[46]

Joining processes also needs to be analyzed properly. For example should joint design, the selected material, and service conditions be regarded when selecting process. The service conditions are especially important since these determine the permanence of the joint. If a service operator needs to be able to disassemble the joint often, it must be non permanent. However, if this is done more seldom or never, the joint can be semi-permanent or non permanent. A joint is semi-permanent if it is possible to disassemble it without major damage to the parts, however, it cannot be done as easily as

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[42] Ibid.
[43] Ibid.
[44] Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.
[45] Ibid.
[46] Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition.

unscrewing a screw. Shrink fits, press fits, and blind rivets are examples of semi-permanent joints[47]. This is further explained in the chapter Joining Processes on page 49.

On top of this the joining should be examined from a functional, technical, spatial, and economic point of view. A functional view is when the mechanical properties are being examined to make sure that the joint will be able to withstand the load required. The technical view does instead focus on the type of material which is to be joint, operating temperatures for the part, and required corrosion resistance, among similar specifications. The type of material is important since not all joining process can be used to join all materials. The spatial view looks at the geometry and weight of the joint to make sure that these requirements are not exceeded. Finally, the economic point of view take consideration to production rate, production quantity, ease of automation, tool needed, et cetera, to make sure that the process makes economical sense.[48]

Selecting material and processes is a difficult task. Unfortunately, design teams often only consider the options which they are familiar with. Instead, they should match material and process characteristics, from all available materials and processes, with required product attributes. On the options discovered, they should then do an economical evaluation at a conceptual stage. All to make sure that no opportunity is missed.[49]

3.2 Thermoplastic Materials[50]

Thermoplastics are plastic materials that can be reshaped by heating them to a temperature so that they become viscous and then cooling them again so that they once again solidify. This enables manufacturers to reshape the plastic after first processed. Even though thermoplastics can be reshaped, they cannot be reshaped to many times without repercussions. After repeated reheating the material suffers from degradation, also called thermal aging.

What happens with thermoplastics when the temperature increases is that the secondary, weaker, adjacent bonds between the molecules become even weaker. The primary covalent bonds, that keep the molecules together, are not affected in the same way. When the temperature is increased to the glass transition temperature, T_g, the plastic becomes leathery. If the temperatures continues to increase it becomes rubbery. Finally, if the next point is passed, it becomes a viscous fluid. The last point is the melting point, T_m, for crystalline thermoplastics. That a thermoplastic is crystalline means that the molecules have an orderly arrangement. If the molecules are not arranged, it is called amorphous.

Some thermoplastics are able to absorb water. If they do, the water acts as a plasticizing agent. The water lubricates the chains in amorphous areas. It usually also results in lowering the yield stress and glass-transition temperature.

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[47] Ibid.

[48] Ibid.

[49] Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

[50] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Both the thermal and the electrical conductivity of thermoplastics are typically low. This is why these often are used as insulators in electrical components and in applications which involves heat. The low thermal conductivity, however, sometimes becomes a problem when thermoplastics a processed. Because it does that it takes long time for thick intersections to cool down.[51]

3.2.1 Material A[52]

Information cannot be given about this specific material due to the public nature of this report.

3.2.2 Material B[53]

Information cannot be given about this specific material due to the public nature of this report.

3.2.3 Material C[54]

Information cannot be given about this specific material due to the public nature of this report.

3.3 Manufacturing Processes for Thermoplastics

Presented in this chapter are some of the most common manufacturing processes for thermoplastics.

3.3.1 Injection Molding

Injection molding uses thermoplastic pellets which are heated by friction and fed forward by either a piston or a rotating and reciprocating screw, see Figure 11. Most new machines are of the screw type. In the case of the piston, it forces the pellets past a torpedo with large friction. The heat generated from the friction and the heating elements melts the material. The melt is then injected into the mold. In the case of the screw, it feeds the material forward by rotation and forces itself backwards as the molten plastic is stuffed in front of the nozzle. Heat is generated in the same ways as for the previously mentioned process. When enough pressure has been created, the screw stops to rotate, the inlet to the mold is opened, and the plastic fills the cavity using the built up pressure. The inlet is then closed and the process is repeated.[55]

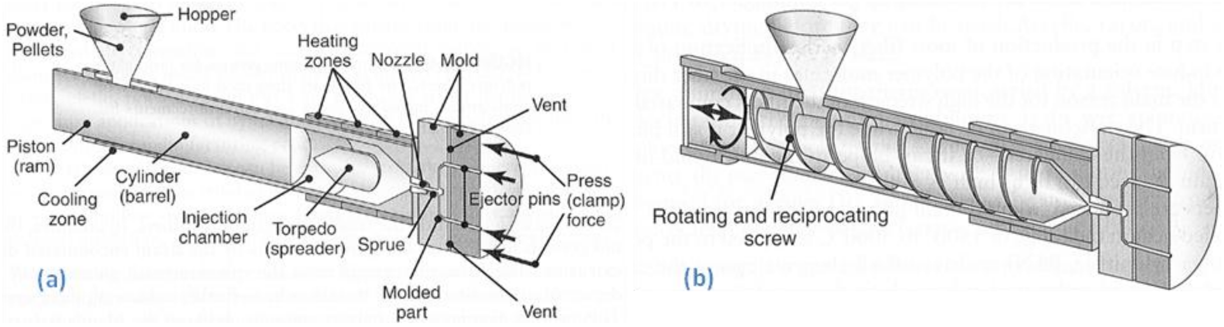

Figure 11 (a) Plunger injection molding and (b) reciprocating rotating screw injection molding.

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[51] Alessandro Mattozzi, ABB Corporate Research and Development, Västerås

[52] Edshammar, Lars-Erik (2002) *Plasthandboken - en materialguide för industrin*. Industrilitteratur AB. First Edition. Uppsala.

[53] Ibid.

[54] Ibid.

[55] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Since there is no longer any heat generated and because of cooling canals in the mold, the molten material starts to cool down as it has filled the mold. When the part has solidified, the mold is opened and the part is ejected. The part falls down in a container and the mold is closed for the next injection.[56]

The ejected part often needs trimming after it has left the mold, see Figure 12 b. The sprue and runners needs to be removed from the part. In some cases there also some flash which needs to be removed. Flash is material leakage which can occur when the mold has not been closed properly. The removed material can be chopped and reused. However, as mentioned earlier, thermoplastic material age and cannot be reused too many times without repercussions.[57]

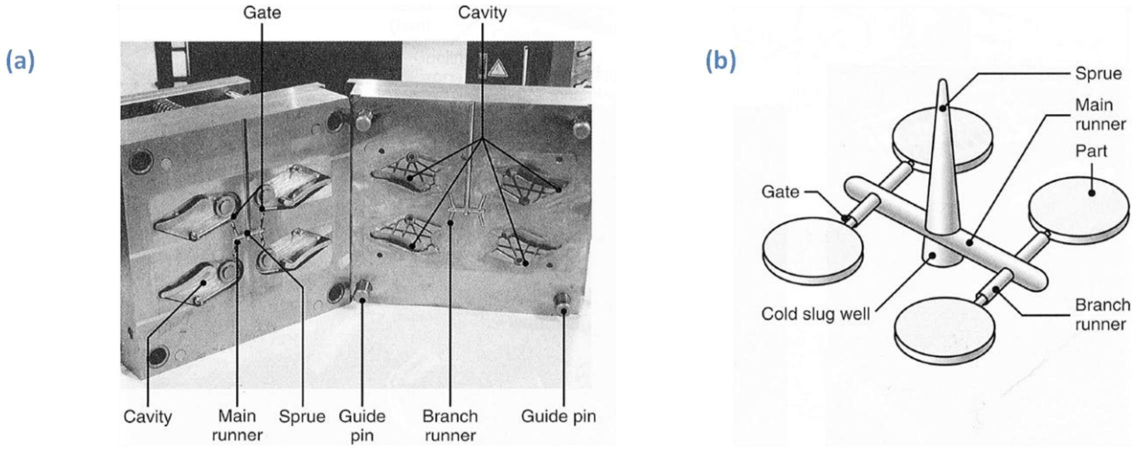

Figure 12 (a) Cold-runner two-plate mold and (b) part ejected from injection molding.

The screw used in injection molding is similar to the screw used in extrusion. A typical screw used for injection molding can be seen in Figure 13. The material is placed in the hopper and falls through the feed opening into the injection chamber. The pellets are packed more and more as it is transported by the screw. The check valve, located in the front of the screw, is a device which prevents the melt to be pressured back into the injection chamber during injection. The check valve shown in the figure is called a sliding ring check valve. However, there are also other types of valves.[58]

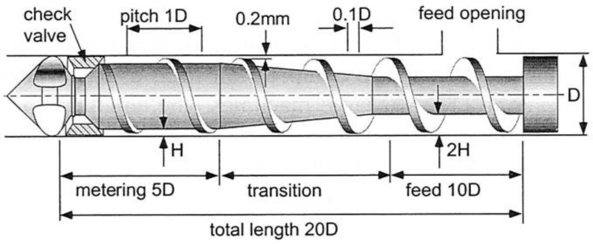

Figure 13 Typical extruder screw for injection molding.

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[56] Ibid.

[57] Ibid.

[58] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

As mentioned, the screw is used to convey and melt the pellets, but is has one more purpose. It is also used to mix the material. This is for example important because the melt needs to be thermally homogenous when injected into the cavity. To ensure proper mixing, a section of the screw can be dedicated to this by designing it especially to this purpose.[59]

During injection the molten material flows through the nozzle, the sprue, the runners, and gates to reach the mold cavity. How easy it is for the material to reach the cavity, very much depends on the viscosity of the melt; the lower the viscosity the easier. One way of measuring the viscosity is by heating the material to a specific temperature while it is in a cylinder with a hole in the bottom. Then a weight is placed on the material. The material is extruded due to the pressure applied, and by measuring the length of the extruded string during a specific time span, the melt flow index, MFI, can be estimated.[60]

The design and location of the runners is very important for the final result. For example, several cavities can be used to increase the production rate. In this case, the length of the runners to all gates should preferably be the same. This also applies when several gates are used to produce one part. An example of this can be seen in Figure 14 c.[61]

The design and location of the gate or gates are also important for the result. Several design alternatives for gates can be seen in Figure 14. For example, the risk of warpage, weld lines, and short shot can be minimized by proper gate design and location. These flaws are further discussed later on. Another potential problem with gates is that mark is left after trimming. Because of this, it can be preferable to place the gate where appearance is not so important. To make the mark smaller, and to ease parting of the runner and the part, the gate can be made smaller. However, by making the gate smaller, the flow of material is reduced. This increases the risk of a short shot. So by reducing one problem the risk of another is increased. In general, the diameter of the gate is 30 to 70 percent of the wall thickness of the part.[62]

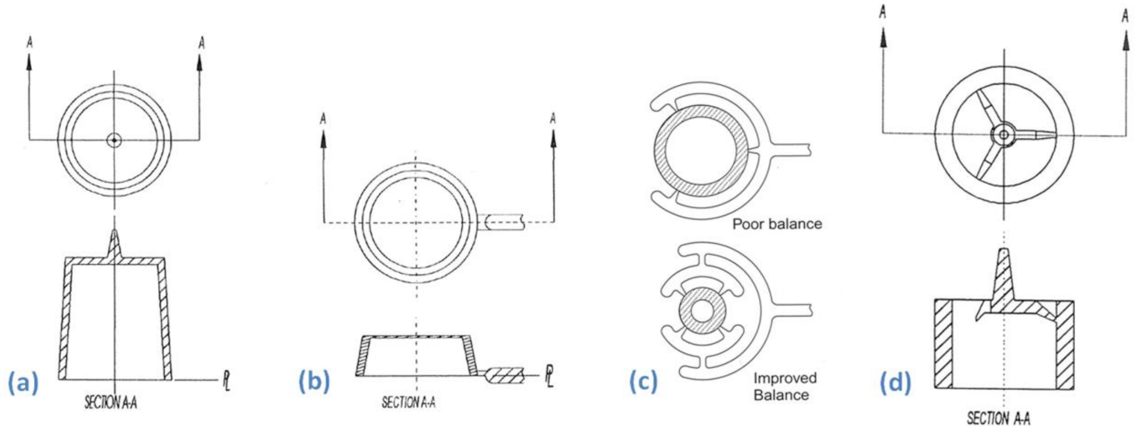

Figure 14 (a) Sprue gate, (b) tab gate, (c) ring gate design guidelines, and (d) diaphragm gate.

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[59] Ibid.
[60] Ibid.
[61] Ibid.
[62] Ibid.

Another way of reducing the gate marks is to use shut-off nozzles. There is a mechanical shut-off nozzle which simply closes the gate when injection is finished, and there is a thermal shut-off nozzle which freezes the gate. These mechanical or thermal aids, which are built into the mold, greatly reduce gate marks. An additional benefit is that they enable the use of large gates. However, they also increase the cost of the mold.[63]

When the material fills the mold the two mold halves are kept together by a clamp. The pressure of this clamp can be applied by hydraulics, mechanics, or a combination of the two. Hydraulics is often favored due to its simplicity and because it is more easy to set up. The amount of force that is required depends upon injection time, injection temperature, and selected material[64]. However, it usually ranges from 0.9 to 2.2 MN.[65]

As soon as the molten material reaches the cavity walls it solidifies. This is because the cavity walls are kept cool by the use of cooling canals. Cold water, oil, or water-glycol solution can be used as cooling agent in these canals. The canals must be placed in the molds in such a way that no variations in mold temperature occur since this could lead to warping. [66]

To make sure that no air is captured in the cavity as it is filled with the melt, small ventilation holes are created in the mold. If the air cannot escape, it may cause burn marks on the parts and prevent the filling of the cavity. The ventilation holes should if possible be placed at the feature of the part which is last filled and in the parting plane of the mold, and the size of them should not exceed 0.03mm times 2mm. However, the size depends on the material viscosity since they should be small enough that no material leakage can occur.[67]

After the material has been injected into the cavity and it has solidified, it is time to open the mold and eject the part. This can for example be done by the use of ejector pins, showed in Figure 11, or stripper plates, showed in Figure 19 a. There are also other methods. A problem with ejector pins is that they often leave marks in the part since the material is still somewhat warm. This can be helped by oversizing the pins so that the force is applied to a larger area. To further ease the ejection, a draft of the walls which are parallel to the mold opening direction is required. This is especially important for surfaces of internal cavities of parts, for example holes in the part. Since the material shrinks when its temperature is decreased, parts would shrink onto the mold cavity without a draft on these features. This would make demolding very difficult and increase the risk of damaging the parts surface. There are also other ways of simplifying demolding. For example by polishing the cavity walls in the mold opening direction,

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[63] Ibid.
[64] Ibid.
[65] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.
[66] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.
[67] Ibid.

or by using release agents such as silicone, demolding can be eased. However, release agents must often be removed to improve the adherence if the parts are going to be painted or coated.[68]

The cycle time of the injection molding process can be divided into the following steps:[69]

1. Closing of mold
2. Injection
3. Pressure holding and cooling
4. Mold opening and ejection of part

An illustration of the steps can be seen in Figure 15. Worth noting is that the cooling time often represents the largest part of the cycle time. The sealing point is the point when the material in the gate freezes and thereby closes the inlet to the cavity. The risk of reversed flow back into the injection chamber is greatly reduced after this.[70]

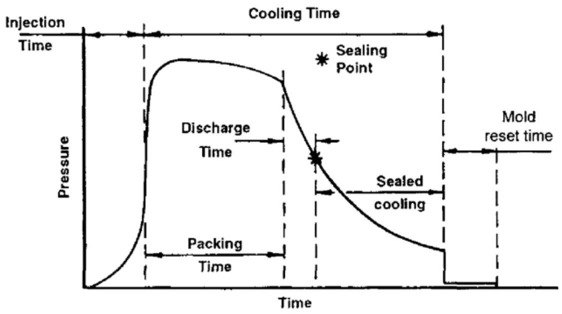

Figure 15 Steps of the injection molding process.

Injection molding is a production process with a high production rate and a process which requires a high initial investment. Many thermoplastic materials can be used, and fiber reinforced materials can be molded without any problems. So in total, it is a very flexible process with many possibilities.

3.3.1.1 The mold

Figure 16 shows a typical injection mold. It consists of many plates which all has their specific purpose. It is between the cavity plate and the core plate which the molten plastic is injected. The rest of the plates are there either to support the cavity or core plate or to make ejection of the parts possible.[71]

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[68] Ibid.

[69] Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

[70] Ibid.

[71] Ibid.

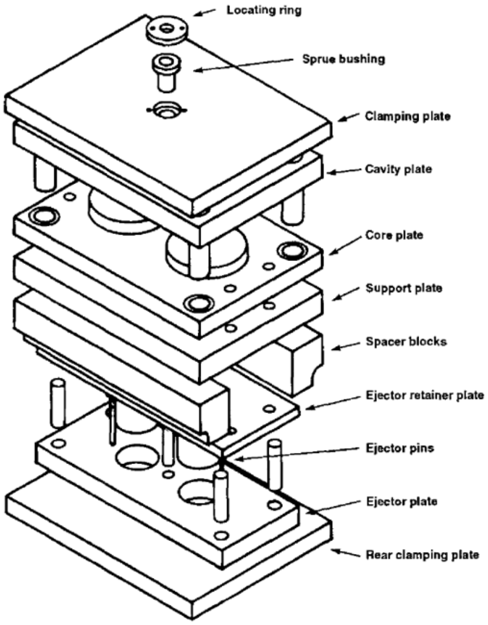

Figure 16 Typical Injection molding mold.

Generally there are three types of molds; cold-runner two-plate molds, cold-runner three-plate molds, and hot-runner molds. The mold types can be seen in Figure 17. The cold-runner-two-plate mold is the simplest type of mold. It simply consists of two mold halves. The cold-runner three-plate mold is somewhat similar. The difference is that there is an extra plate which separates the sprue and runner from the part. This extra plate enables automatic trimming of the sprue and runner when the mold is opened. A hot-runner mold is similar to the cold-runner three-plate mold. The difference is that the extra plate which separates the sprue and runner from the part is heated. This makes it possible to save this material for next cycle. However, these types of molds are much more expensive than the other, so high production volumes are necessary.[72]

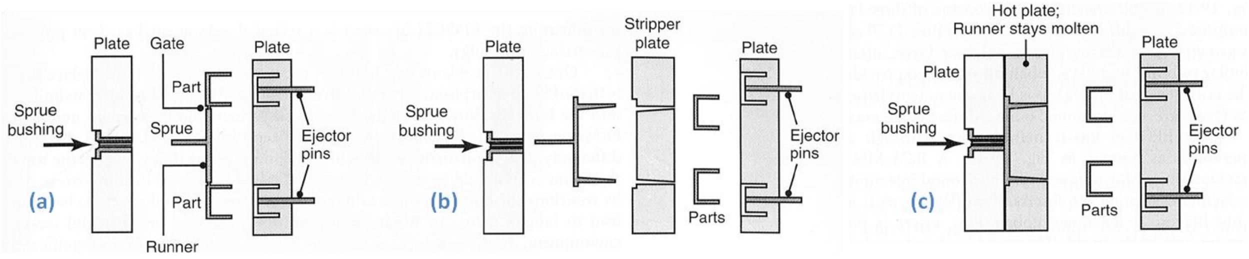

Figure 17 (a) Cold-runner two-plate mold, (b) cold-runner three-plate mold, and (c) hot-runner mold.

The heated molds can either be externally heated, internally heated, or insulated. If it is insulated it is just the heat of the molten material which heats the plate. This is the cheapest version of the three but it has limits when it comes to controlling the temperature of the heated plate. The externally heated plate has heating elements in the plate which heats it. This type of hot-runner mold offers bad insulation of the heated plate relative to the other plates, which are to be kept cold. The internally heated plate,

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[72] Ibid.

which has a heating element in the middle of the runner, on the other hand offers better insulation. However, it is more complex, and therefore more expensive, than an externally heated plate.[73]

All the molds which are used for injection molding are expensive. How expensive it is depends on type of steel used, part complexity, part size, et cetera. A large mold can cost as much as $100,000, but may last for 2 million cycles. The high initial investment requires high production volumes to be justified. [74]

It is very hard to say how much a mold will wear. It depends on the geometry of the part produced and the type of steel used. However, when selecting the type of steel for the mold, consideration must also be taken to other factors than wear resistance. Examples of these other factors are the thermal conductivity of the material, machinability of the material, and the material's ability to resist fatigue. If the mold is manufactured from a material with bad thermal conductivity, this will increase cycle time and therefore also the processing cost of the part. The machinability of the material influences the cost of machining the cavity of the mold and also the time necessary to produce it. Finally, the material's ability to resist fatigue affects how long the mold will last and the quality of the parts produced, just as its wear resistance.[75]

Even though molds for injection molding are expensive, there are methods which can help lower the costs. For example, modular molds and mold inserts can be used. Modular molds are standard sized parts of the molds, for example clamping plates. Since these are produced without customization, the volume can be increased and the costs can be lowered. Mold inserts are parts of the cavity which can be switched in one generic mold. Using these, similar parts can be produced using only one mold with some minor interchangeable parts.[76] Another way of lowering the cost of the molds is the use of aluminum molds. These molds are able to produce fewer parts, but are cheaper[77].

3.3.1.1.1 Machining of the Mold

The cavities of the molds used in injection molding are machined using end milling. Most often are TiAlN-coated ball nose end mills used. They are a round tops and are therefore well suited to create advanced sculptured shapes.[78]

The speed by which cavities can be machined varies, partly depending on the surface smoothness which is to be achieved and type of steel. In general, the approximate parameters specified in Table 1 can be

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[73] Ibid.

[74] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[75] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

[76] Ibid.

[77] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[78] Ibid.

used. Please note that different settings are used if only the rough contours are created or if the final cavity surface is to be created.[79]

Table 1 Parameters when milling steel molds.

	Speed (m/min)	Feed (mm/tooth)	Axial depth of cut(mm)	Radial width of cut (mm)
Rough	100 to 250	0.10	1.91	0.64
Finishing	200 to 1200	0.05	0.64	0.25

As mentioned, the parameters do vary depending on type of steel used. As an example, parameters from the steels Unimax and Vanadis 10 from Uddeholm can be viewed in Table 2. The parameters are for milling when using a solid carbide tool with TiCN-coating and a diameter of 10 to 20mm. The parameters for speed truly differ. Vandis is a type of steel with high resistance to wear for long series production and Unimax is a type of softer steel for shorter series. However, both steels can be used for injection molding molds.[80]

Table 2 Milling parameters of Uddeholm steels.

	Speed (m/min)	Feed (mm/tooth)	Axial depth of cut(mm)	Radial width of cut (mm)
Unimax	120 to 150	0.02 to 0.04	10 to 20	10 to 20
Vanadis 10	30 to 40	0.02 to 0.04	10 to 20	10 to 20

These numbers can be compared to if aluminum is machined instead. In this case the speed is usually between 610 and 900m/min, the feed between 0.13 and 0.23mm/tooth, and depths-of-cut of between 1 and 8mm.[81]

When designing the cavity it is always preferable if consideration is taken to that standard milling cutters can be used and that no sharp corners are created. Sharp corners are hard to create since there always is some radius on the edge of the milling tool.[82]

3.3.1.1.2 Mold Cost Estimation[83]

The cost of a mold varies because each mold cavity is unique. This makes it difficult to estimate the cost of a new mold. However, based on empirical studies there are methods which try to give an approximate answer to the question.

The cost of a mold can be divided into two cost drivers. These are the cost of a mold base and the cost of adaption of it by machining. The machining can in turn be divided into three more specific cost drivers

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[79] Becze, C.E., et al.(2000) High-speed five-axis milling of hardened tool steel. International Journal of Machine Tools & Manufacture. Issue 40. Page 869–885.

[80] External product information sheets of the two steel types Unimax and Vanadis 10, downloaded from the official Uddeholm website, http://www.uddeholm.se/swedish/b_91.htm. 2010-11-02.

81 Kalpakjian, S. & Schmid, S. (2006) Manufacturing, Engineering and Technology. Prentice Hall. Fifth Edition. Singapore.

[82] Ibid.

83 Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) Product Design for Manufacture and Assembly. CRC Press. Second Edition. New York.

which are ejection system, geometrical complexity of the part, and size of the part. The geometrical complexity of a part for example take consideration to factor such as undercuts, texture patters, tolerances, and required parting plane.

The cost of the base mold can be derived from two factors; area of the cavity plate, and the thickness of the core and cavity plates. When calculating the area and required thickness consideration must be taken to the fact that a cavity must have some clearance to the edges of the mold and to other potential cavities in the same mold. The clearance needed can be estimated to 7.5cm. Furthermore, if undercuts are to be created, for example using side-pulls, additional clearance must be added. Side-pulls result in an extra 7.5cm which is to be added to either the thickness, width, or the length of the mold base. The calculated area and the thickness are used in Equation 1, where A_c is the area of the cavity plate in cm^2, h_p is the combined thickness of the cavity and core plates in cm, and V_b is the cost of the mold base in USD.

Equation 1 Mold base cost.

$$V_b = 1000 + 0.45 A_c h_p^{0.4}$$

However, the molds need to be adapted to the specific parts, for example by tailored cooling systems. Due to this the cost of the base mold calculated in Equation 1 can be doubled to get the total cost of the base mold.

The next step is to try to estimate the cost of the ejection system. The amount of ejection pins needed depends on a lot of factors. However, it has been shown that there is a correlation between A_p, the projected part area, and the number of pins necessary. This has lead to that machining time, M_e, needed to manufacture the ejection system can be estimated using Equation 2. M_e is the time in hours.

Equation 2 Machining time needed for the ejection system.

$$M_e = 2.5 \times A_p^{0.5}$$

The only thing left to estimate is the manufacturing time needed to machine the cavity. This can be done using Equation 3 and Equation 4, where M_x is the machining time which is dependant of part complexity, M_{po} is the machining time which is dependant of part size, and X_i and X_o is the inner and outer complexity of the part. M_x and M_{po} is the machining time in hours.

Equation 3 Machining time needed for the cavity, dependant on part complexity.

$$M_x = 5.83 (X_i + X_o)^{1.27}$$

Equation 4 Machining time needed for the cavity, dependant on part size.

$$M_{po} = 5 + 0.085 \times A_p^{1.2}$$

X_i and X_o can be calculated by examining the number of flat or smoothly curved surfaces a part has and then count the number of surface patches. The number of patches can be multiplied with 0.1 to get the complexity. For example the part shown in Figure 18 has X_i 0.1*2 =0.2 and X_o 0.1*4=0.4. However, if there are repeated features in the part a power index of 0.7 can be used. For example if a part has 100 dimples, the number of surface patches can be reduced to $100^{0.7}$ for those features.

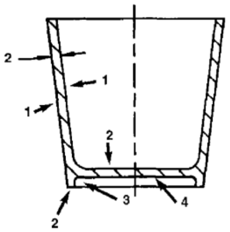


Figure 18 Number of surface patches.

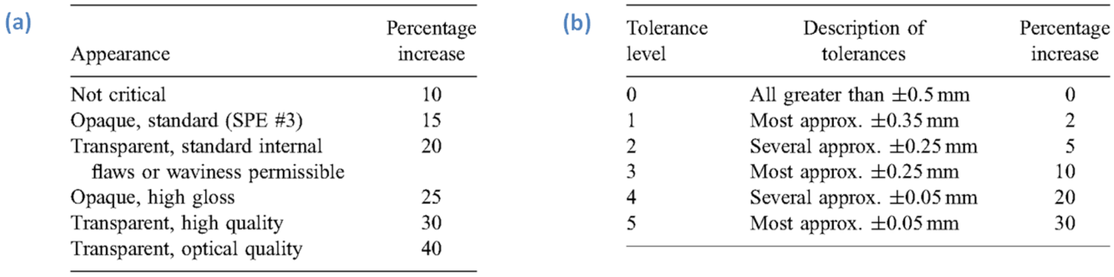
The sum of Equation 2, Equation 3, and Equation 4 equals the total hours necessary to machine the mold cavity and ejection system. However, there are other factors that must be taken into consideration. These are occurrence of undercuts, textures on the surfaces, surface specifications, tolerances, and geometry of parting plane.

The machining needed to create molds which can produce undercuts greatly depends on the type of undercut and the geometry of it. Generally it involves extra machining time in the rage of 50 to 80 hours to make a side-pull mechanism, 100 to 200 hours to make an internal core pin, and 200 to 300 hours to make an unscrewing mechanism which can make screw threads.

If texture patterns or shallow texts are to be machined into the cavities of the molds this approximately increases both M_x and M_{po} with 5%.

Molds which are to produce parts with smooth surfaces or extra tight tolerances further extend the machining time necessary to produce the cavities. How extended the machining time becomes depends upon the level required, see Table 3. The surface levels showed in Table 3 are standard surface qualities determined by the Society of Plastic Engineers (SPE). For extra surface requirements the percentage show in the table can be added to M_x and M_{po}, and for extra tight tolerances a percentage can be added to M_x.

Table 3 (a) Surface and (b) tolerance requirements effect on cavity machining time.



(a)

Appearance	Percentage increase
Not critical	10
Opaque, standard (SPE #3)	15
Transparent, standard internal flaws or waviness permissible	20
Opaque, high gloss	25
Transparent, high quality	30
Transparent, optical quality	40

(b)

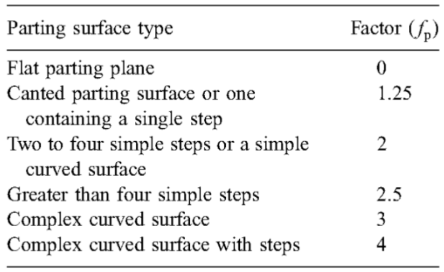
Tolerance level	Description of tolerances	Percentage increase
0	All greater than ±0.5 mm	0
1	Most approx. ±0.35 mm	2
2	Several approx. ±0.25 mm	5
3	Most approx. ±0.25 mm	10
4	Several approx. ±0.05 mm	20
5	Most approx. ±0.05 mm	30

The last thing that consideration needs to be taken to is the geometry of the parting plane of the two mold halves. To calculate the extra machining time, M_s, needed to machine a special parting plate Equation 5 can be used. f_p can be determined from Table 4 and M_s is the machining time in hours.

Equation 5 Extra machining time needed for special parting planes.

$$M_s = f_p A_p^{0.5}$$

Table 4 The effect of the geometry of the parting plane on machining time.



Parting surface type	Factor (f_p)
Flat parting plane	0
Canted parting surface or one containing a single step	1.25
Two to four simple steps or a simple curved surface	2
Greater than four simple steps	2.5
Complex curved surface	3
Complex curved surface with steps	4

When the total machining time has been estimated the only thing left to do is to multiply it to the machining cost of the specific machine used.

3.3.1.2 Design for Injection Molding

Complex geometries can be created using injection molding. However, there are limits. For example, consideration must be taken to the fact that the mold must be able to be opened. Therefore, undercuts cannot be created using a regular mold. An undercut can for example be a hole which is perpendicular to the mold opening direction. To create these features moving and unscrewing mandrels can be incorporated into the mold.[84] Since sliding features usually increase the cost of the mold by an additional 15 to 30 percent, undercuts should be avoided whenever possible. For some special features it is, however, possible to create undercuts without sliding parts in the mold. Examples of these features are undercuts used for snap fit solutions. In these cases the parts can be bent away from the mold while the part is still warm so that the part can regain its old geometry. An example of how this can be done can be seen in Figure 19 a, and other types of methods for the creation of undercuts can be seen in Figure 19 b and c.[85]

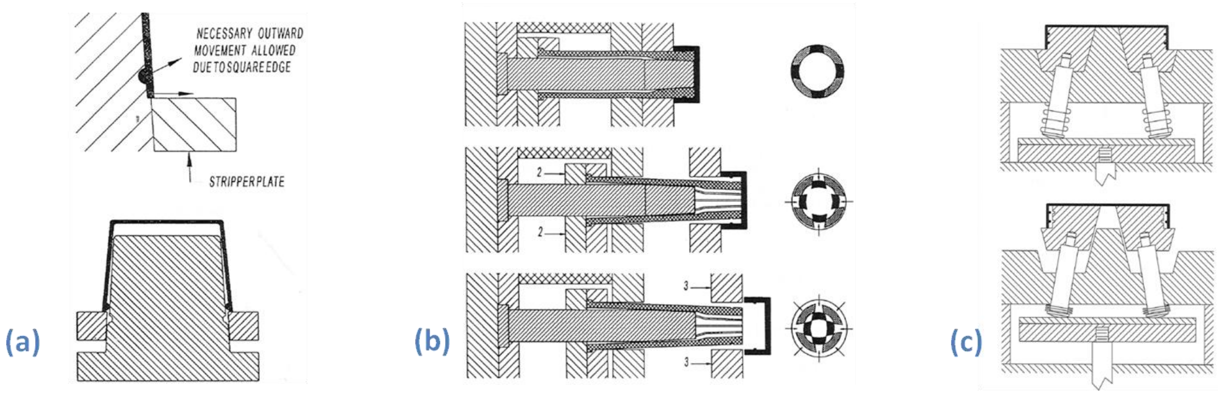


Figure 19 (a) Undercuts created by the use of stripper plate, (b) collapsible core, and (c) split core.

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[84] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

[85] Rosato, Dominick V. & Rosato, Donald V. (1986) *Injection Molding Handbook*. Van Nostrand Reinhold Company Inc. First Edition. New York.

Even wall thickness, thin walls, and round corners are design guidelines which were briefly mentioned in the chapter Design for Manufacturing and Assembly (DFMA) on page 15. Uneven wall thickness could result in a cascade of problems. Uneven walls increase the risk of uneven shrinkage of the parts. If uneven shrinkage occurs, the proportions of the part changes and this may cause problems in assembly. Uneven shrinkage could also result in warpage, which would change the geometry of the part. However, if uneven wall thickness really is necessary, the transitions should be smooth to ease the flow material and gates should be placed in thick sections. If gates are placed in thin sections the friction from the walls may prevent material to properly fill thick sections. Most uneven wall thickness problems are caused by the bad thermal conductivity of thermoplastics, and so is the problem with thick walls. Since the cooling time increases exponentially with increasing wall thickness, thin walls are preferable. If thick walls are designed due to mechanical stability reasons, it is recommended that these issues are solved by the use of a foaming material or by implementing ribs in the design instead. Foaming materials will be discussed further later on, and even though ribs in the design increase the cost of the mold, money is often saved in the long run by decreased cycle time. It should also be mentioned that too thin walls is not good either. This is because too thin walls obstruct the flow of material.[86]

That sharp corners can increase wear on molds has been mentioned. However, there is another problem with sharp corners in part design. Stresses are increased in these areas. This makes the corners brittle. For a recommendation of how corners should be design see Figure 20. The figure shows that R_1 should at least be 0.02 inches. This is equivalent to 0.508 millimeters.[87]

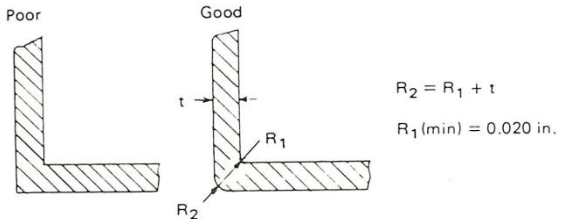

Figure 20 Corner design for injection molding.

Other potential problems which consideration must be taken to during design, are weld lines, porosity or voids, and sink marks. Weld lines can occur when the material flow is joined after being split. The material can for example be split by a cylinder in the mold, which purpose is to create a hole. The result is decreased strength compared to the rest of the part. There are mainly two reasons to why weld lines occurs. One is that the flow front of the plastic pressure air, moist and lubricant in front of itself. So when two fronts meet they capture impurities into the weld. The other is that the two fronts have decreased temperature. The result may be that the temperature of the front is not high enough to create a good weld.[88]

Problems like porosity or voids in a molded part can occur when the part has thick walls. Solidification of the material closest to the cavity wall in thick intersections may cause the forming of porosity or voids in

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[86] Ibid.
[87] Ibid.
[88] Ibid.

the centre of the wall when the material cools down. This is due to the thermal expansion of plastics. Sink marks can appear as bumps on the opposite side of a rib in the design. To minimize the risk of them, a rib should preferably have two thirds of the original wall thickness, somewhat dependant on material viscosity. For an illustration see Figure 21.[89]

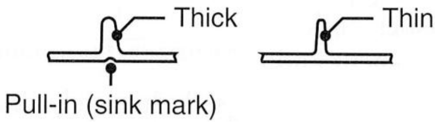

Figure 21 Sink mark.

3.3.1.3 Special Injection Molding Processes

In this chapter some special versions of injection molding are described.

3.3.1.3.1 Gas-Assisted Injection Molding[90]

In gas-assisted injection molding the mold is filled partly or almost fully by molten plastic. Then gas, usually nitrogen, is injected into the mold. This can be done through the gate or by a separate inlet. The gas fills the mold and pressures the molten plastic along the walls of the cavity. The gas always takes the paths with the least resistance. They are usually the sections with the thickest walls. When the gas has been injected, the pressure is held until the part has solidified. Sometimes the pressure must be increased during this stage to compensate for material shrinkage. After this, the pressure is released and the part is demolded.

There are many advantages of this process. For example, it does decrease cooling time for parts with thick walls by filling thick sections with air, and most thermoplastic materials can be processed. It also reduces part weight, material consumption, the risk for sink marks, and the risk for warping. However, the process is more complex than regular injection molding, and does therefore require people with experience. Experience from regular injection molding is not sufficient, since the processes are so different.

There is a special version of the process where water is used instead of gas. The water enables extra efficient cooling which further decrease cycle time.

3.3.1.3.2 Structural Foam Injection Molding[91]

Structural foam injection molding is a process used to produce large and thick parts. By using gas, usually nitrogen, which is mixed into the molten plastic before injection, bubbles are created in the injected polymer. Only a quarter to half the mold is filled during injection. The gas pressure forces the polymer to fill the rest of the cavity. The result is a part with foamed structure.

The benefits of the process are many. For example, only a tenth of the pressure from conventional injection molding is needed and parts with very thick walls can be produced. Furthermore, the parts

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[89] Ibid.

[90] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

[91] Ibid.

produced have better strength to weight ratio than parts produced with conventional injection molding and the part weight reduction can reach 10 to 15 percent. However, the there are drawbacks as well. The biggest one is the rough surface of the parts produced.

3.3.1.3.3 Overmolding

Overmolding, or multicomponent injection molding, is a several step injection molding process. There are three different types of overmolding. The first type is carried out just as a several step regular injection molding process. A part is molded and then laid in a new larger mold cavity with which a second injection is made. This can then be repeated to combine even more materials. The second type is carried out with the help of a rotational core mold. The process is similar to the first process. However, it is done automatically with the help of several complementary molds. A first injection is made, and then the core mold rotates 180 degrees to a new complementary mold where a second injection is made. The process can be adapted to three or more injections. For an example see Figure 22 a. The third type is done by the help of a mold with moving slides or cores. A first injection is made, the first gate is closed, the cores move to expand the mold, and a second injection is made from a second gate. Figure 22 b shows an illustration of the process.[92]

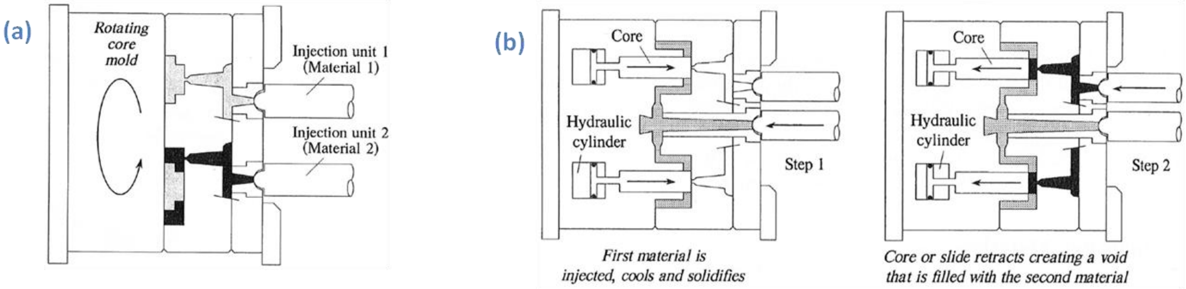

Figure 22 Overmolding processes.

The purpose of the process is to combine the properties of two or more materials, to create products with several colors, or to create movement between two parts in a product.[93] [94] Either way the combination of materials must be examined to ensure that purpose can be achieved. For example if movement is wanted, two different materials should be selected between which weak bonds are created.[95]

The benefit of the process is that no extra stage in manufacturing is needed, for example assembly. However, the investments needed are high. Either several molds must be created, or advanced automated systems must be acquired.[96]

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[92] Ibid.

[93] Ibid.

[94] Rosato, Dominick V. & Rosato, Donald V. (1986) *Injection Molding Handbook*. Van Nostrand Reinhold Company Inc. First Edition. New York.

[95] Ibid.

[96] Ibid.

3.3.1.3.4 Insert Molding[97]

Metal inserts can be placed in the mold prior to injection. When the molten plastic flows into the mold the insert molded into the part, and becomes a part of it.

Insert molding can be a way to minimize supplementary work, such as machining and screwing. However, the mold for the process is more expensive than the mold used in regular injection molding. It should also be noted that the inserts should not have sharp corners for the same reasons as to why the part itself should not; it build up stress.

3.3.1.3.5 Microinjection Molding

Microinjection molding is a process which can be used to produce parts with micrometer specifications. It can be used to produce very small parts in the rage of a few milligrams, normal sized parts with some features which are very small, or it can be used for normally sized parts with very tight tolerances. This can be achieved by heating the molds to temperatures over the glass transition temperature before injection. In some cases it is also necessary to evacuate the mold using a vacuum pump to ensure that trapped air does not prevent the molten plastic to entirely fill the cavity[98]. However, the heating of the molds extends the cycle time of the process. Another downside is that the level of waste from runners is often large in comparison to the material used for the part when producing small parts.[99]

The temperature of the mold can be raised by convection, conduction, induction, or by radiation from infrared lamps. Convection heating can be done either by water or oil circuits in the mold, or by hot air or steam. Conduction heating is usually done by incorporating electric or ceramic heating cartridges in the mold. A heat increase by 30°C/s and a cooling effect of 10°C/s has been achieved using these methods. Induction heating is carries out either by an inductor in the mold or as a cage around the mold. Thanks to recent developments of microinjection molding, the cycle time needed to heat and cool the mold has been greatly decreased.[100]

For a comparison between conventional injection molding and RHCM, see Figure 23. This has made the process frequently used to achieve smooth surfaces in one process. The process is also regularly used to create parts with less stress and invisible weld lines[101]. The recent developments have resulted in a name change of the process, which now more often is referred to as hot/cold thermal cycling, rapid heat cycle molding (RHCM).[102]

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[97] Ibid.

[98] Gornik, Christian (2004) *Injection Moulding of Parts with Microstructured Surfaces for Medical Applications*. Macromolecular Symposia. Volume 217. Issue 1. Page 365 – 374.

[99] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

[100] http://www.ptonline.com/articles/201004fa2.html. The article *Hot/Cold Thermal Cycling of Injection Molds Heats Up* from Plastics Technology. 2010-09-16.

[101] http://www.ptonline.com/articles/200805fa4.html. The article *Thermal Cycling of Injection Molds Boosts Surface Quality* from Plastics Technology. 2010-09-16.

[102] Ibid.

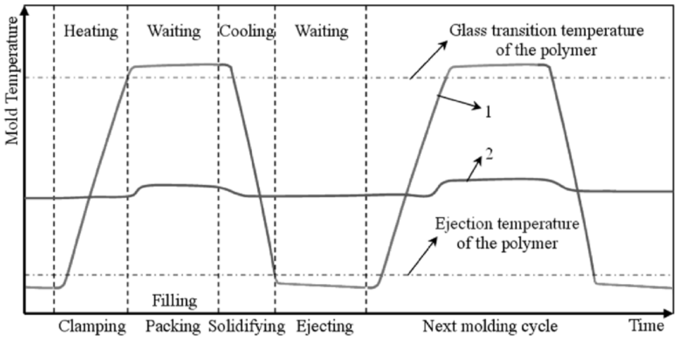

Figure 23 A mold temperature comparison between RHCM (1) and conventional injection molding (2).

3.3.1.3.6 Microcellular Molding

Microcellular molding uses a gas, often nitrogen or carbon dioxide, in a super-critical stage which is dissolved in the molted polymer before injection. The gas forms small bubbles in the polymer. The diameter of these bubbles is between 0.1 micrometer and 10 micrometer. In conventional foam molding process the diameter is approximately 250 micrometer. The bubbles reduce the viscosity and the glass transition temperature of the thermoplastic. This result in that the temperature and pressure used in the process can be lowered. Furthermore, the risk for warpage and sink marks is reduced. However, the process still has problems to produce parts with an even quality and with reaching a high enough production rate for mass production.[103]

Using a combination of this process and RHCM described above, microcellular molding parts can be produced with smooth surfaces. The process is using steam to heat and water-cooling channels to cool the mold. The extension of the cycle time is estimated to five percent..[104]

3.3.1.3.7 Fusible Core Injection Molding[105]

Fusible core injection molding is a way of producing parts with complex internal geometries. The process is somewhat similar to insert molding described above. First a core is manufactured from wax, a thermoplastic, or a tin-bismuth alloy. The core is then laid in the mold cavity and the molten plastic is injected around it. To get rid of the core, it can either be melted or dissolved by the use of chemicals.

The materials which can be used are many. However, the process is very expensive. This is due to the extra steps involved in the process compared to conventional injection molding and due to the extra large injection machine required by the process.

3.3.1.3.8 Injection-Compression Molding[106]

Injection-compression molding is, just as its name suggests, a process which combines injection molding and compression molding. First the polymer is injected into the mold cavity. The cavity is somewhat

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[103] Ibid.

[104] ? (2004) *The Smooth Way to Mold Microcellular Foam Parts*. Plastics Technology. Volume 50. Issue 12. Page 35.

[105] Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

[106] Ibid.

open at this stage. When the polymer has been injected into the mold, the cavity closes and thereby forces the polymer to entirely fill the mold.

This process produces parts with less internal stress and the risk of warpage is reduced. This is due to that the pressure is perpendicular to the wall surface. The reduced internal stress makes the process useful for optical products, such as CDs and lenses. However, the molds used are more expensive than the ones used for conventional injection molding and additional process control equipment is needed for the injection machine. The result is that the process is only used for mass production purposes.

3.3.1.3.9 Low-Pressure Injection Molding[107]

The usage of low-pressure injection molding results in reduced injection pressure, reduced clamp force, and therefore less expensive molds. This is achieved by optimizing the process with regard to these parameters and the usage of large gates. The optimization is carried out by sophisticated software which controls the injection speed and injection temperature.

Since the process is the same as conventional injection molding the same materials can be processes with no other drawback than the initial investment for the software and the initial set-up cost.

3.3.1.3.10 Thin-Wall molding[108]

The problem with creating thin-walled parts is that the cavity walls are cool and therefore makes the polymer solidify when it is reached. This makes it harder for the melt to fill the rest of the cavity since the flow path has decreased.

Thin-wall molding is a process which is used to produce parts which have a wall thickness which is less than 1.2 millimeters or part with a flow-length-to-wall-thickness ratio of more than 100:1. To create these parts the melt temperature can be increased by as much as 38°C to 65°C or the injection speed can be increased. Other ways to overcome these problems are the use of hot runners and multiple gates.

The downsides with thin-walled molding is that it sometimes needs more costly machines which can inject at a higher pressure, more costly molds that can cope with these pressure, or extensions in cycle time due to higher process temperature.

3.3.1.3.11 Other processes[109]

On top of the processes described above, there are others. For example, push-pull injection molding and multiple live-feed injection molding can control the orientation of fiber fillers. Lamellar injection molding and co-injection molding can produce parts with layers of several thermoplastics. In-mold decoration and in-mold lamination are processes which can create parts with printed foil or textile attached to their surfaces.

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[107] Ibid.
[108] Ibid.
[109] Ibid.

There are also processes which allows for other materials to be processed using injection molding. Reaction injection molding (RIM) is a process where thermosets can be produced by mixing the reactants just before they are injected into the mold. Compared to conventional injection molding, RIM has shorter cycle times and can be carried out at lower pressure. Rubber can be injection molded using rubber injection. Finally, metal or ceramic powder can be mixed into the polymer binder to create parts with complex geometries. After the part has been injection molded, the polymer binder is removed and the part is sintered.

3.3.2 Thermoforming

Thermoforming is a thermoplastic manufacturing process which is used to forms plastic sheets. The process can be divided into several stages. A sheet is first clamped to be held in place. Then it is heated to a temperature at which it can be formed by the use of a single faced tool. The forming of the sheet can be done in many ways, for example by the use of vacuum, air pressure, air blowing, or mechanical aids. Some of these processes can be seen in Figure 24. Quite often a combination of several is used. When it has been shaped to the desired form, it is kept in place until it is cooled enough so that it can be removed. The final stage is that the area which is used to keep the sheet in place is trimmed off.[110]

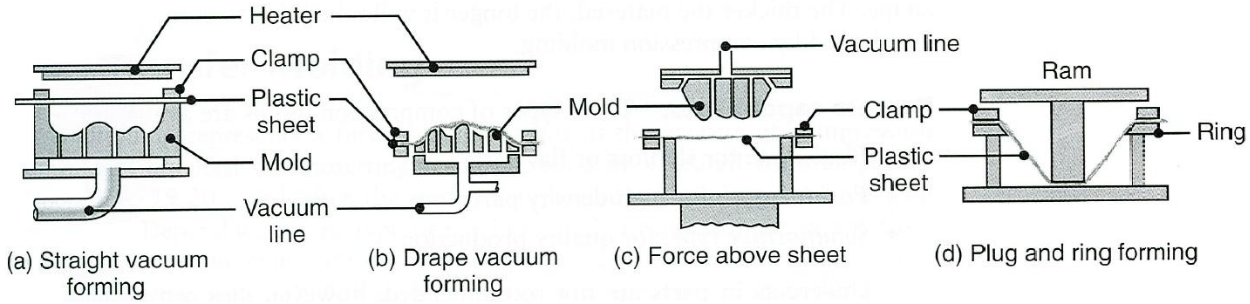

Figure 24 Different thermoforming processes.

3.3.2.1 *The Sheets*

The raw material used for this process is, as mentioned, a thermoplastic sheet. These has been created by processing plastic granulates in an extruder. Therefore the sheets are more expensive than granulates, which are used in most other thermoplastic processes. There is another big difference between processing of granulates and sheets. Sheets have history. This means that since the sheets already have been processed, they can have defects or a specific orientation. A sheet with orientation behaves differently in different directions. For example it may shrink more in one direction than another during cooling. Therefore the thermoforming manufacturer should select supplier with care, and properly examine the tolerances and general quality of the sheets supplied.[111]

The sheets used can be anything from just a few tenths of a millimeter to 50 mm. If the sheet has a thickness which is less than 1.5 mm the process is called thin-gauge forming, and if it is more than 3 mm it is called heavy-gauge forming. In addition to these categories there are sub-categories. Forming sheets

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[110] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[111] Schwarzmann, P. & Illing, A. (2001) *Thermoforming – A Practical Guide*. Hanser Publishers. First Edition. Munich.

which are less than 0.25 mm this is called film forming, and if it is more than 10 mm this is called plate forming.[112]

Thermoplastic sheets absorb moist from the air. However, the sheets cannot be processed when the sheets are moist. There are two solutions to this. The first solution is that the supplier sends the sheets packed in plastic bags. These bags are to be opened just before the sheet is processed. If the bags were to be opened a couple of hours before, the sheet absorb moist from the air and they are no good. The second solution is that the sheets can be dried in an air circulating hot oven. The time needed depends upon the thickness of the sheet and the type of thermoplastic.[113]

3.3.2.2 The Process

The process begins with the sheet being clamped to be held in place. The next step is that the sheet is heated. There are three ways to do this; conduction, convection, and radiation. Conduction, or contact heating, is when the plastic is in contact with a hot surface. The risk for overheating using this type of method is low, and energy losses can be kept small. This makes this method especially efficient for heating thin sheets. However, there is a risk that the sheet sticks to the surface which is heating it, and it can be hard to get uniform surface contact to ensure even heating. Convection heating is when the heat is transferred using a medium, for example air or water. This is for example the method used in the drying ovens mentioned earlier. Radiation heating is the most used method[114]. In this case infrared waves from ceramic, synthetic silica, halogen or gas heaters are used to heat the sheet. The four different methods of heating by ration have their individual pros and cons. For example, ceramic heaters are the most used method thanks to their robustness. Unfortunately, they are heavy and very slow when it comes to adjusting temperature. Silica heaters are even heavier and just as slow to heat up, but are faster to make adjustments in temperature. It could also be good to know that old silica heaters age much faster than ceramic heaters. That is, the old ones are not as good as new. Halogen heaters are extremely fast at adjusting temperature and are very light, but have different heating times for plastic with different colors. They also have a narrow radiation band. This makes halogen heaters unfavorable to use when the plastic sheets are very thin. The gas heaters are also fast. They have a similar heating performance to the ceramic heaters, but are much more sensitive when it comes to repeatability.[115]

One problem when heating the sheets is the low thermal conductivity of plastic. When the surface has a high temperature the center may still be cold. Therefore, it could be good to use heating method which has a broad range of radiation wavelengths when heating thick sheets. This is because some wavelengths are more easily absorbed by a certain type of plastic than others. As the wavelengths which are easily absorbed are caught by the surface, the others reach deeper. Another tip is that both sides should be heated if the sheet is thicker than 2.5mm.[116]

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[112] Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9.
[113] Schwarzmann, P. & Illing, A. (2001) *Thermoforming – A Practical Guide*. Hanser Publishers. First Edition. Munich.
[114] Ibid.
[115] Ibid.
[116] Ibid.

Another problem in the heating process is to measure the temperature of the sheet. This is can only be done at the surface without damaging the sheet. However, during preproduction stage inserts can be inserted into the sheet to enable operators to examine the effect of different heating intensities and durations. During production, temperature can for example be measured by the use of an infrared measuring device or a thermometer. Examples of infrared measuring devices are cameras and strips. Cameras have the problem that they also measure reflected infrared waves from the heating device. That increases the risk that the camera overestimates the heat. Strips on the other hand may leave permanent markings on the sheet. Thermometers can measure the temperature using a medium, for example air, or be in direct contact with the sheet. If in contact it may stick and damage the sheet. However if the thermometer is not in contact the temperature measured is less exact.[117]

When the correct temperature has been reached it is time to form the sheet. Which the correct temperature is, depends on the type of thermoplastic. For most types, the temperature is slightly over glass-transition temperature. However, some semi-crystalline thermoplastics the sheet may be needed to be heated close to the melt temperature, and for some others, even over.[118]

The forming sometimes begins with prestretching the sheet to ensure more uniform stretching. Prestretching is usually done if the H:D ratio is large or if the shape desired is complex. Large H:D ratio means that the depth of the draw, H, is large in comparison with the diameter or length of the sheet used, D. H and D can be seen in Figure 25. Other ways of describing draw ratio is area draw ratio and linear draw ratio. Area draw ratio is when the area of the sheet before and after the process is compared. This is the same as comparing the change of average wall thickness. Linear ratio is when an intersection of the sheet is studied. Before and after length of the intersection is compared. However, none of these ratios can alone determine the complexity of the process. Therefore none of them can be used to find out whether or not a prestretching is needed.

Prestretching can be done with air blowing, mechanical aid, or both. Mechanical aids used to prestretch must not be manufactured in a material which chill nor sticks to the sheet. Figure 26 shows a prestretching process which uses a combination of both methods. It should also be mentioned that some level of prestretching is always carried out due to thermal expansion of the plastic sheet and because the sheet often sags under its own weight when heated to the forming temperature.[119]

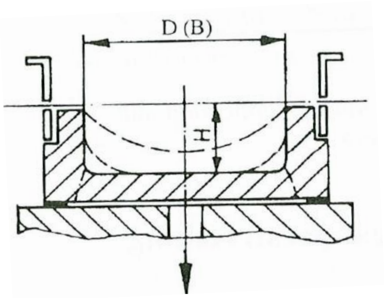

Figure 25 H and D in negative thermoforming.

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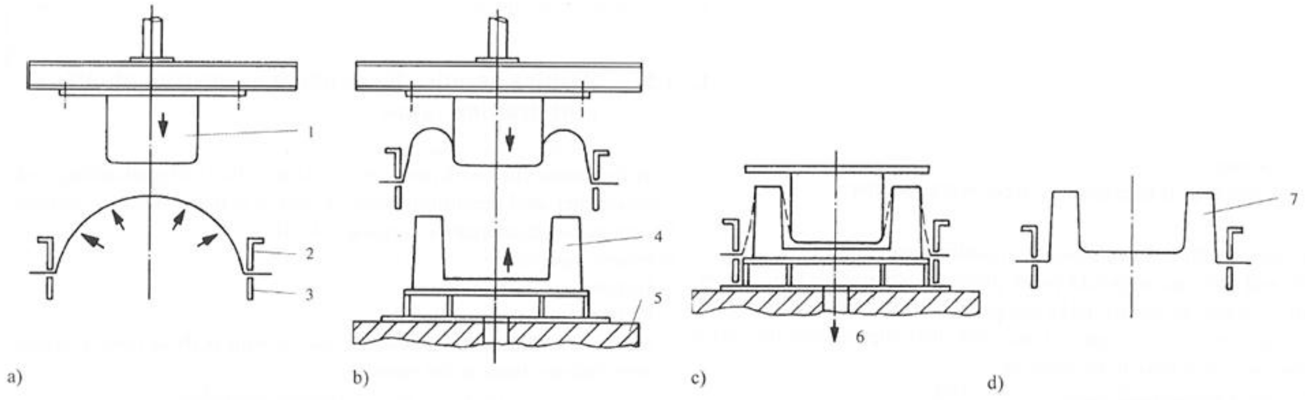
[117] Ibid.
[118] Ibid.
[119] Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9.

When the sheet has the right temperature and, if needed, has been prestretched, it is time to form the sheet. This is often done with a single faced mold in aluminum, epoxy, wood, steel, or fiber wood. The type of material used in the mold depends on the material shaped and the volume produced. For example, the materials shaped must not stick to the mold, and the larger volumes which are going to be produced the more advanced and wear-resistant material is selected for the mold. Therefore, epoxy, wood, and fiber board molds are mostly used for low volume prototyping. Especially since these are much worse heat conductors than aluminum, and therefore prolong the cycle time of the process. Another factor to take into consideration is the temperature used in the process. This is the reason that steel molds may be used for high temperature forming in those cases when aluminum cannot.[120]



Positive-negative-forming incl. preblowing and inversion
a) to d) processing sequence
1 prestretcher, *2* upper frame, *3* lower frame, *4* tool, *5* table,
6 vacuum, *7* completed article

Figure 26 Prestretching in mixed thermoforming.

The mold used can be male, female, or mixed. They are also called positive, negative, or androgynous. The types of molds can be seen in Figure 26 and Figure 27. Dependant on what type of mold used, the distribution of wall thickness is different. Corners often get thick or thin walls, and surfaces which are vertical to the movement of the sheet often get thick walls. Therefore, design teams should avoid sharp corners on parts which are going to be produced with thermoforming. Another thing that design teams should take into account when designing products is that since only one surface of the sheet is in contact with a mold, the geometry of only one side can be exact. Because even though finite element methods, computer aided engineering, computer aided machining, and pre production experimentation can help in determining wall distribution, it is still very hard to make an accurate determination of wall thickness.[121]

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[120] Ibid.
[121] Ibid.

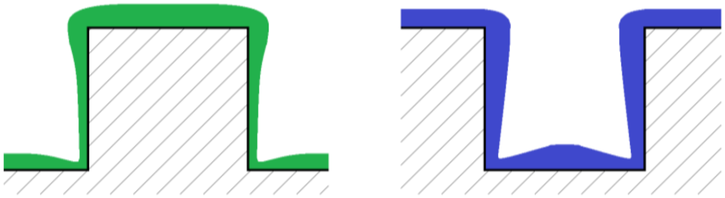

Figure 27 Male and female mold.

The way which sheets are formed using the molds somewhat differs. Sometimes mechanical dies are used to stretch the sheet. However, most common is the use of vacuum forming. In this case, small drilled holes in the mold suck the sheet to it. The holes are usually around 0.5mm. Larger holes would leave markings on the sheet. If greater precision in the geometry is needed or if the H:D ratio is large, air pressure can be applied. The air pressure is applied to the side which is not affected by the vacuum suction, to further press the sheet onto the mold. If the air pressure difference of the two sides of the sheet is larger than 1 ATM, the process is called pressure forming.[122]

One occasional problem in thermoforming is small bumps in the surface of the part. This may be due to air captured between the mold and the sheet. One solution to this is to roughen the surface of the mold by sandblastering, and by doing so allowing air to find its way to the holes. However, if really smooth surfaces are to be achieved, polishing the surfaces of the mold is ironically a solution.

Two important differences between injection molding and thermoforming are that most often only one mold is used for vacuum forming, and that mold is often made from aluminum. These two differences lower the initial cost of vacuum forming compared to injection molding, which uses two molds made from steel. Of course two molds are more expensive than one, and steel molds are much more expensive to machine.[123]

The next step in the process is demolding, that is removing the part from the mold. All thermoplastics shrink when cooled from their shape-temperature due to thermal expansion. This can be a problem when positive molds are used. Because when the sheet cools, it shrinks onto the mold. The result may be that the sheet gets stuck or even cracks. To avoid this problem the sheet must be removed before it has gotten to cold, but not before it has solidified enough so that the sheet gets damaged or deformed. Even for negative molds the future parts should not be cold longer than necessary in the molds due to the lengthened cycle times. Furthermore, a positive mold should have at least a half degree draft to further ease demolding. A negative mold does not have to have any draft if the demolding goes slowly. However, all thermoforming molds usually have a three to five degree draft.[124]

When the part has cooled enough so that it can be ejected, this can be done by either ejector pins or compressed air. However, this should be done carefully so that the part is not damaged. It is also good

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[122] Ibid.

[123] Alessandro Mattozzi, ABB Corporate Research and Development, Västerås

[124] Schwarzmann, P. & Illing, A. (2001) *Thermoforming – A Practical Guide*. Hanser Publishers. First Edition. Munich.

to bear in mind that the pats can continue to shrink, sometimes for days, after they have been ejected.[125]

Once the almost finished part has been demolded, the last thing to do is to trim off the material which was used to clamp the sheet in order to hold it in place. Usually between 25% and 75% is trimmed away. This material can be reused, but as mentioned in the chapter Thermoplastic Materials, thermoplastic age and cannot be reused to many times without aging.[126]

Some of the trimming methods used are machining, water jet cutter, laser cutter, and hot wire cutter. Different types of machining are sawing, milling, shear, and punching. The trimming methods all have their pros and cons. For example, saws may cause burr, are relatively slow, but are flexible. CNC milling machines, water jet cutting machines, and laser cutting machines are also flexible and can manage tighter tolerances but have higher acquisition costs. The type of trimming used in a specific case depends on, for example, sheet thickness, material, tolerances, number of parts produced, and production rate required.[127]

In general, thermoforming is a combination of a drawing and stretching process for thermoplastic products which have high area to thickness ratio. It is process with high levels of trim and high energy consumption. As a matter of fact, energy is often the single highest or the next highest cost. Its initial costs are much lower than injection molding but the production rate is slower. These factors make the process appropriate for short series production. The material for the process should preferably be an amorphous thermoplastic with low density, high thermal conductivity, and good hot strength. However, most thermoplastics can be formed using this method.[128]

3.3.2.3 Special processes

There are some special versions of thermoforming. For example, small undercuts can be manufactured if the material can cope with enough elastic deformation to be stretched out of the mold. For an example of an undercut see Figure 28. If the sheet is not elastic enough flexible molds or moving parts in molds must be used. [129]

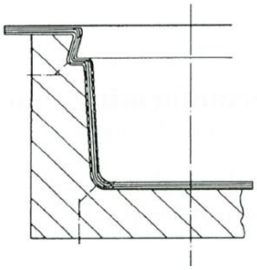

Figure 28 An undercut in thermoforming (demolding direction is up).

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[125] Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9.

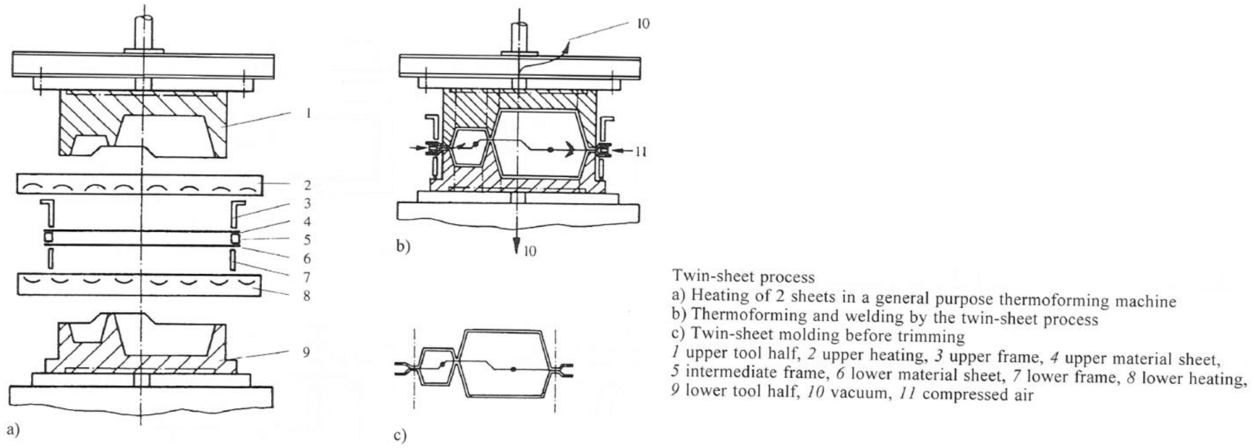
[126] Ibid.

[127] Schwarzmann, P. & Illing, A. (2001) *Thermoforming – A Practical Guide*. Hanser Publishers. First Edition. Munich.

[128] Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9

[129] Ibid.

Another special thermoforming process is the use of heat balanced molds. These can be heated either due to material requirements or to increase surface finish, and then cooled to improve cycle times. A final special process is twin-sheet thermoforming. In this process two thermoforming processes take place, and in the final stage are the two sheets joined to form a hollow structure. A sketch of the process can be seen in Figure 29.[130]



Twin-sheet process
a) Heating of 2 sheets in a general purpose thermoforming machine
b) Thermoforming and welding by the twin-sheet process
c) Twin-sheet molding before trimming
1 upper tool half, *2* upper heating, *3* upper frame, *4* upper material sheet, *5* intermediate frame, *6* lower material sheet, *7* lower frame, *8* lower heating, *9* lower tool half, *10* vacuum, *11* compressed air

Figure 29 Twin-sheet thermoforming.

3.3.3 Compression Molding[131]

Compression molding is a form of closed-die forging for thermosets and for thermoplastics. The material is placed in a heated mold at around 200°C and simply forced into the shape of the cavity. Pressure used is generally around 10 to 150MPa and the curing times are typically around 0.5 to 5minutes, but depend on wall thickness. So the production rate is much lower than for injection molding, but the dimensional stability better and the dies are usually less expensive since they also usually are less complex.

3.3.4 Rapid Prototyping Processes[132]

Rapid prototyping processes are all of those processes by which a single or a few solid parts can be produced from a CAD-file in an economical way. Examples of these processes are fused-deposition modeling, selective laser sintering, and stereolithography, see Figure 30. They are described below.

3.3.4.1 Fused-Deposition Modeling

Fused-deposition modeling (FDM) uses a small extruder to extrude thermoplastic in layers. The horizontal location of the extruder is controlled by a robot. Once one layer is finished, the plate which the parts is extruded onto, is lowered to enable the creation of the next. To be able to create features which are unsupported by the primary material, supportive material can be extruded to create supporting structures. The support material is removed when the part is finished.

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[130] Ibid.

[131] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[132] Ibid.

Since the process uses thin layers in the range of 0.25 to 0.5mm, the tolerance in the vertical, z, plane is limited. However, in the x-y plane tolerances can be as good as 0.025mm. Materials which can be used are for example ABS and Polycarbonate.

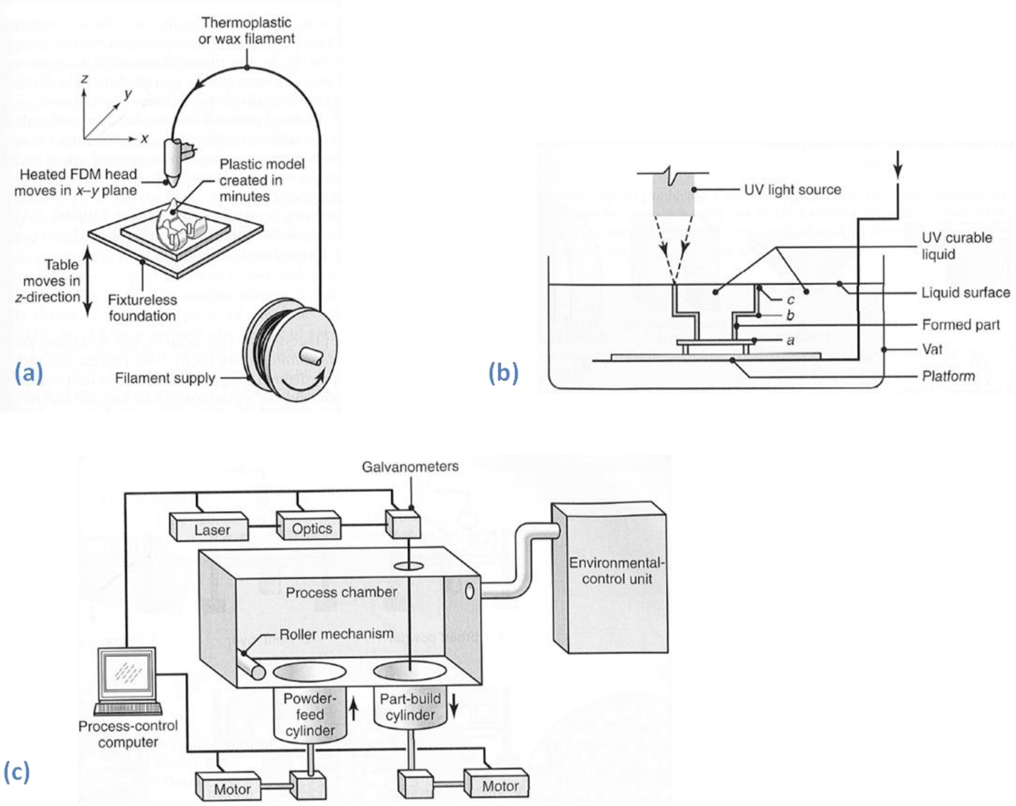


Figure 30 (a) Fused-deposistion modeling, (b) stereolithography, and (c) selective laser sintering.

3.3.4.2 Stereolithography

Stereolithography (SLA), just as FDM, builds a part layer by layer. It uses UV light which moves freely in the horizontal plane to locally cure liquid onto a platform. Once one layer has been created, the platform moves down one instance to enable the creation of the next. Support structures of perforated structures of the primary material can be used to support the primary geometry. This material is removed after the part is finished and before it is placed in a curing oven.

The tightest tolerances which can be achieved using this process are in the range of 0.0125mm, and materials which can be used are epoxies and acrylates. Furthermore, the liquid used generally cost $300 per gallon.

3.3.4.3 Selective Laser Sintering

Selective laser sintering (SLS) is a process which is similar to SLA. Instead of liquid this process uses powder which is melted by a laser which moves in the horizontal plane. More powder is fed by a feed cylinder and smoothened out over the lowered part by a roller mechanism when one layer has been created.

By this process a large variation of material can be used. For example polyester, ABS, polyvinyl chloride, polycarbonate, polyamide, and epoxies, but also metals and ceramics with binders can be used. The binder used to join metals and ceramics is often some kind of polymer.

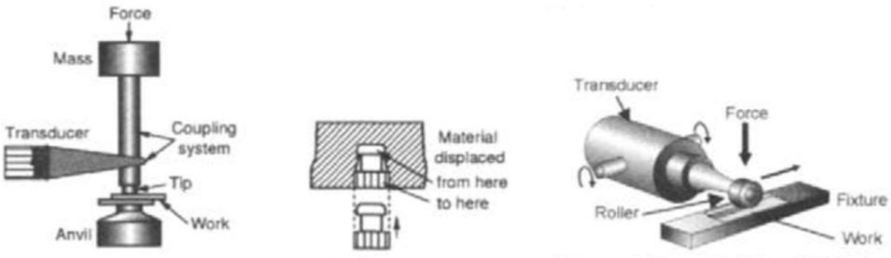
3.4 Joining Processes

This chapter describes joining processes for thermoplastics.

3.4.1 Ultrasonic Welding

Ultrasonic welding is a type of solid state welding. This means that no liquid or molten material is involved in the bonding. Instead the method uses pressure and vibrations which are perpendicular to the pressure applied. The frequency used is usually between 10 kHz and 75 kHz, and this is enough to locally heat the material to between one third and half of its melting temperature.[133]

This process can be used to join metals and plastics. It should also be noted that even dissimilar metals and plastics can be joined. Furthermore, the different versions of the process can be used to join parts with a lot of different geometries. Some of these processes can be seen in Figure 31. For example, ultrasonic insertion can be used to inert metal plugs into plastic parts, and ultrasonic seam welding can be used to seal plastic containers. [134]



Ultrasonic Welding (USW) **Ultrasonic Insertion** **Ultrasonic Seam Welding (USEW)**

Figure 31 Ultrasonic welding methods.

Ultrasonic welding is a process which offers moderate production rate, is rather easy to automate, produces no scrap, and the equipment needed is relatively inexpensive. However, some skilled labor is required. All of this makes the process useful for low to medium production runs.[135]

The quality of the result somewhat depends upon alignment of the parts which are to be joined and their geometry. Generally the results are bonds as strong as the base material, with moderate tolerances, and good surface finish.[136]

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[133] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[134] Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition.

[135] Ibid.

[136] Ibid.

3.4.2 Friction Welding[137]

Friction welding is, just as ultrasonic welding, a type of solid state welding. In this process two rotating rods are pushed together. The friction causes the material to melt and form a joint. The process can be used for many materials, for example metals and thermoplastics. An illustration of the process can be seen in Figure 32.

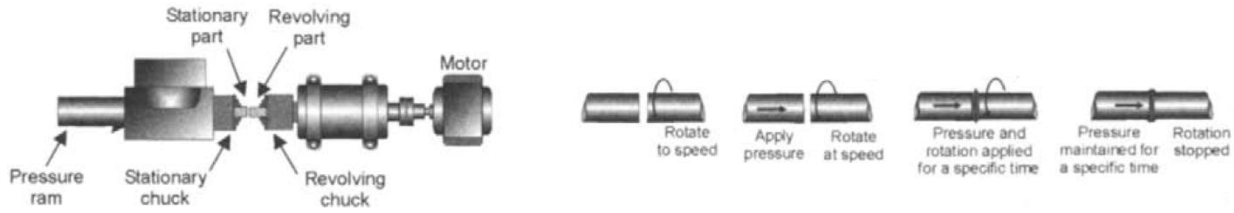

Figure 32 Friction welding.

The process is economical for low volumes, even though the equipment needed is expensive. In most cases some excess material is created, this can be removed using grinding or machining.

3.4.3 Laser Welding[138]

Laser, a high power density narrow beam of light, can be used to join parts. The process requires that one of the materials joint is laser transmittable and the other absorbs the energy of the laser. This causes the local heating and melting of materials, and thereby the forming of the weld. The process has a moderate production rate, high power consumption, short set-up times, high equipment costs, and is economical for low to medium production runs.

Laser welding is most suitable for welding sheets and can be used to join parts with a thickness of between 0.1 millimeter and 20 millimeter.

3.4.4 Gas Welding[139]

In gas welding, fuel and oxygen burns and melts the material of the parts which are to be joined. The production rates are usually very low and the tolerances are usually ±1 millimeter. However, it is economical for short production runs, can be used for great variations in geometries, and has low equipment costs.

3.4.5 Adhesive Bonding

There is a large amount of different adhesives. For example, there are thermoplastic, thermosetting, rubber, and natural animal adhesives. The adhesive can be applied in the form of, for example, liquids, gels, pastes, tapes, powders, and rods, and cured by the use of, for example, heat, pressure, time, chemical catalysts, or a combination of these. Using this wide selection, most materials, and combinations of materials can be joined.[140]

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[137] Ibid.
[138] Ibid.
[139] Ibid.
[140] Ibid.

High production rates can be achieved with adhesive bonding, especially if the process is automated. However, curing times vary between a few seconds to hours.[141]

The process can be used for short series production since the required equipment is not very expensive, even though fixtures generally are needed to hold the parts in place during curing.[142] The total process cost depends upon bond specifications. For example, adhesives that are able to withstand high temperature are more expensive than those which are not. [143]

The quality of the bond partly depends upon the type of bond. Different types of bonds can be seen in Figure 33. However, it also depends upon how well cleaned the joint surfaces are. Any dirt in the bond can greatly reduce bond strength.[144]

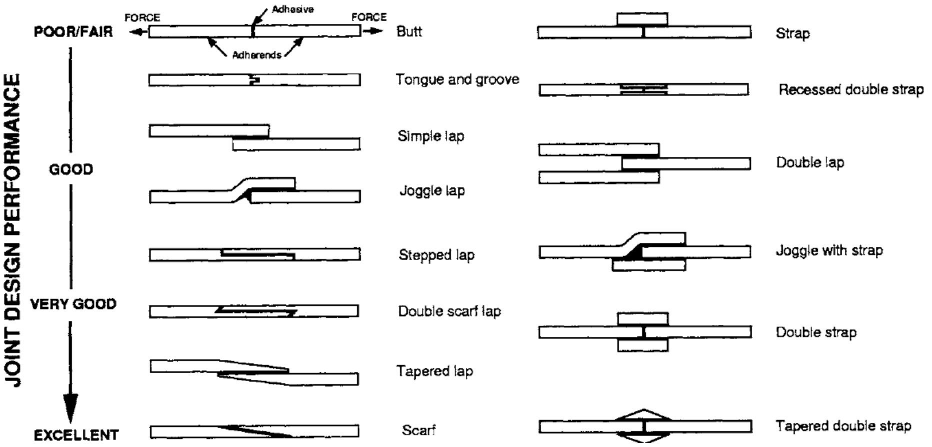

Figure 33 Joint designs using adhesive bonding.

To improve the joint even further, adhesives can be used in combination with other joining methods, such as mechanical joining.[145]

3.4.6 Thermoplastic Welding[146]

In thermoplastic welding the joint is heated by a gas heater so that it is softened. Then, a consumable filler material is added to ensure that the joint is sealed. The consumable material is same material as the parts which are to be joined. An illustration of the process can be seen in Figure 34.

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[141] Ibid.

[142] Ibid.

[143] [143] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[144] Ibid.

[145] Ibid.

[146] Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition.

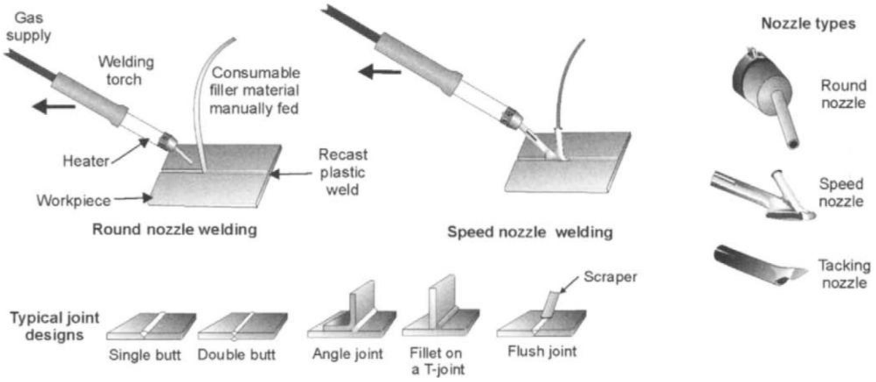

Figure 34 Thermoplastic welding.

The production rates of the process are very low, usually around 1.5 meters per second. However, since the equipment costs are low and the process is flexible, it is suited for short series production.

The quality of the joint is fairly good. For example, the weld strength is usually around 50 to 100 percent of the base material, surface finish is fair, and tolerances are around ±0.5mm.

3.4.7 Mechanical Fastening[147]

A mechanical fastening system uses a separate device or an integral component to join two or more other parts. These systems can be divided into three sub-groups; permanent, semi-permanent, and non-permanent. A permanent joint cannot be opened without severe damage to the parts which are joined. Examples of this type of systems are riveting, stapling, and seaming. These and more permanent systems can be seen in Figure 35.

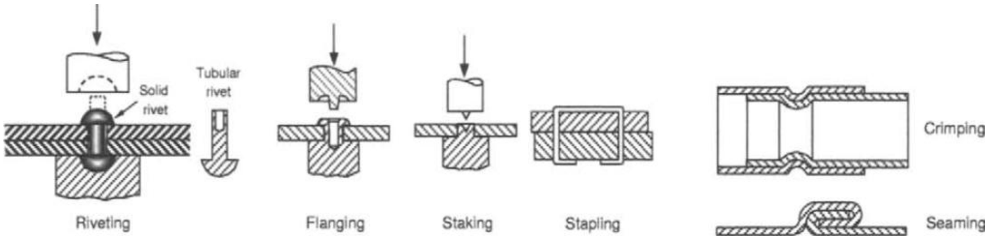

Figure 35 A selection of permanent mechanical fastening systems.

A semi-permanent joint can be opened a limited amount of times, and not without some damage to the joint parts. Examples of these joining systems are snap-fit, blind rivet, and press-fit. These can be seen in Figure 36. Semi-permanent joints are usually used when the parts have to be able to be opened at some point, but not on regular basis. However, if regular disassembly is needed, the joint must be done by the use of a non-permanent fastening system. These can be opened regularly without damage to the parts joined.

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[147] Ibid.

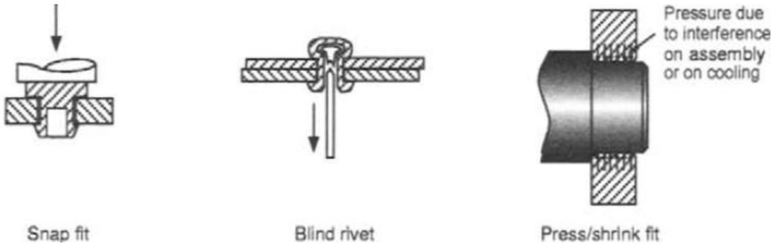

Figure 36 A selection of semi-permanent mechanical fastening systems.

Examples of non-permanent systems are retaining rings, self-tapping screws, and bolts with nuts. These and other examples can be seen in Figure 37. A problem which could arise with these types of threaded fasteners is that they might unscrew automatically if the joint is exposed to vibrations. This problem can be solved by the use of special purpose screws and bolts.

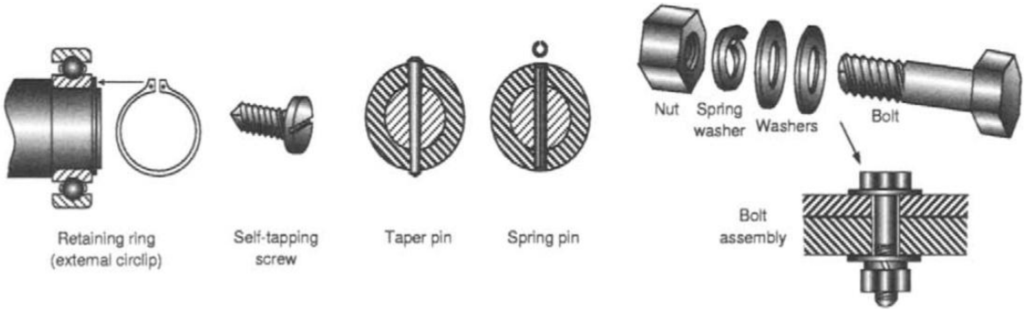

Figure 37 A selection of non-permanent mechanical fastening systems.

Most materials and combination of materials can be joined by mechanical fasteners. However, consideration needs to be taken to combination of materials so that corrosion does not occur.

The production rate varies greatly, and depends upon level of automation; the higher the level of automation, the higher the production rate, and the larger volumes must be produced to spread the large initial investment of setting up an automated system. Snap-fits, which are usually used for plastic parts, most often requires large volumes as well. This is because snap-fit solutions require advanced part geometries. Since molds used to mold plastic parts gets more expensive as the part geometry gets more advanced, large volumes are required to spread the cost of an advanced mold.

Other mechanical fasteners can, however, be economical for small series. That is if the level of automation is low, and that it is acceptable that the production rate is low.

The quality of these very flexible systems very much depends on joint design and type of fastener. That is, it can be very good or very bad.

3.5 Coating Materials and Processes

Some of the most common reasons to why a part should be coated are to increase resistance to both or either corrosion and wear. The only alternative to coat the part if this is to be achieved, is to manufacture the entire part in a material with the required properties. This is usually very expensive.[148]

The different types of wear can be divided into three categories; abrasive, adhesive, and fatigue. Abrasive wear occurs when the bodies are in contact with and move relative to each other. In this case, the body with the harder material grinds material from the other. A subset of abrasive wear is erosive wear. This is when small particles hit a surface with enough force so that material is removed from the surface. Adhesive wear also occurs between two bodies, but in this case the material is not machined. Instead the surfaces are welded together because of localized high temperatures. As the bodies continue to move some material is torn off from the body with the weaker material, and thereby transferred to the other body. Fatigue wear occurs when repeated loads lead to cracks in the material. The cracks can be located either at the surface or below it.[149]

How well a material is able to withstand wear depends on many factors. For example, it depends on its hardness, elastic modulus, fracture toughness, thermal conductivity, adsorption characteristics, and chemical resistance.[150]

The types of corrosion can also be divided into three categories. These are dry, wet, and stress enhanced corrosion. All three depends on chemical processes which degrade material. Dry corrosion is when these reactions occur in a dry environment, usually involving some gas. In wet corrosion there is some liquid involved in the reaction. Stress enhanced corrosion is the name for when corrosion occurs in an otherwise noncorroding environment due to high stress levels.[151]

The cost of wear and corrosions problems arose to more than $300 billion in USA during 2001.[152]

The selection of coating material and process usually begins with an examination of the environment of the part to be able to discover wear and corrosion problems. When this is done, the type of wear and corrosion can be established. This information helps selecting coating and process candidates. The candidates are then further evaluated with other criteria to be able to select a combination of coating material and process. A general guide for selecting primary candidates can be seen in Table 5, and some of the criteria to take into consideration when making the final selection can be seen in Figure 38. In Table 5 there are some abbreviations of the process names. TSC, PVD, CVD, ElsP, and EP stands for thermal spraying coating, physical vapor deposition, chemical vapor deposition, electroless plating, and electroplating, respectively.[153]

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[148] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.
[149] Ibid.
[150] Ibid.
[151] Ibid.
[152] Ibid.
[153] Ibid.

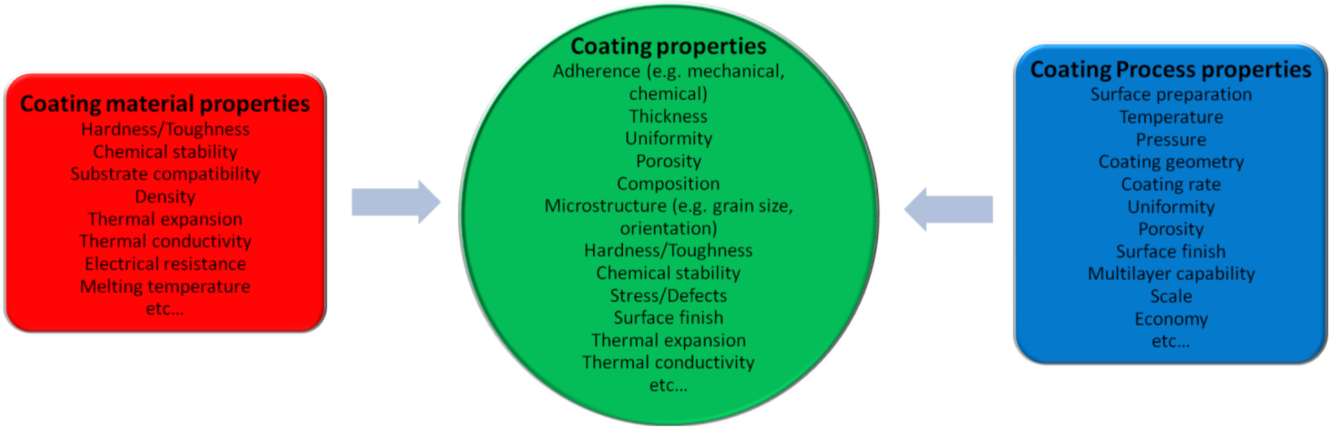
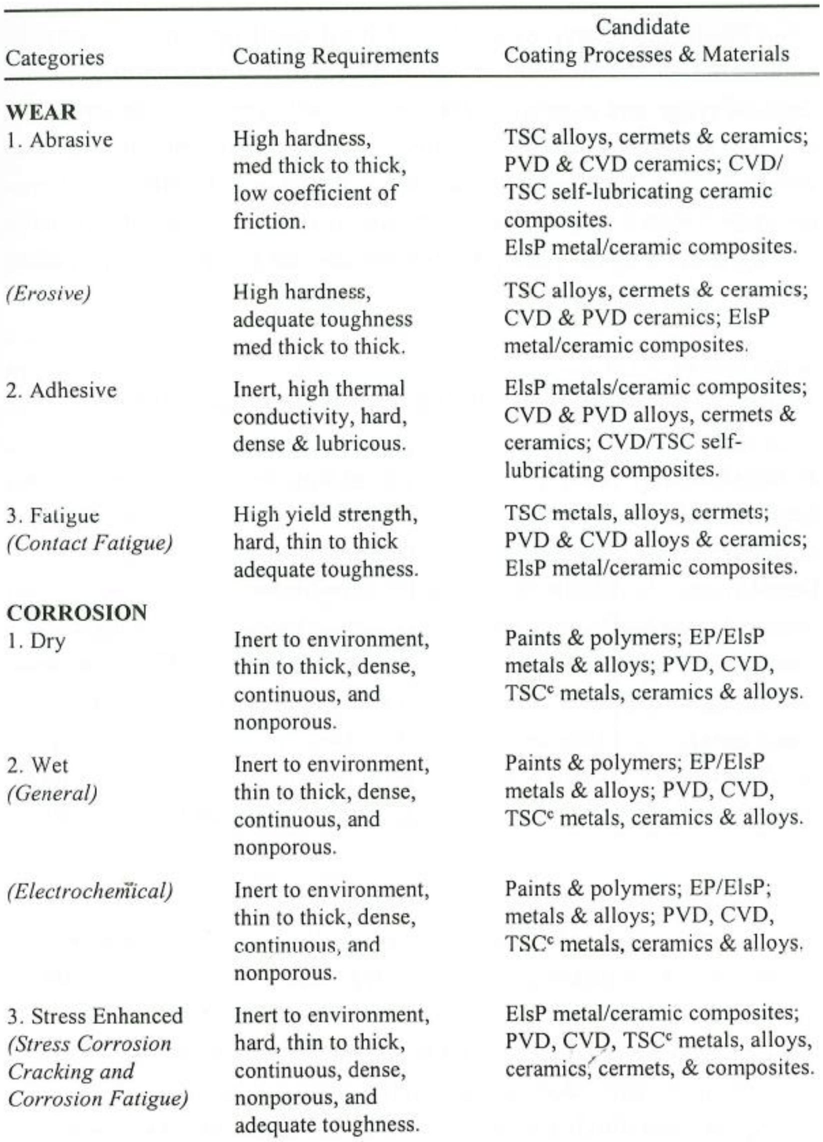


Figure 38 The effect of selection of coating material and process on the coating properties.

Table 5 Coating material and processes candidates based on type of wear and corrosion.



Categories	Coating Requirements	Candidate Coating Processes & Materials
WEAR		
1. Abrasive	High hardness, med thick to thick, low coefficient of friction.	TSC alloys, cermets & ceramics; PVD & CVD ceramics; CVD/TSC self-lubricating ceramic composites. ElsP metal/ceramic composites.
(Erosive)	High hardness, adequate toughness med thick to thick.	TSC alloys, cermets & ceramics; CVD & PVD ceramics; ElsP metal/ceramic composites.
2. Adhesive	Inert, high thermal conductivity, hard, dense & lubricous.	ElsP metals/ceramic composites; CVD & PVD alloys, cermets & ceramics; CVD/TSC self-lubricating composites.
3. Fatigue *(Contact Fatigue)*	High yield strength, hard, thin to thick adequate toughness.	TSC metals, alloys, cermets; PVD & CVD alloys & ceramics; ElsP metal/ceramic composites.
CORROSION		
1. Dry	Inert to environment, thin to thick, dense, continuous, and nonporous.	Paints & polymers; EP/ElsP metals & alloys; PVD, CVD, TSC^c metals, ceramics & alloys.
2. Wet *(General)*	Inert to environment, thin to thick, dense, continuous, and nonporous.	Paints & polymers; EP/ElsP metals & alloys; PVD, CVD, TSC^c metals, ceramics & alloys.
(Electrochemical)	Inert to environment, thin to thick, dense, continuous, and nonporous.	Paints & polymers; EP/ElsP; metals & alloys; PVD, CVD, TSC^c metals, ceramics & alloys.
3. Stress Enhanced *(Stress Corrosion Cracking and Corrosion Fatigue)*	Inert to environment, hard, thin to thick, continuous, dense, nonporous, and adequate toughness.	ElsP metal/ceramic composites; PVD, CVD, TSC^c metals, alloys, ceramics, cermets, & composites.

No matter which coating material or process is selected, it is still important to keep the surface, which is to be coated, clean. Two common ways of testing this is wiping the surface with a cloth and check if it gets dirty, and pouring some water onto the surface. If the water forms droplets, instead of spreading evenly, the surface is dirty.[154]

In the rest of this chapter, some typical coating materials and some coating processes for hard coatings are introduced. Hard coatings are for example coatings with good tribological properties. This means properties with good resistance to wear and supplies low friction. It should also be mentioned that there are a lot of special versions of the processes presented. [155]

3.5.1 Coating Materials

Below typical coating materials are described.

3.5.1.1 Polymer Coatings

There is a large amount of polymer coatings, most of which are used as corrosion protection. This can also be seen in Table 5. There is also a large amount of coating processes for polymers, both physical and chemical.[156]

3.5.1.2 Metal Coatings

The properties of a metal coating depend upon the type of metal applied to the substrate. Some are better for corrosions protection, and some are better for wear resistance and to decrease friction.

The coatings may be applied to substrates by the use of molten metal, as atoms or ions, or by the use of a chemical process. Examples of liquid metal processes, which use molten metal, are galvanizing and thermal spraying. The latter is explained further down. The former is a process where the iron or steel part is dipped into a bath of zinc. This is done to protect the part from corrosion. However, the coating is not hard, so the layer will easily wear away.[157]

Metal coating processes which are based on depositing atoms are vacuum evaporation and sputtering. These are physical vapor deposition processes which are further explained below. Chemical vapor deposition is the chemical way of applying metal coatings. This process is also explained further down.[158]

Another chemical coating process is electroplating. In this process the substrate and the metal used for coating is put in a bath of water-based electrolytic solution. An illustration of the process can be seen in Figure 39. The coating material becomes the anode and the substrate the cathode. Metal ions then wander from the anode onto the cathode and form the coating. Typical metal coatings which are deposited using electro plating are nickel for corrosion resistance, copper for corrosion resistance and electrical conductivity, and chromium for corrosion resistance and wear. Electroplating is a flexible process in the sense that simple or complex and large or small parts can be coated. However, sharp

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[154] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[155] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

[156] Tracton, Arthur A., et al. (2006) *Coating Technology Handbook*. Taylor & Francis. Third Edition.

[157] Ibid.

[158] Ibid.

corners in the geometry should be avoided if the coating thickness must be uniform. Substrates needs to be conductive, but even plastics can be coated with electroplating if they are pretreated in a electroless nickel plating process. Electroless plating is a similar process to electroplating. However, it is a chemical process, conducted without the use of an external source of energy. This enables the coating of plastics, but also ceramics, with for example copper or nickel.[159]

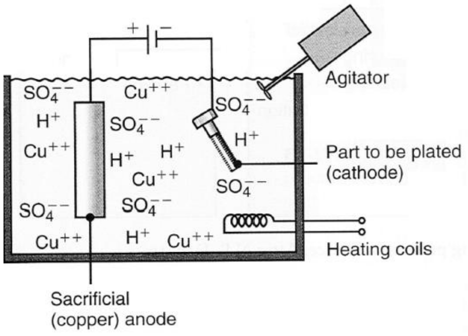

Figure 39 Electroplating.

3.5.1.3 Solgel Coatings

Solgel coatings is the family name for all of those coatings which undergo a solgel transition process. This is the process when a solution or sol solidifies into a rigid and porous mass. A solution is a single-phase liquid, and when small particles are solved in a liquid medium it is called a sol.[160]

The sol or solution can be applied to the substrate by spinning, dipping, flowing, or spraying. Most often, this is carried out at room temperatures. However, heating is usually needed to cure the coating. Some of the processes can be seen in Figure 40. The result is usually a 1µm coating with uniform thickness, even when using substrates with complex geometries. Most substrate materials can be coated, for example polymers, ceramics, and metals.[161]

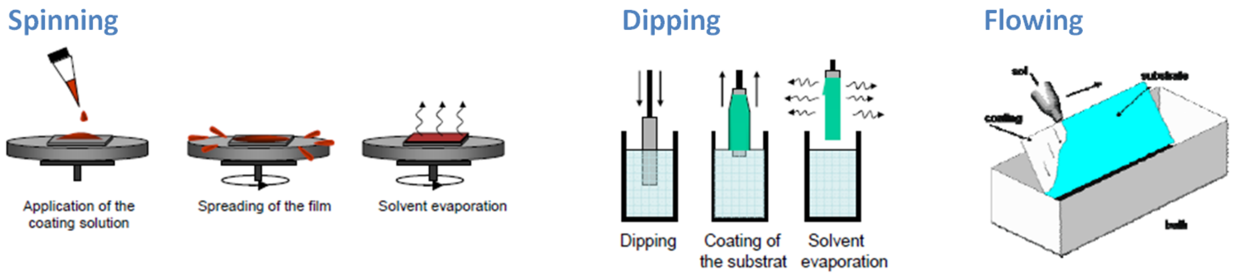

Figure 40 Solgel coating processes.

Solgel coatings have several applications. It can for example be used as an abrasion coating due to its high hardness, and as a protective coating to provide chemical resistance. The equipment needed to

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[159] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[160] Tracton, Arthur A., et al. (2006) *Coating Technology Handbook*. Taylor & Francis. Third Edition.

[161] Ibid.

carry of the processes is inexpensive, especially compared to coating processes which require vacuum, and the waste of coating material is small because excess material can be recovered and reused.[162]

3.5.1.4 Silicone Hard Coatings

Silicone hard coatings have good abrasion resistance and are chemically resistant. They can be applied by spinning, dipping, flowing, and spraying. See Figure 40 for illustrations. However, before coating, the substrate must be cleaned properly with for example solvents. Cure times after coating of the substrate varies between five minutes to three hours. The coating generally cost $70 to $200 per gallon, and a gallon can be used for between 300 square feet to 2000 square feet.[163]

3.5.1.5 Ceramic Coatings

Ceramic coatings are famous for their harness, corrosion behavior, and thermal stability. Common coatings are aluminum oxide, alone or in combination with titanium oxide, partially stabilized zirconium oxide, and chromium oxide.[164] These coatings are usually applied by thermal spraying processes which are described below.[165]

Titanium nitride is another ceramic coating, usually applied to machining tools by either physical vapor disposition or chemical vapor deposition, both of which are explained further down.

3.5.1.6 Diamond-Like Carbon and Diamond Coatings

Diamond, which has a hardness of 7000 to 8000 HK, is the hardest substrate known. This is why diamond-like carbon, DLC, is so wear resistant. Furthermore, diamond has high thermal conductivity, but is brittle and decomposes at 700^{o}C.[166]

There are several ways of applying diamond coatings, for example plasma assisted chemical vapor deposition (PACVD), physical vapor deposition (PVD), and ion beam methods. However, PVD processes are not used extensively for diamond coating. PACVD and PVD processes are explained further down. Ion based methods is a generic name for two type of processes. In one of them, an ion accelerator is used to shoot beams of carbon atoms onto the surface of the substrate. The very short and localized, but huge, increase in temperature, combined with the impact of the atom, creates the diamond coating. For example, in the process can temperatures as high as 75,000^{o}C and pressures as high as 100,000 be reached. The other ion beam method is called ion beam enhanced deposition (IBED). In this process a primary ion beam applies the coating to the surface of the substrate, and a second bombards it. [167]

The benefit of PACVD is that the equipment used is less expensive than ion based methods. However, substrate temperatures are usually kept around 850^{o}C to 1050^{o}C for high quality PACVD diamond coatings. At the same time, temperatures can be kept lower than 100^{o}C for IBED. Deposition rates for

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[162] Ibid.
[163] Ibid.
[164] Ibid.
[165] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.
[166] Ibid
[167] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

PACVD ranges from 0.1µm/h to 1mm/h. Deposition rates for IBED are very low, usually less than 0.1µm/h. The very low deposition rates, combined with the high equipment cost, are the reasons why IBED is not used to a large extent. [168]

Another way of applying diamond coatings is by the use of finished diamond films. The films are laser cut to fit the geometry of the substrate and then brazed onto its surface.

3.5.2 Coating Processes

In this chapter are some typical coating processes described.

3.5.2.1 Thermal Spraying

Thermal spraying coating is a process which can apply metal, ceramic, glass, and plastic coatings to surfaces[169]. The coating material is melted and then transferred to the substrate as droplets. The droplets solidify when it reaches the substrate, and by doing so form the coating. Even though the temperatures of the droplets can be very high, the temperature of the substrate rarely exceeds 150°C. This does that even wood and plastics substrates can be coated.[170]

There are two categories of thermal spraying; combustion spraying and plasma spraying. Illustrations of the processes can be seen in Figure 41. Combustion spraying uses an oxygen-fuel flame to melt the material. The material, which is in the shape of a wire or powder, is then applied to the substrate by the pressure of the exploding gas. Examples of fuel-gases are acetylene, methyl acetylene, methane, propane, and propylene. Some of these burn at temperatures up to 3000°C and deliver the coating particles at a speed of up to 900m/s.

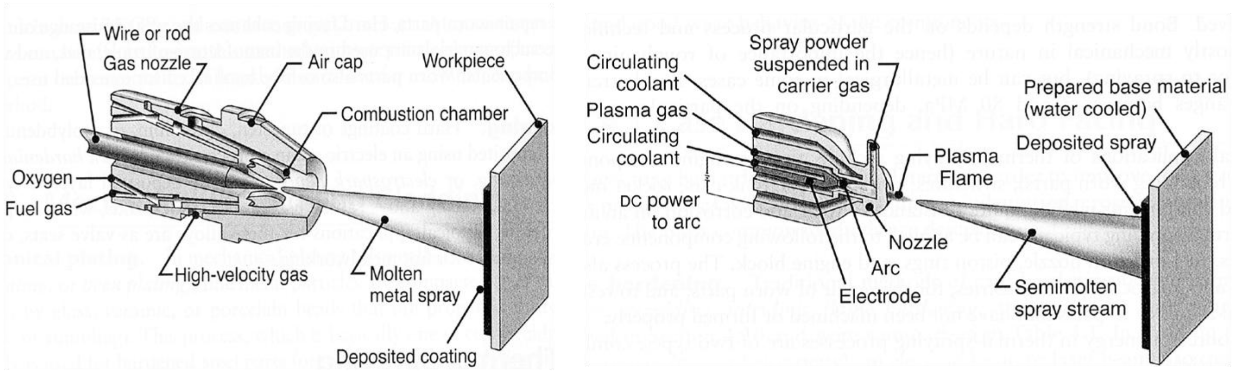

Figure 41 Left: Thermal wire spray, Right: Plasma spray.

Plasma spraying is a somewhat similar process. The difference is that there is an electric arc which heats and ionizes the plasma gas. The gas is usually argon, nitrogen, helium, or a combination of these. As the gases are heated they expand and accelerate out of the nozzle. The result is a coating with an approximate thickness between 50µm and 250µm. Temperatures over 10 000K can be reached in this

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[168] Ibid.

[169] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[170] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

process due to exothermic reactions, and the particles are delivered in speeds between 300 and 700m/s. [171]

3.5.2.2 Vapor Deposition

Vapor deposition is the generic name for the coating processes which use vapor of the coating material to coat the substrate. The vapor reacts chemically with the surface of the substrate to form a coating which usually is a few µm thick. Coating materials can be metals, alloys, carbides, nitrides, borides, ceramics, or oxides, and these can be applied to most substrate materials. These processes are for example coat tools, dies and other wear surfaces.[172]

There are two types of vapor deposition types; physical vapor deposition and chemical vapor deposition. Comparing the two, it can be said that the equipment cost for PVD is generally much lower than CVD, that PVD has higher restrictions of the shape complexity of the substrate, and that PVD is the more versatile when it comes to which materials can be used for coating and as substrates. Using a PVD process, almost any coating material can be used to coat almost any substrate material. The exception is that certain polymers cannot be used for coating.[173]

3.5.2.2.1 Physical Vapor Deposition

In physical vapor deposition, PVD, the coating material is deposited physically, rather than by chemical reactions as the case is for chemical vapor deposition. With this physical process, deposition rates up to 25µm/s can be reached.[174] This means that 25µm of coating is transmitted per second, which is relatively very high. PVD is divided into three generic types of processes. These are vacuum deposition/arc deposition, sputtering, and ion plating. All of these processes are usually carried out at evaluated temperatures around 200ºC to 500ºC.[175]

The vacuum deposition process begins with heating of the coating material in vacuum to the extent so that that is evaporated. For example can resistance, induction, electron beam, and laser heaters be used. Of these are resistance heaters simplest and the least expensive. Laser heaters are usually very hard to set up and consideration must be taken to the type of material. This is because certain materials absorb certain types of wavelengths. Finally, the benefit of electron beam heating is that it can accomplish very high power density levels. After heating, the evaporated material travels the usually 20cm to the substrate and solidifies on its surface. Using this process, uniform thicknesses can be achieved and complex parts can be coated.[176]

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[171] Ibid.

[172] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[173] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

[174] Ibid.

[175] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[176] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

Arc deposition is a version of vacuum deposition process which can be seen in Figure 42. The process usually uses several evaporators. Electric arcs heat the coating material and ionize the vapor[177]. This creates plasma which coat the substrate. Arc heaters enables deposition rates up to several µm/s and substrate temperatures as low as 70⁰C. This can be compared to the usual deposition rates for vacuum deposition, which are around 100 to 1000nm/s. The low substrate temperatures make it possible to coat polymers as well.[178]

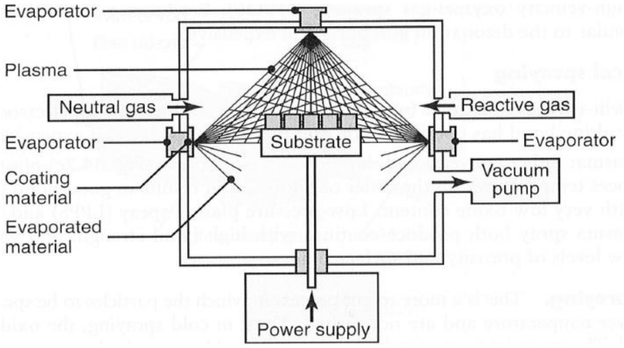

Figure 42 The physical vapor deposition process (vacuum deposition).

Another type of PVD process is sputtering. A sketch of the process can be seen in Figure 43. In this process an electric field ionize an inert gas, usually argon. This makes positive ions bombard the coating material, which is the cathode. The bombardment causes small particles to be sputtered away from the coating material and onto the substrate.[179]

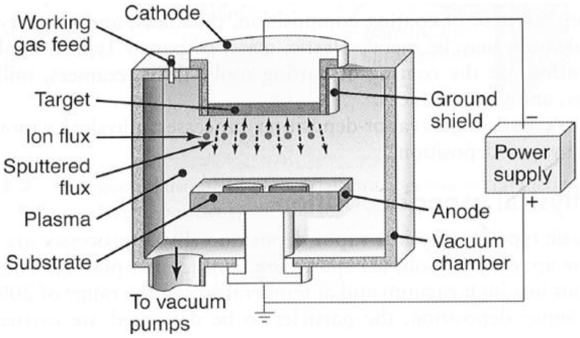

Figure 43 The sputtering process.

To increase the flow of sputtered particles, a magnetic field can be used. The field holds the positive ions close to the coating material and thereby increases the chance that they will lose their energy to it. This

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[177] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[178] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

[179] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

process is called magnetron sputter deposition. Another version of the process is RF sputter deposition. Here, RF frequencies are used so that non conductive coating materials can be used for coating.[180]

Reactive sputtering is when the inert gas is replaced by a reactive gas, for example oxygen. What happens in this case is that the sputtered atoms oxidize. This process is used for depositing carbide, nitride, and thin polymer coatings.[181]

The last process described here is ion plating. This is a generic name for processes which combine vacuum deposition, sputtering and CVD. Figure 44 shows an illustration of the process. In this process, coating material is first vaporized by thermal energy, vaporized by momentum, or supplied as a vapor. Thermal energy is used in vacuum deposition, momentum is used in sputtering, and the coating material is supplied as a vapor in chemical vapor deposition. An electric field causes a glow discharge of the vaporized coating material which generates plasma. The vaporized atoms are partly ionized. Approximately one percent of the atoms are ionized. However, these bombard the substrate and stick to the surface. As the atoms hit the surface they also sputter away atoms from the substrate. This is of less importance, but as more and more coating material stick to the surface, the risk increase that the coating material itself is sputtered away by bombarding atoms.[182]

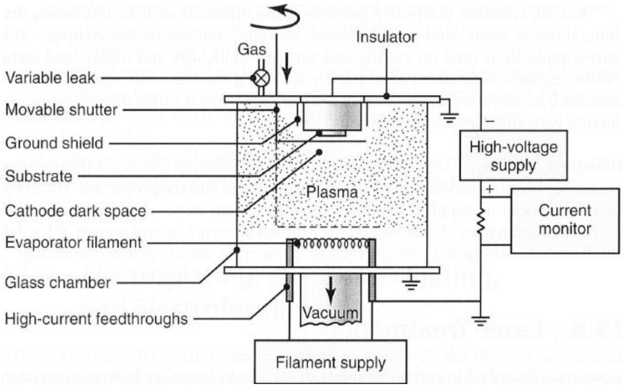

Figure 44 The ion plating process.

3.5.2.2.2 Chemical Vapor Deposition

Chemical vapor deposition is a deposition process that uses chemical vapors instead of physical. An illustration of the process can be seen in Figure 45. In the process, chemicals are injected into the chamber where the substrate is. There, the temperature is increased. This makes the chemicals react and solidify on the surface of the substrate.[183]

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[180] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

[181] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[182] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

[183] Ibid.

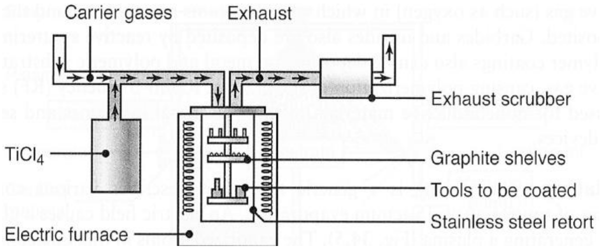

Figure 45 The chemical vapor deposition process.

There are two ways of heating the chemicals. One is called hot wall CVD-reactor. This is the principle used in Figure 45. Here, the walls of the furnace are heated. This makes it easy to coat several parts at the same time. However, it also increases the risk that the chemicals react by the walls, and thereby coat them instead of the substrate. The other method is to heat the substrate itself. This method has the opposite pro and con.[184]

What generally can be said about the process is that the coatings generally are thicker than PVD, that the temperatures used are very high, that the cycle times are very long, complex substrate shapes can be coated with uniform coating thickness[185], and that material selection of coating and substrate is fairly unrestricted. How thick the coatings get depends on gases flow rates, process time, and temperature. How high temperatures are used varies, but for example, the substrate is heated to 1000^{o}C when cutting tools are coated with titanium nitride. The long cycle times usually consist of three hours of heating, four hours of coating, and six to eight hours of cooling.[186]

What has been describes is conventional CVD, also known as thermal CVD. Another type is plasma assisted CVD, PACVD, also known as plasma enhanced CVD. In this process the chemicals are helped by electric discharges to solidify. This makes it possible to keep the temperature lower than usual, even less than 300^{o}C. Furthermore, deposition rates are higher using this version of the process, but the quality of the coating is generally lower.[187]

3.6 Cost of Production[188]

Calculating the cost of producing a part or a product is important to be able to determine the price at which it is going to be sold with profit. However, to be able to estimate the costs, a lot of information about the production facilities is needed. This information is then transformed into variables. A full list of these can be viewed in Table 6. These variables are finally inserted into Equation 6 to get the production cost of one part.

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[184] Ibid.

[185] Ibid.

[186] Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

[187] Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

[188] Ståhl, Jan-Eric (2009) *Industriella Tillverkningssystem del II*. Industriell Produktion vid Lunds Tekniska Högskola. Second Edition. Lund.

Equation 6 Cost of production.

$$k = \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)(1-q_B)}\right]_b + \frac{k_{CP}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right]_{c1} + \frac{k_{CS}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\cdot\frac{q_S}{(1-q_S)} + T_{su}\right]_{c2} + \frac{k_D}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su}\right]_d$$

Table 6 Variables used when calculating cost of production.

k = The production cost of one part	q_Q = Scrap rate
k_B = The cost of material per part	q_B = Material waste ratio
k_{CP} = The machine cost per hour when running	q_P = Loss of production rate ratio
k_{CS} = The machine cost per hour during a standstill	q_S = Standstill ratio
k_D = The salary cost per hour	t_0 = Nominal cycle time in minutes
N_0 = Nominal production quantity	T_{su}= Set-up time in minutes

The first part of the equation, noted b, is the material cost of one part. Here consideration has been taken to defects parts and material which is trimmed off. If the part is produced in near-net-shape q_B can be very close to zero.

The second part of the equation, noted c1, is the active process cost. Active processing time is when the production is actually running. Here consideration has been taken to defect parts and periods with lowered production rate. Lowered production rate is not a standstill, because the production is in fact running. However, for some reason, the speed must be lowered for a period. q_P is the quota of average time lost due to lowered production rate. Active and passive production cost must be divided because k_{CP} differs from k_{CS}. This is for example because of higher wear on the machine and tools and higher energy consumption during active production time.

The part of the equation which is noted c2 is the passive processing cost. Consideration have been taken to all the factors which a considered in c1. However, the set-up time for changing to a new product has been added.

The last part of the equation is the cost of operators, noted d. This part regards q_Q, q_P, q_S, and T_{su}. All of these factors are taken into account because operators are needed whether the production goes slowly, stands still, or produces defect products.

However, even though Equation 6 considers many factors, it is not a perfect solution in itself. For example no consideration is in this case taken to the usage of production capacity. If a company has overcapacity, a fewer amount of products than could had been produced must carry the same costs. The result is that the less parts being produced with the same machines, the higher the costs for those parts. One way to take this into account is to add an extra set-up time to c2 and d. This extra set-up time is a part of the production time not used, which should be proportional to the active time of that batch.

It should be noted that what Equation 6 describes is only the production of one part in one step of production. If several steps are required to produce a product, k in the previous step becomes k_B in the next.

Finally, what has been described here is only the cost of production. To get the complete cost of a sold part, costs from sales, marketing, administrative functions, and research and development, must be added.

3.7 Investment Appraisal Using Net Present Value

The net present value, (NPV) of an investment can be calculated using Equation 7 and the variables summarized in Table 7. All the cash flows are discounted back to the initial year of the investments to illustrate the true value of the investment. This is done to be able to compare investments which different initial investment, salvage value, and cash flows.[189]

Equation 7 Net present value (NPV).

$$NPV = -G + \sum_{i=1}^{n} \frac{a_i}{(1+r)^i} + \frac{R}{(1+r)^n}$$

Table 7 Variables used when calculating NPV.

NPV = The net present value of an investment G = The initial investment a_i = The cash flow of year i	r = The cost of capital of a company R = The salvage value of the investment n = The number of years during which the investment makes money

The cost of capital for a company, r, can be derived from the average expected return on capital of the investors of the company.[190]

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[189] Persson, I & Nilsson, S.-Å. (1999) *Investeringsbedömning*, Liber. Sixth Edition.

[190] Becker, Mona (2009) *Kompendium i Industriell ekonomi AK*. 2009.

4 Empirical Results

This chapter describes the empirical results from investigating the design of the robotic tool parts and supplier capabilities. Information about the robotic tool parts is gathered from the ABB design team. Information from the suppliers is gathered from a contact at each company. Since this is the public version of this report, neither the company names nor the contact names can be reviled.

When cost estimations are given in local currency, the following approximation is made, SEK 1 = $7 = €10.

4.1 The Robotic tool[191]

When this project begun, there was already an initial design of the new robotic tool body. However, there was no design suggestion of a new part F. Therefore, when the initial design of part F is mentioned, this refers to the design of the previous part F.

The body cover consist of five parts; A, B, C, D, and E. In general it can be said that outer and inner geometry must be kept to ensure safe interaction with other parts. However, the design cannot be discussed further since this is the public report.

It should be mentioned that the parts A through E needs to be separate due service requirements. This means that for example part B and C cannot be integrated into each other, and that the parts need to be joined in a non permanent way.

Anticipated mature annual volume for the body and part F cannot be reviled due to the public nature of this report.[192]

4.2 Material Requirements[193]

There are two thermoplastic materials which are interesting for outer body parts of the robotic tool. These are MATERIAL A and MATERIAL B. The reason why these materials are interesting is because they have sufficient chemical resistance and mechanical strength. MATERIAL C would also be able to fill the requirement. However, since the properties of MATERIAL A and MATERIAL B probably are sufficient, and MATERIAL C is much more expensive, MATERIAL A and MATERIAL B are likely the best options for these parts.

The chemical resistance of MATERIAL A and MATERIAL B are being tested to make sure that they actually have sufficient resistance. The chemical resistance pre-study, which these tests are based on, can be seen in Appendix 2 – Chemical resistance chart.

For part C and E, the material selection is still relatively open. Since these parts are protected from the chemicals, the only requirement is mechanical strength.

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[191] The source of this information must be kept a secret.

[192] Alessandro Mattozzi, ABB Corporate Research and Development, Västerås

[193] Alessandro Mattozzi, ABB Corporate Research and Development, Västerås

For the thermoplastic part F, MATERIAL B and MATERIAL C are the two thermoplastic materials which potentially could have the chemical resistance and the mechanical properties needed.

Polytetrafluoroethylene, PTFE, has the chemical resistance needed for both the outer body parts and part F and it has been considered. However, it is too soft.

4.3 Material Suppliers

In this chapter material suppliers are listed. Information gathered from these suppliers can be found below each headline.

All information gathered is non-binding, unless other is stated.

4.3.1 Pellets

4.3.1.1 Material Supplier 1 (MS 1)

MS 1 is a distributer of advanced plastics. Contact was taken to find out more about the opportunities and problems when using injection molding to produce part F in thermoplastics.

Information gathered from contact one:

There is a problem if part F is to be produced with injection molding. Neither MATERIAL B nor MATERIAL C would probably be able to reach the mold at the edge due to air captured in the mold. So no matter which material chosen, some kind of machining will be necessary.

There is a possibility that it would be possible to let the captured air out by having the mold somewhat open during the initial stage of filling it. However, it is doubtful if this could be done just long enough so that the material would not leak. So most likely, this procedure would result in flashing, which probably would have to been machined away anyhow.

One solution is to oversize the mold and then machine the part to the right dimensions, for example by turning. The approximate cost of this would be between €0.5 and €1.

If the small tip in the smaller part of the internal circular cavity have a purpose and have to be there, it would most likely have to be machined. Most likely there has to be some machining of the centre hole anyhow. This is because that the gate is probably going to be located here.

There is another problem with the geometry of part F; the variations of thickness of part F. Since the thickest intersection will determine the cycle time, it would be good if part F could be designed with a thinner and more even wall thickness.

There could be a problem with selecting MATERIAL B as material for part F; the edge could get to brittle. MATERIAL C would not have the same problem. However, whether or not selecting MATERIAL B as material could cause problems depends upon the environment of the part.

It could be a good idea to do a prototype of part F, to be able to make a proper evaluation of the design.

Information gathered for contact two:

Both MATERIAL B and MATERIAL C grades with fiber have a rougher surface than those without. Because of this and the specifications of part F, a grade without fiber is most preferable. They do not supply MATERIAL B without fibers.

4.3.1.2 MS 2

MS 2 is a supplier of plastics and rubbers on the Nordic market. Contact was taken to find out if Part B and D can be injection molded without problems with warpage.

Information gathered:

It would be preferable if a material which is amorphous could be selected instead of MATERIAL A or MATERIAL B, since this would greatly decrease the risk of warpage. However, if the parts must be manufactured in these materials, there are other ways of decreasing the risk. For example, they can perform a simulation of the injection molding process if they are chosen as material supplier. In the case that the parts produced warps despite this analysis, some modification of the mold can be done before it is hardened.

4.3.1.3 MS 3

MS 3 is a global supplier of thermoplastics. Contact was taken to get recommendations regarding which MATERIAL B grades would be suitable for part F.

Information gathered:

They have a MATERIAL B grade with some level of filler and glass fiber. It has very good dimensional stability and good surface finish, and might be applicable for part F.

4.3.2 Semiproducts

4.3.2.1 Semiproduct Supplier 1 (SS 1)

SS 1 is a Swedish supplier of semiproducts, such as plates, rods, and tubes. They do also machine these semiproducts into finished parts. Contact was taken to find out how much it would cost to produce part A, part E and part F by machining of semiproducts, and to get prices of MATERIAL A sheets for thermoforming.

Information gathered:

Cost estimations of how much it would cost to machine parts A, E, and F, and how much it would cost to purchase MATERIAL A sheets have been gathered, but cannot be revived due to the public nature of this report.

4.3.2.2 SS 2

SS 2 is a Swedish semiproduct supplier of thermoplastics. They do also deliver machined and thermoformed products. Contact was taken to find out if they could supply thin MATERIAL B sheets for thermoforming.

Information gathered:

One way to create MATERIAL B sheets with a thickness of around 4mm is to take a sheet with a thickness of 8mm, which is more common, and machine it. However, this would be very expensive.

They are able to supply sheets with a thickness of 5mm and 6mm in the sizes 525x1000mm and 525x3000mm which are extruded. The minimum order quantity of the 525x3000mm sheets with a thickness of 5mm is ten sheets.

Cost estimations how much it would cost to purchase MATERIAL A and MATERIAL B sheets have been gathered but cannot be reviled due to the public nature of this report.

4.3.2.3 SS 3

SS 3 is a worldwide supplier of advanced thermoplastics. Contact was taken to find out if they could supply MATERIAL B sheets with an approximate thickness of 4mm for thermoforming.

Information gathered:

They used to have MATERIAL B sheets for thermoforming with a thickness of 3mm. So it is definitely possible to produce MATERIAL B using this manufacturing process. However, these sheets are no longer being produced.

4.3.2.4 SS 4

SS 4 is an American supplier of advanced thermoplastics. Contact was taken to find out if they could supply MATERIAL B sheets with an approximate thickness of 4mm for thermoforming.

Information gathered:

They have sheets of both unfilled MATERIAL B and MATERIAL B reinforced with 30% glass fiber with a thickness of roughly 4 mm. Standard sizes of these sheets are 2x4ft (609.6x1,219.2mm). However, they can provide any length which is 2 feet wide.

Cost estimations how much it would cost to purchase MATERIAL B sheets have been gathered but cannot be reviled due to the public nature of this report.

4.4 Manufacturing Suppliers

In this chapter manufacturing suppliers are listed. Information gathered from these suppliers can be found below each headline. The suppliers are divided into manufacturing methods.

All information gathered is non-binding, unless other is stated.

4.4.1 Injection Molding

4.4.1.1 Injection Molding Manufacturer 1 (IMM 1)

IMM 1 is a mold manufacturer for injection molding. Contact was taken to find out how much it would cost to process the part F and part A with injection molding, but also to find out which geometric features of the parts are hard to produce. The information gathered of the production of part F is based on a simplified sketch of the part.

Information gathered:

There are a couple of problems if part F is going to be produced with injection molding. One of them is that it would be hard to get the material to reach the sharp edge of the part. It would good to speak with the supplier of the material, to be able to get a clear view of how the specific material would be able to reach the edge.

IMM 2 has the possibility to produce prototype tools which are only a fifth of the cost compared to a real tool. However, these tools are only able to produce between 200 and 300 parts. If stretched, they could produce 1000 parts. This is compared to the 10,000 to 100,000 parts a real tool would be able to produce. It would be a good idea to speak with the supplier of the material to be able to figure out how fast the molds would wear, and whether or not a prototype tool would be able to be used.

An injection molding machine for these parts would cost approximately €10 per hour to rent in China, including operator.

Cost estimations of how much it would cost to produce part A and F have been gathered but cannot be reviled due to the public nature of this report.

4.4.1.2 IMM 2

IMM 2 is into the entire value chain of injection molding, from mold machining to trimming of parts. The purpose of the contact was to find out how much it would cost to process part F, part A and part E, with injection molding, but also to find out which geometric features of the parts are hard to produce.

Information gathered:

A general tool for injection molding usually costs between €3,000 and €4,000. On top of this, there are usually production costs of between €0.2 and €0.8, and for every batch there is a start up cost of €150.

On all surfaces which are perpendicular to the mold opening direction, draft angels of one degree are needed. This is especially important for internal surfaces of cavities, for example the internal circular cavities of part A and E, and part F.

Tight tolerances and good repeatability can be achieved with injection molding. For example, tolerances down to 0.1 millimeter can be achieved. By dividing the creation of the mold into two steps tolerances can be improved by a factor two. The reason that closer tolerances cannot be created is that plastic is a living material, that change. For example, the level of moist in the plastic granulates used for injection molding differs. This does that the result of one batch of granulates does not give the same result as the next. Not even after the part is created, the material constellation is kept the same. Since the material expansion change with the material constellation, the geometries change as well.

A rule of thumb is that walls created by injection molding should not exceed two to three millimeters.

It should be possible to mold cake piece shaped parts of part F, and then mount them together.

Lead time from received order to first injection is approximately five weeks.

4.4.1.3 IMM 3

IMM 3 is a Swedish injection molding company specializing in advanced materials and short series production. Contact was taken to get quotations of the production of parts C and D, and to find out which problems and opportunities there are if the parts are going to be produced using injection molding.

Information gathered:

Problems from injection molding thermoplastics which require high molding temperatures using aluminum molds can be overcome by coating these molds. However, the coating process usually cost enough to make it more rational to use a steel mold instead.

IMM 3 has experience from producing small series using steel molds. These molds are produced in China using high-speed milling machines. When these types of machines are used, the time difference between milling aluminum molds and steel molds is relatively small. Therefore there is a relatively small cost difference between these molds as well.

Lead-time to get start to produce large parts is approximately eight to nine weeks, such as part C, and five to six weeks for small parts, such as part A.

Cost estimations of how much it would cost to produce part C and D have been gathered but cannot be reviled due to the public nature of this report.

4.4.1.4 IMM 4

IMM 4 is a Swedish injection molding company. They have experience from advanced materials and short series production. Contact was taken to gather information about injection molding and the costs of injection molding.

Information gathered:

If part D is to be manufactured using injection molding it has to have a minimum thickness of 2mm. Furthermore, it would be beneficial to use a material which is amorphous and has a high material flow index (MFI) to avoid warping of the part. Glass fiber can be mixed into the molten plastic to enhance the mechanical properties of the part.

A cost estimation of how much it would cost to produce part D has been gathered but cannot be reviled due to the public nature of this report.

The initial design of part F cannot be manufactured using injection molding without making the walls thinner. The edge may, however, be possible to create using injection molding.

4.4.1.5 IMM 5

IMM 5 is an injection molding and compression molding company based in Sweden. Contact was taken to get an estimation of how much it would cost to manufacture part A and C using injection molding.

More information about the compression molding capabilities of IMM 5 can be found below in the sub-chapter Compression Molding on page 80.

Cost estimations of how much it would cost to produce part A and C have been gathered but cannot be reviled due to the public nature of this report.

Design guidelines regarding part A:

- The runner and the gates would have to be located in the centre of the part to ensure desired shape.
- Thick walls and non uniform wall thickness increase the cycle time. If the walls would be uniformly thinner this would decrease the production cost.
- If MATERIAL B with no glass fiber would be selected as material, this would probably decrease the cost of the mold.

Design guidelines regarding part C:

- There are some undercuts in the design, such as holes which are not parallel to the mold opening direction. If these could be avoided, this would lower the cost of the mold by €2,000 to 3,000. However, manual machining of the holes would increase the production cost by €2 to €3/part. Therefore, it could be a good idea to try to include the hole-making in the injection molding process.
- Further examination is needed to determine if it is possible to make the holes in the circular head in the injection molding process. However, it should be possible, but there is a risk that they might be too large and too close to the edges, and therefore decrease the flow of the plastic material.
- A potential problem when injection molding this part could be warping and shrinking. However, the risk of having problems with this is reduced if thermoplastic reinforced with glass fiber is used as material. For example, shrinkage can be reduced to 0.2mm for glass fiber reinforced MATERIAL B.

4.4.1.6 IMM 6

IMM 6 is an injection molding and prototyping company based in Sweden. They are focusing on low volume production and Rapid Prototyping. Contact was primarily taken to find out whether or not aluminum molds could be used to produce the parts and to produce a prototype of the thermoplastic part F.

Information gathered:

Aluminum molds are less expensive than steel molds because they are more easy to machine. Because they are more easy to machine, they also take less time to produce. So the benefit is twofold. It is hard to say how much cheaper these types of molds are compared to steel molds. However, two things can be said. First, as a best case scenario, the cost can be reduced to one third. Second, the more complex the geometry of the part is, the more there is to gain by using aluminum molds.

There are also some downsides by using aluminum. For the same reason why they are more easy to machine, they are also less resistant against wear. So the amounts of parts which can be produced with the molds are greatly less than for steel molds. How many parts that can be produced depend upon the geometric complexity of the part and selected thermoplastic. For example, if fiber reinforced thermoplastics are used, this increases the wear. The second downside is that aluminum molds are not able to withstand the same temperatures as steel molds. Therefore, it is important to make sure that the mold temperature does not increase above a certain level. The selected material and part geometry, is what determines which molding temperature is needed.

They have a lot of experience from using aluminum molds to produce parts in MATERIAL A. So producing the parts in MATERIAL A would not be a problem from a material point of view. They have some experience from glass fiber reinforced MATERIAL B. The problem with this material selection is that it flashes quite a lot. They do not have much experience from MATERIAL C. However, they have done it and they know that it works, but it is more difficult because of the required high mold temperature.

Both part A and C can be produced using aluminum molds. However, if part A is to be produced in MATERIAL B this would increase the level of wear on the mold due to flashing. Even if the part is to be produced using a steel mold, there could be problems with wear.

A problem which both part A and C has is that they have rather thick intersections. Cycle time would be much shortened if these intersections could be ribbed. Furthermore, the risk that part A and C warps during the cooling stage can be decreased if the wall thickness is decreased by for example creating a ribbed structure.

Cost estimations of how much it would cost to produce part A and C have been gathered but cannot be reviled due to the public nature of this report.

Part F prototype info:

For prototype products the lead time from order until first injection is 3 weeks. For production of real production the lead time is approximately 2 weeks longer due to higher requirements of the mold in terms of surface finish and tolerances.

They do not have any capabilities to join parts, such as thermoplastic or ultrasonic welding. However, they have external partners which have. If parts are going to be joined with adhesives, this is something that they can do as long as they are supplied with the right type of adhesive and the geometry is too complex.

The original part F cannot be manufactured in one piece without decreasing the wall thickness. This can be achieved by dividing it into two parts. It would be preferable to decrease the wall thickness of these parts to 3mm in order to improve dimensional stability, and the two parts should be manufactured in two different molds to enable gating in the internal cavity of the parts by the use of a diaphragm gate. This would ensure that the flowing distance to the edge is the same, and would decrease the risk of problems with weld lines. It might be a good idea to use a large gate to ease material flow and then machine the remaining flash.

The creation of a sharp edge is possible since this feature is located in the plate parting plane. However, these sharp edges are going to be very fragile. This may especially be a problem if the part is going to be produced in MATERIAL B. The edge therefore requires extended cycle time for careful handling during demolding.

It would be good if the sharp edges on the smaller part can be blunter. This can be made possible with a cylindrical notch along the backside of the larger part.

The ejection procedure should not be a problem for the big part as long as the ejection pins are located on the side with the small diameter.

The screw threaded feature of part F which is located in the internal cavity might be both hard and expensive to produce in the injection molding process. By placing a threaded metal insert in the mold or by machining this feature, this might be possible to solve for low volumes. If the feature is going to be created in the injection molding process, the parts most likely have to be unscrewed from the mold by hand. An automatic solution would be too expensive for these volumes.

To be able to produce a prototype of part F an exact CAD drawing is needed. This is to minimize the risk of misunderstandings that oral agreements could lead to.

Cost estimations of how much it would cost to produce part F have been gathered but cannot be reviled due to the public nature of this report.

The aluminum mold which could be used to manufacture the prototypes could probably produce a few thousand parts. If the geometry would have been more complex only a few hundred could be expected. The cost of a similar mold made out of steel, varies depending on the type of steel selected. The cost could be the same or three times as high.

The selection of material should be made with consideration to the potential problems of each material. MATERIAL B filled with glass fiber has an increased risk of warpage and MATERIAL B or MATERIAL C without glass fiber shrink more than MATERIAL B with glass fiber. Furthermore, all material combinations cannot be tested with the use of one mold due to different levels of shrinkage.

If MATERIAL B with fiber is selected as material, there is a risk that the surface is rough after molding.

4.4.1.7 IMM 7

IMM 7 is an American injection molding company which uses heat treated aluminum molds. Contact was taken with them to figure out whether or not aluminum molds could be used in the production of the parts.

Information gathered:

One advantage of aluminum molds are that that they are easier to machine. Not only because aluminum is softer than steel but also because it does not build up as much stress during machining as steel. They can machine aluminum molds with CNC machines 24 hours a day seven days a week, unattended. This is very rare in machining of steel molds. Because when steel molds are being machined it needs to be heat treated after a while to release stresses.

Another advantage is that the cycle times of the injection molding process can be decreased. Aluminum molds reaches required temperature quicker in the beginning of the process. Furthermore, it is easier to control the temperature of the mold during the process. Steel molds will always overshoot the temperate, which results in increased cycle times. Aluminum molds does never overshoot the temperature.

They recommend only using general purpose unfilled plastic resins when using the aluminum molds. No glass filling could be used because it is too abrasive. Additionally, only materials which require a mold temperature below 93^{o}C should be used. Otherwise, there is a risk that their type of aluminum begins to anneal, resulting in decreased mechanical properties.

Another disadvantage of the aluminum molds is that they are not able to produce as many parts using them, compared to steel molds. However, for certain part geometries and materials series of 1,000,000 parts have been produced. This is with no sign of wear on the mold.

Regular machines could use the aluminum molds, even though the operators needed to get some level of special education. This is because injection pressure and clamp pressure needs to lower than when using steel molds.

Most part geometries can be created. However, small thin blades in the mold should be avoided because these would be run over by the plastic flow front. If this would be needed, a copper alloy can be inserted into the mold to create these features.

4.4.1.8 IMM 8

IMM 8 is a production company which produces plastic, rubber, and metal components. Contact was taken to find out if part F could be produced using gas assisted injection molding.

Information gathered:

Given that part F was to be produced in MATERIAL B or MATERIAL C, it should be possible to produce the initial design of part F using gas assisted injection molding.

To be able to gather more information, such as quotation estimations, a CAD-file and all the pertinent commercial information is needed. Commercial information is for example shipment conditions.

4.4.1.9 IMM 9

IMM 9 is a Swedish injection molding company. They also offer special versions of injection molding, such as gas-assisted injection molding, over molding, and metal inserts into molded components. Contact was taken to find out if part F could be produced using gas assisted injection molding.

Information gathered:

It is not possible to produce part F using gas assisted injection molding. This is because it is very hard to create cylindrical shapes such as this.

MATERIAL B and MATERIAL C are advanced and rather unusual materials. Therefore, they have little experience from them. This makes it even harder to produce part F using gas assisted injection molding.

The only solution is to produce part F with this design is to create two separate parts and weld them together.

4.4.1.10 IMM 10

IMM 10 is an injection molding company based in Sweden. They are into conventional injection molding, gas assisted injection molding, and injection molding using a mix of materials. Contact was taken to find out if the originally designed part F could be produced with gas assisted injection molding.

Information gathered:

There is a cost difference between producing parts with regular injection molding compared to gas assisted injection molding. Since the gas assisted process is more advanced, the cost of developing the mold is higher. However, since the process decreases cycle time, due to that it enables production with thinner walls; the variable production costs are usually decreased.

The gas assisted process' capability to produce symmetrical captured cavities is generally good. The level of symmetry depends on the geometry of the part.

IMM 10 also has the capability to produce parts in foamed thermoplastics. This can reduce production costs for parts with thick walls.

It would be possible to produce part F using gas-assisted injection molding in MATERIAL B. However, it will be very difficult, the gas will most probably leak from the shaped cavity, and it will not be possible to get it balanced enough. They have no experience from gas-assisted injection molding of MATERIAL C.

4.4.1.11 IMM 11

IMM 11 is a German manufacturing company which specializing in advanced polymer processing such as stereolithography, RHCM, gas-assisted injection molding, insert molding, et cetera. Contact was initiated to find out if the RHCM process could be used to manufacture part F.

Information gathered:

Since high temperatures are needed to process MATERIAL B and MATERIAL C, the part which is going to be produced using the RHCM process should not be too big. A part which is of the size of part F is small enough.

Part F is probably possible to produce in a RHCM process. A mold base with an oil heating and water cooling could be produced using a LaserCUSING® process. LaserCUSING® is a way to use laser sintering to produce steel inserts into injection molding molds. However, to machine some special features in the mold is impossible with regular milling, grinding, or eroding. It might be possible using nano technology, but this is not within their competence.

4.4.1.12 IMM 12

IMM 12 is an American injection molding company which uses a microcellular molding process. Contact was initiated to find out if this process could be used to manufacture part F in one piece.

Information gathered:

It is possible to produce MATERIAL A, MATERIAL B and MATERIAL C parts using the microcellular molding process. In fact, all thermoplastics can be produced with the process except for liquid crystal polymer. Furthermore, if the material formed is filled with glass of carbon fiber, this is beneficial. This is because a filled material has more starting points for nucleation.

It might be possible to manufacture part F including a sharp edge using a microcellular molding process. A benefit of the microcellular molding process is that is lowers the viscosity of the material by 10 to 30 percent. In order to properly examine this possibility, tests must be carried out.

In order to use the process a specific screw, a barrel, a super critical fluid unit, and an injector must be acquired. These extra initial investments are often covered by a 10 to 30 percent decrease of material usage and a 15 to 30 percent decrease in cycle time. The reduction in cycle time is due to no or little hold time is required.

Another benefit of the process is that the part is the internal stress is reduced. This also reduces the risk of warpage. However, the amount of shrinkage is increased by 10 percent.

The cost of the mold used in the microcellular molding process is the same as for conventional injection molding.

4.4.1.13 IMM 13

IMM 13 is a rapid manufacturing company which has specialized in processes with short lead times and low initial cost. They have techniques for polymers and metals. For example, they create epoxy molds for injection molding prototyping.

4.4.1.14 IMM 14

IMM 14 is a multinational rapid injection molding company which produces prototypes and short series. They are specialized in fast deliveries using an automated quotation process.

4.4.2 Thermoforming

4.4.2.1 Thermoform Manufacturer 1 (TM1)

TM 1 is a Swedish vacuum forming manufacturer. Contact was taken to find out more about thermoforming and if there would be a possibility to use this process to produce the thin body parts, part B and D.

Information gathered:

Cost estimations of how much it would cost to produce part B and D have been gathered but cannot be reviled due to the public nature of this report.

The molds have a standard interface with the machine, and can therefore be moved, to for example China, and used in machines there.

The geometry of parts produced by vacuum forming has limits. The producer can only determine the geometry of one side, the side closest to the mold. Another problem is that the thickness of the part can vary, and is hard to control. When the sheet is stretched it is generally stretched a factor of four. For example, to get a final part with thickness 1mm, the producer must start with a sheet of 4mm. Sheets with a thickness of up to 40mm can be processed using vacuum forming.

There are three ways of heating the sheet; by ceramic, by quartz, and by halogen. Ceramic is the slowest and the oldest one, halogen is the fastest and newest one, and quartz is in between.

A general rule is that for each mm the cycle time increases one min. For example, a part which has a thickness of 1mm has a cycle time of 1min. Switching a mold to start producing another part take 10 to 15 min.

The ratio of defect parts is generally 2 to 3%. Defects can be seen as bubbles on the surface of the sheet after processing due to hydroscopic nature of thermoplastics.

20 percent to 30 percent of the material needs to be thrown away after processing since it is only used to hold the sheet and then trimmed off.

All thermoplastics can be produced by vacuum forming, even MATERIAL B. However, when processing MATERIAL B, the temperature needs to be higher than when molding most other thermoplastics. Therefore a heating device needs to be incorporated into the mold. This would result in a small extra charge for the mold and an additional 20% in cycle time. Processing MATERIAL A is also possible, but only in limited volumes.

The lead time from agreeing on an offer till full scale production is 5 to 6 weeks.

It is not possible to manufacture the geometry of part B and D in MATERIAL A using regular thermoforming. However, it is possible if large over pressure is used.

It is only possible to get extruded MATERIAL B plates which are at least 10 millimeter. To thermoform the parts B and D, sheets which are four millimeter are needed.

4.4.2.2 TM 2

TM 2 is a Swedish thermoforming company. Contact was taken to find out if part B and D could be thermoformed.

Information gathered:

Nor MATERIAL A or MATERIAL B are usually thermoformed, and TM 2 has no experience from these materials. However, they have been in contact with a semiproducts supplier which supplies plastic sheets of MATERIAL A and MATERIAL B. This supplier said that MATERIAL A and MATERIAL B are not thermoformed.

4.4.2.3 TM 3

TM 3 is a Swedish thermoforming company. Contact was taken to find out if part B and D could be thermoformed in MATERIAL A or MATERIAL B.

Information gathered:

It would be good if part D had a draft on the sides which are parallel to the mold opening direction. It is possible to produce parts without draft, but it is hard.

Smooth areas such as the ones on part B and D have worse stiffness than those which are waved. To increase the stiffness, the surfaces could be made waved.

The radii of the parts are large, and are therefore suited for thermoforming.

TM 3 has no experience from vacuum forming parts in MATERIAL B. It is, on the other hand, possible to produce parts in MATERIAL A even though it is difficult, and they cannot leave any guarantee that any specific part is possible to produce before testing. Part D is especially difficult to produce in MATERIAL A because of the relatively high H:D ratio.

Cost estimations of how much it would cost to test form and produce part B and D using MATERIAL A, MATERIAL B, and PVC have been gathered but cannot be reviled due to the public nature of this report.

It is impossible to determine process costs for parts produced in MATERIAL A before test molding have been carried out.

4.4.2.4 TM 4

TM 4 is a Swedish thermoforming company. Contact was taken to find out if part B and D could be thermoformed in MATERIAL A or MATERIAL B.

Information gathered:

They have no experience from thermoforming MATERIAL A, and have no interest in finding out if it is possible.

They have never heard of MATERIAL B, and have no interest in finding out if it could be thermoformed.

4.4.2.5 TM 5

TM 5 is a Swedish thermoforming company. Contact was taken to find out if part B and D could be thermoformed in MATERIAL A or MATERIAL B.

Information gathered:

They have no experience from vacuum forming either MATERIAL A or MATERIAL B, and have no interest in figuring out whether or not it is possible.

4.4.2.6 TM 6

TM 6 is a Swedish thermoforming manufacturer. Contact was taken to find out if part B and D could be thermoformed in MATERIAL A or MATERIAL B.

Information gathered:

They have no experience from thermoforming of either MATERIAL A or MATERIAL B.

4.4.2.7 TM 7

TM 7 is a German thermoforming manufacturer which offers machineries and tools. Contact was taken to find out if part B and D could be thermoformed in MATERIAL A.

Information gathered:

MATERIAL A can be thermoformed, and another material can be used as a reference material. Which the other material is cannot be reviled due to the public nature of this report.

It should also be remembered that thermoformed parts are relatively brittle if no heat treatment is used after forming.

4.4.2.8 TM 8

TM 8 is a Swedish thermoforming manufacturer which offers machineries and tools. Contact was taken to find out if part B and D could be thermoformed in MATERIAL A. They are also the Swedish representative of the thermoforming company TM 7 mentioned above.

Information gathered:

Cost estimations of how much it would cost to test form part B and D have been gathered but cannot be reviled due to the public nature of this report.

4.4.3 Compression Molding

4.4.3.1 Compression Molding Manufacturer 1 (CMM 1)

CMM 1 is a Swedish compression molding and injection molding company. Contact was taken to find out more about compression molding as a manufacturing process and the economics of compression molding relative to injection molding.

More information about the injection molding capabilities of CMM 1 can be found above in the sub-chapter Injection Molding above.

Information gathered:

CMM 1 has no experience from compression molding of thermoplastics, only from thermosets. Their cost for a compression molding mold is the same as a mold used for injection molding.

4.4.3.2 CMM 2

CMM 2 is a Swedish compression molding company. Contact was taken to find out more about compression molding as a manufacturing process and the economics of compression molding compared to injection molding.

Information gathered:

The cost for a compression mold is about the same as for an injection mold. This is because the processes are very similar, and that the molds for this reason are affected by the same stresses and level of wear.

Cost estimations of how much it would cost to produce part C have been gathered but cannot be reviled due to the public nature of this report.

4.4.4 Machining

This manufacturing method is handed in the chapter Semiproducts on page 68.

4.4.5 Rapid Prototyping

4.4.5.1 Rapid Prototyping Manufacturer 1 (RPM 1)

RPM 1 is a Swedish prototyping company which supplies most rapid manufacturing solutions. Contact was taken to get more information about the process, and to find out if any of these processes could be used to produce any of the parts of the robotic tool.

Information gathered:

SLA can produce transparent parts from epoxy with relatively smooth surfaces since the layer thickness is only 0.05mm. The process is not appropriate for series production and has some problems with dimensional stability.

Using FDM polycarbonate, ABS, and polyetherimide (PEI) parts can be produced. Three different types of layer thicknesses are available; 0.127, 0.178, and 0.254mm. The parts produced have good dimensional stability, but not so good surface finish due to the layer thicknesses. Tolerances in the horizontal plane are in the rage of ±0.1 to 0.2mm and the tolerance in the vertical plane is approximately selected layer thickness divided by two. The process may in some cases be appropriate for series production but it is rather expensive. Polycarbonate parts generally cost €2.8/cm^3 and ABS parts cost €4.6/cm^3.

4.5 Joining Method Suppliers

In this chapter joining method suppliers are listed. Information gathered from these suppliers can be found below each headline. The discussions with these suppliers are based on simplified sketches of part F.

All information gathered is non-binding, unless other is stated.

4.5.1 Joining Method Supplier 1 (JMS 1)

JMS 1 is an international company which among other things sells adhesives. Contact was taken to find out if they have any adhesives which would be applicable in the case of a divided part F.

Information gathered:

The adhesives which are the most resistant to chemicals are epoxy-based adhesives. Intermittent contact with solvents is usually not a problem. However, if the contact is constant, problems could occur. For example, the cohesiveness and the adhesiveness of the adhesive may be compromised. A primer can be used to protect the joint from adhesiveness problems and improve the adhesiveness.

JMS 1 has recommended some specific adhesives. Which these are cannot be reviled due to the public nature of this report.

When applying these types of glues 50ml is enough for 6.56m of joint, given that the joint is 3mm wide. If the joint instead is 4 or 5mm, 50ml is enough for 3.69 and 2.36 respectively.

4.5.2 JMS 2

JMS 2 is a German paper, plastic welding, and lubrication company. Contact was initiated to evaluate different joining methods for the divided part F.

Information gathered:

The joining methods which they supply are laser welding, friction welding, ultrasonic welding, hot gas welding, infrared welding, and hotplate welding. For the two parted part F, rotational friction welding would be an appropriate solution based on its symmetrical geometry.

They have recently done some tests of friction welding MATERIAL B with MATERIAL B and MATERIAL C with MATERIAL C, and the strength of these welds where good.

Based on the geometry of the part, it would be appropriate to use friction welding to join the two parts.

Cost estimations of how much it would cost to join the two parts using friction welding have been gathered, but cannot be reviled due to the public nature of this report.

4.5.3 JMS 3

JMS 3 is an international company which is much diversified. For example, it is into manufacturing, plastics, construction, and health care. Contact was initiated to evaluate different joining methods for the divided part F.

Information gathered:

Since they do supply neither MATERIAL B nor MATERIAL C, they are unable to help with the joining of these materials. However, they did suggest Polyamide, PA, as a material instead.

4.5.4 JMS 4

JMS 4 is a Swedish distributer of adhesives. Contact was taken to get prices of and potentially order the glues recommended by JMS 1.

Information gathered:

Cost estimations of how much it would cost to join the two parts using adhesives have been gathered, but cannot be reviled due to the public nature of this report.

If the primer or the glue flashes, this can be removed by the use of a cloth if this is done immediately after the parts are joined.

4.5.5 JMS 5

JMS 5 is a Swedish distributer of adhesives. Contact was taken to get prices of and potentially order the glues recommended by JMS 1.

Information gathered:

Cost estimations of how much it would cost to join the two parts using adhesives have been gathered, but cannot be reviled due to the public nature of this report.

4.6 Coating Suppliers

In this chapter coating suppliers are listed. Information gathered from these suppliers can be found below each headline. The suppliers are divided by the different coating materials used.

This empirical study is based on a pre-study at ABB Corporate Research in Västerås.

All information gathered is non-binding, unless other is stated.

4.6.1 Coating Supplier 1 (CS 1)

CS 1 is a Swedish based company which produces molded parts in polyurethane, but also coats parts with the same material.

Information gathered:

The coating is wear resistant and can protect parts from corrosion. It is applied by a spraying gun which creates an aerosol of the polymer that coats the substrate. The thickness of the coating can vary from between a few millimeters to several centimeters.

4.6.2 CS 2

CS 2 is a German based coating company. Contact was taken to find out if they have a coating solution for part F.

Information gathered:

They have three types of coatings. One is for parquet floors, et cetera, the second is for decorative parts, et cetera, and the third is for Poly methyl methacrylate, PMMA, parts. PMMA is a thermoplastic. The first is applied by rolling and the second and third are applied by spray coating.

4.6.3 CS 3

CS 3 has a technology which enables integrated coating in the injection molding process. Contact was taken to find out if this process could be used in the case of part F.

Information gathered:

The process is only able to apply a layer of coating to Poly methyl methacrylate, PMMA. PMMA is a type of thermoplastic. The coating is scratch resistant and has good chemical resistance.

4.6.4 CS 4

Contact was taken to find out if they could supply a coating which suited the specifications of part F.

Information gathered:

Purely theoretically, zinc ethyl silicate would is a coating which would be able to withstand the chemicals, but to prevent the chemicals to reach the substrate will be hard. However, the solvents would have to be totally free from water since the coating consists of zinc.

Normally the coating is used as a coating base on steel parts. Parts with all geometries cannot be used. There are restrictions on the geometry. The process begins with blasting of the substrate to a surface roughness of 75 µm to 100 µm. This is followed by spraying an approximately 75 µm to 100 µm coating layer on the substrate. However, they have no experience from applying this coating on polymer substrates.

4.6.5 CS 5

Contact was taken to find out whether or not their coating could be used for part F.

Information gathered:

Their coating is applied as a 1 µm to 30 µm thick layer. However, since it the coating is so thin, it does not protect the substrate against wear.

4.6.6 CS 6

CS 6 is a German based special glass company. Contact was taken in regard to one of their scratch resistant coatings for plastic displays, and if this or any other of their coatings could be used for part F.

No information is gathered, since no answer been received.

4.6.7 CS 7

CS 7 is a German based coating company. Contact was taken to find out if they have a coating solution for part F.

No information is gathered, since no answer been received.

4.6.8 CS 8

CS 8 is a German based company which produces sol-gel coatings. Contact was taken to find out if they have a coating which would fill the specifications of part F.

Information gathered:

They have some sol-gel solutions which have good chemical resistance. However, not all chemicals which part F comes in contact with have been tested. Therefore, further testing is needed to be able to determine whether or not the coating is resistant against the other coatings.

Cost estimations of how much it would cost to coat part F have been gathered, but cannot be reviled due to the public nature of this report.

Regarding the geometry of part F; there is a problem if the tube inside of part F must be coated. Because then a special spray gun must be used, and this would make the process more expensive.

Most likely MATERIAL B and MATERIAL C must be pretreated with plasma to get the coating to stick. They are unsure if they have a coating which does not need this pretreatment.

It is hard to say whether or not it is possible to coat a part F which is divided and joined with adhesives. To find out whether or not this is possible tests needs to be carried out.

4.6.9 CS 9

CS 9 is a German coating company which uses plasma processes to clean and coat surfaces. Contact was taken to find out whether or not they supply a coating which could be used for part F.

Information gathered:

One of their coatings, which is applicable, is only 3 µm thick. Due to this, it is important to bear in mind that the substrate is not too soft. If it is, there is a risk that the surface of the coating breaks if affected by a sharp tip.

The equipment required for the process is expensive. Therefore, based on the annual volume of the part, it would not make economical sense to by own equipment. In this case it would be better to rent capacity.

Cost estimations of how much it would cost to coat part F have been gathered, but cannot be reviled due to the public nature of this report.

If the divided part F is going to be glued together this may affect the coating result. However, it is impossible to determine this before test coatings have been done.

4.6.10 CS 10

CS 10 is a coating company which uses their own coating method to apply their proprietary coatings. Contact was taken to find out if they had a coating which could be used for part F.

Information gathered:

They can make coatings which are chemically resistant to the chemicals which part F needs to be able to withstand. However, it is needed that the substrate material is able to withstand chemicals as well. That is, the coatings cannot protect the substrate from chemicals.

If part F is going to be coated there could be two problems. The first is that the coating may have problems sticking to the surface if glue residues are left on it. The second is that since the process is carried out in vacuum, there needs to be some small ventilations holes to let air and moist out from the enclosed cavity.

Cost estimations of how much it would cost to coat part F have been gathered, but cannot be reviled due to the public nature of this report.

4.6.11 CS 11

CS 11 is a global supplier of PVD coatings. Contact was taken to find out if they have a coating which can be used for part F.

Information gathered:

CS 11 does not have any experience from coating plastic parts. Either way, plastic materials are too soft for thin and hard coatings. The problem is that the substrate must be able to support the coating; otherwise there is a risk that the coating cracks. It is much like laying a sheet of glass on a mattress. The second problem is that the adhesiveness of coatings on plastic substrates is bad. The plastic surface is too greasy. This even worsens the first mentioned problem, because if the coating cracks, the flakes will easily be removed if the adhesiveness is bad.

The third problem has to do with the coating process temperature. The process temperature cannot be too high if plastics are to be coated. This is important because if the temperature reaches above the glass transition temperature the geometry of the part may change. The lowest process temperature that CS 11 can achieve is between 200^{o}C and 250^{o}C. The substrate surface temperature will in this case be even higher.

The fourth problem has to do with the vacuum in which the coating process is carried out in. Plastic parts do usually have small bubbles of air in the material. This is unless the molding pressure was very high during the molding process of the parts. The small bubbles expand in the vacuum used in the process, and might damage the part.

All of these reasons do not make it worthwhile to even try to coat plastic parts.

4.7 Other sources

In this chapter other sources are listed. Information gathered from these contacts can be found below each headline.

4.7.1 Other Source 1 (OS 1)

OS 1 is a manufacturer of steels for molds. Contact was taken to get more information about the cost of the mold used for injection molding.

Information gathered:

Usually between 60 and 70% of the cost of a regular mold for injection molding is due to the machining of the mold. This is also true for more advanced steels, since they are more difficult to machine. So if a designer is trying to lower the cost of manufacturing by injection molding, he or she should focus on trying to lower the complexity of the part. An example of this would be replacing unnecessary sharp corners with round corners. Therefore the design team should collaborate with the company that makes the molds at an early stage to fully understand how the cost of molds can be reduced.

There are several companies which use modules when creating molds. This is done by standardizing mold sizes, and thereby using for example off the shelf ejection pin modules. The result is lowered lead time for the mold. However, the manufacturers still need to machine the cavity of the mold.

The use of aluminum molds is one way to lower the initial costs of injection molding. However, the amount of parts which can be produced with these types of molds, are limited. To further evaluate this option, the mold manufacturer should be consulted. Another way to go is to use a less advanced type of steel, which is easier to machine and therefore makes the mold less expensive. However, this mold would not be able to manufacture as many parts a mold manufactured from a more advanced type of steel. Therefore, if a company is to produce many parts, several millions, the cost per part could be higher if they would use molds from less advanced types of steel.

4.7.2 OS 2

OS 2 is a mold supplier to mold manufacturers. Contact was taken to find out more about the differences between steel and aluminum molds.

Information gathered:

Unmodified aluminum molds are slightly more expensive than steels molds. However, because the machining of them generally is four times faster and because they do not have to be hardened after machining they are less expensive. The hardening of the steel molds adds more than one extra production step, since the process somewhat alter the dimensions of the cavity. Due to this the geometry of the cavity must be machined to its final shape after hardening. However, there are new soft steels which do not require hardening as well.

Aluminum molds have problems with wear when molding harder thermoplastics and thermoplastics with fibers.

4.7.3 OS 3

OS 3 is a global supplier of unmodified molds. Contact was taken to find out more about the differences between steel and aluminum molds.

Information gathered:

The catalogue prices for standard cavity plates of the size 216x246x96mm in steel (type 3.4365) and aluminum (type 1.2312) is roughly €300 and €350 respectively. However, aluminum is easier to machine than steel due to better chipping.

4.7.4 OS 4

Contact was taken to evaluate different coating materials and processes for part F.

Information gathered:

Polymer coatings have limited applicability in the case of part F. There are no polymer coatings that they are aware of that for sure fits all of the specifications of part F.

Metal coatings can be used as a base for other coatings to enable electrical conductivity of part F. Electroless plating can be used to apply metal coatings. However, sputtering of metal coatings ensure better adherence. Today there is no problem in sputtering rather complex geometries such as part F. Because even though sputtering is a one direction applying process, complex geometries can be coated by rotating the substrate.

There are two things which OS 4 may help with. They can help with finding an already existing coating solution on the market, or they can help with developing a new solution for which the customer can receive intellectual property rights to. The pros of developing an own solution is the possibility of competitive advantage and that it acts as an insurance against coating companies changing their coatings and processes so that they no longer suit the specific need.

5 Analysis

This chapter is divided into several parts. The first part consists of an analysis of the case study. Here the robotic tool new product development is analyzed from a concurrent engineering, material selection, manufacturing selection, and design point of view. The analysis chapter is then finished by analyzing the possibilities of short series production of thermoplastics.

5.1 Concurrent Engineering

This project is carried out by a multifunctional team, just as the theory suggests. The design, the business, and market functions are represented by the design team. Alessandro Mattozzi has wide knowledge about thermoplastic materials. The author researches the possibilities and limits of different manufacturing alternatives. If more specific information from other fields is needed, contact is initiated with a person with knowledge.

The project is now in the third step of the concurrent engineering model. This is when a design is to be established and prototypes are to be developed. As a sub-step within step three, a DFMA analysis can be performed to ensure that the design established takes manufacturing and assembly issues into consideration. To establish the best design concept of the DFMA framework, which is equivalent to the output of step three in the concurrent engineering model, there are several iterative steps. These steps consist of DFA, processes analysis, and materials analysis. It is these iterative steps which are performed in this analysis.

5.1.1 Product Specifications

Every new product development begins with gathering of customer needs which are translated into product specifications. These specifications are then used to make material, process and design selections. In this case, the product specifications have been gathered from the design team, which has the responsibility of representing the market function. However, since the product needs to be kept a secret, the product specification cannot be shared in this public version of the report.

5.1.2 DFA Analysis

When performing a DFA analysis there are three questions which one must ask oneself. These have to with relative movement of parts, different materials of parts, assembly, and disassembly. The questions help designers to find out if two parts really are necessary. Below the different parts are discussed with regard to these questions. A summary of the analysis can be found in Table 8.

Table 8 DFA analysis of the parts.

	Relative movement	Different materials	Assembly/Disassembly
Part F	No	No	Yes
Part A	No	No	Yes
Part B	No	No	Yes
Part C	No	No	Yes
Part D	No	No	Yes
Part E	No	No	Yes

Joining (B,C and D)	No	No	No

Part F does move relative to other parts such as part A. However, it does not move relative to the part of the robotic tool onto which it is mounted. Furthermore, it might be preferable that it consists of another material than other parts because it faces heavy wear, it must be possible to be coated, and it must have excellent chemical resistance. These factors do that only rater expensive thermoplastics can be considered, and therefore it would perhaps not make economical sense to manufacture other materials in this material as well. Either way, it must be possible to exchange the part since it is the part of the robotic tool which faces the heaviest wear.

Part A and E do not move relative to each other or other parts of the body, and they do not have to consist of different materials. However, it is needed that they are separate parts due to the fact that it needs to be possible to disassemble them to make repairs and perform service.

The parts B, C, and D do not either have relative movement to each other, and they do not need different materials. However, the situation is similar to the one of part F. It might be preferable to construct part C from another material since it does not have the same requirements when it comes to chemical resistance. In any case, due to the fact that it needs to be possible to disassemble the parts, they need to be kept separate.

Part B, C, and D needs to be joined by some joining method. For example if screws are selected, this would involve extra parts. However, these parts do not have any relative movement, require another material, or need to be disassembled from both parts it is used to join. For these reasons, the methods used to join parts B, C, and D, do not need to consist of extra parts. Whether or not it would make economical sense to use extra parts anyway is analyzed later on in the manufacturing and design chapters of these parts.

5.2 Material Selection Analysis

There is a risk by selecting materials at a too early stage of a new product development, when there is still little information available. However, the robotic tool is not an entirely new product. Therefore, there is much more information about the product, its users, and the process it is used for, than usual. Due to this, the material selection is much more limited since a general examination of possible candidates already has been performed. So in the case of the body parts, the large question is not which material type is going to be used. This has already been specified to polymers for this project. The big question is rather how the parts are going to be designed and produced.

The situation is a little bit different in the case of part F. This has previously been machined in aluminum, and here is the large question if it is possible to manufacture it using polymer materials instead. So in contrast to the case of the body, there are limits in the amount of available information. However, since the purpose of the project is to examine the opportunity of manufacturing it in a different material rather than developing a product, there is no risk of selection material type at a too early stage.

However, even though the main issues have to do with design and manufacturing since material type already been selected, one specific material needs to be suggested. This suggestion needs to be made with regard to manufacturing and design issues, but also with regard to other factors. All factors are listed and commented below:

- Physical
- Mechanical
- Processing and fabrication factors
- Life of component factors
- Cost and availability

Physical factors which need to be considered for part F have to do with the thickness of it, the variation of thickness, and the sharp edge. These are factors which makes it hard to produce the part using thermoplastic processes. This will be further discussed in the chapter Design Alternatives for Part F further down.

Mechanical material issues are resistance to wear and high strength to enable coating. Both MATERIAL B and MATERIAL C are hard materials, which is good. However, there is nothing here that makes one material stand out. The situation is different when examining processing and fabrication factors. MATERIAL B has lower viscosity than MATERIAL C. This is positive since it eases the creation of the sharp edge of part F, but there is an increased risk of flashing which results in extra high costs for precision trimming and increased wear of the mold. If MATERIAL B is filled with carbon or glass fiber, the wear of the mold would be increased further. However, by using carbon fiber in the material for part F, it becomes conductive, which it needs to be. This could also be solved by applying some conductive coating to part F. Either way, all polymer grades with fiber will probably have a negative effect on the surface of part F.

Regarding the life of component factors, the chemical resistance of MATERIAL C is superior to MATERIAL B. However, MATERIAL C is also more expensive.

When analyzing the same factors for the body parts it can be said that parts B, C, and D have long material flow ratios. Due to this it would be good with a material with low viscosity like MATERIAL B. Furthermore, the mechanical and the life of component factors also promote MATERIAL B. The strength and the chemical resistance of MATERIAL B are better than that of MATERIAL A. For part C and E chemical resistance is not crucial, since they are protected by other parts, but for the other parts it is. However, MATERIAL B has downsides as well. It does as mentioned increases the risk of flashing, and it is also more expensive and is less available. Especially MATERIAL B sheets are very expensive and hard to find.

A drawback for both MATERIAL B and MATERIAL A is very hard to find thermoforming manufacturers which have experience from these materials. This is not help by the fact that since they do not usually form these sheets, they do not have an internal supply for test-forming. Therefore it is hard find out if these materials can be formed with thermoforming as well.

Finally, as the material selection analysis is almost finished, it should also be mentioned that it is suggested in the theory that the materials considered should be grouped by the primary manufacturing processes by which they can be processed. In this case the material type has already been selected. Therefore all materials considered can be processed in similar ways. Due to this, there is no point by grouping the materials in this way in this project.

5.3 Manufacturing Process Selection Analysis

The selection of a manufacturing process can begin with collection of product design specifications, such as annual volume produced, selected material type, and part geometry. This information is then used in a PRIMA selection matrix to find appropriate manufacturing candidates. The matrix can be seen in Appendix 1 – PRIMA Selection Matrix.

If thermoplastics as material and annual volume are used in the PRIMA selection process matrix, the processes compression molding, vacuum forming, blow molding, and rotational molding are suggested. To these processes, injection molding and extrusion may also be added, despite that they usually are used for larger volumes, and the rapid prototyping processes FDM and SLS may be added despite that is usually used for smaller volumes.

The next step is to examine different PRIMAs to examine the capabilities of the processes. When doing this it is discovered that blow molding, rotational molding, and extrusion cannot be used as processes due to limits in the geometric complexity of the parts produced. Blow molding and rotational molding can only be used to create hollow parts with a low degree of internal complexity, and extrusion can only create pats with a two-dimensional intersection.

The processes which are left are injection molding, compression molding, vacuum forming, and rapid prototyping processes. To be able to determine which of these manufacturing alternatives are appropriate, cost estimations must be made.

In the empirical study it was discovered that the molds used for compression molding cost at least as much as those used for injection molding. As a matter of fact, the cost estimation for a compression molding mold for part C was the highest.

Furthermore, the cycle times are much longer for compression molding, partly due to manual handling. This does that the processing cost also is increased for compression molding. A graph of how the part cost varies with annual volume can be seen in Figure 46. The annual volume shown in the graph refers to an annual volume of that quantity during five years. This means that an annual volume of 50 over five years results in a total production of 250 parts.

The calculations are made using mold, material, and processing costs. No consideration is taken to costs of standstills, cost of poor quality, or any other factors that ABB are not going to have to carry the costs for.

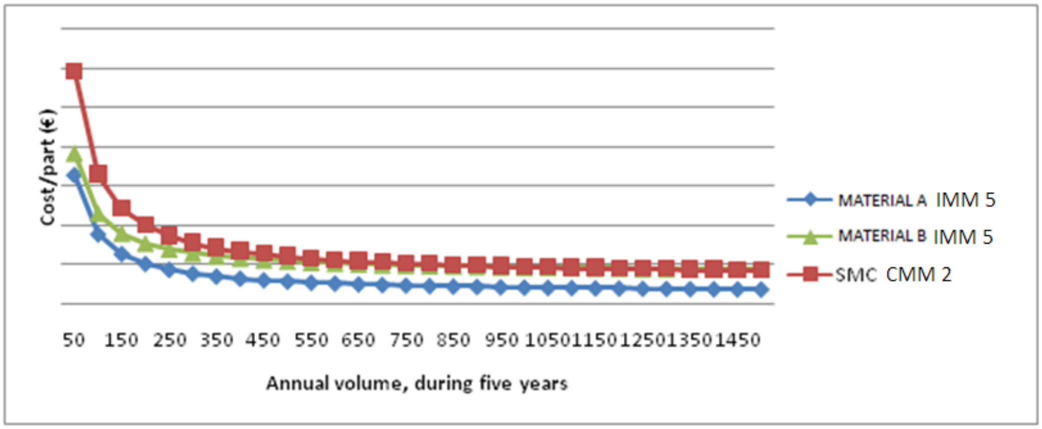


Figure 46 Injection molding versus compression molding of part C

Because of the information showed, there is no point in selecting compression molding prior to injection molding due to cost reasons.

The two rapid prototyping processes which are able to produce parts from thermoplastics are SLS and FDM. If no consideration is taken to the fact that FDM is not able to produce parts in MATERIAL A, MATERIAL B or MATERIAL C, the process is still very expensive relative to other processes. If for example polycarbonate is selected as material, the approximate cost per cubic centimeter is €2.8. Due to this, and the volume of the parts, it does not make sense to produce any of the parts using FDM.

The only material which is interesting and could be processed by SLS is MATERIAL C. Due to the high cost of FDM, it can be assumed that SLS processing of MATERIAL C would be even more expensive.

The result is that injection molding and vacuum forming are the processes which are to be further examined. This work will continue below for each of the parts.

5.3.1 Manufacturing Analysis of Part F

The different manufacturing alternatives which are candidates to produce part F are injection molding, and machining. Vacuum forming is not added due to its limitations in creating complex geometric shapes, and machining is manly used as a reference due to its high variable cost.

The rest of the manufacturing analysis is based on the design changes suggested for injection molding. This is due to machining costs of part F is less sensitive to the design of it. This analysis is therefore continued under the chapter Manufacturing Analysis of the Final Design Suggestion on page 100. Machining will still be used as a reference.

5.3.2 Manufacturing Analysis of the Body

Below the different body parts are analyzed from a manufacturing point of view.

5.3.2.1 Part A

The manufacturing of part A cannot be done with vacuum forming due to geometric complexity. This only leaves injection molding as process alternative. However, a cost estimate for machining the part has been gathered and will be used as a comparison. Some cost estimates has been gathered in Figure

47. The cost for machining part A in MATERIAL B is not shown in this graph because it is too high to be seen in the graph. The estimations shown are based on that the annual volume shown on the x-axis is going to be produced for five years, and on that the production will be carried out in two batches per year. Just as previously, the calculations are made using mold, material, and processing costs, and no other costs, such as costs of standstills or cost of poor quality.

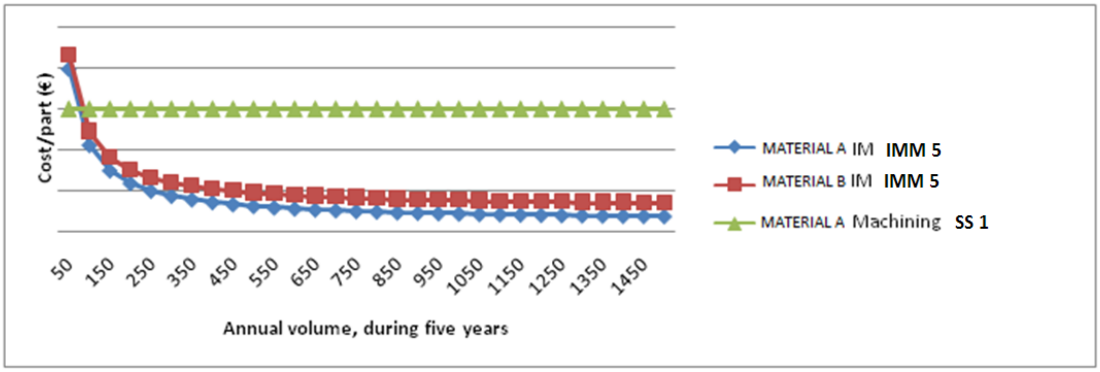


Figure 47 Cost estimations of part A.

The figure shows that it would only be economically sensible to use machining for very low volumes. Therefore, injection molding is preferably going to be used as manufacturing process.

When manufacturing the part with injection molding, the gate should preferably be placed in the central cavity to reduce the risk of gate marks on the surface of the part and to minimize the length of the runners.

The treads in the hole of the part makes it complicated to manufacture with injection molding. There are four alternatives by which it can be manufactured; either with an automatic unscrewing mechanism which creates it in the process, it can be created in the process and the part can be unscrewed from the mold by hand, by the use of a threaded insert, or it can be machined afterwards. Whether or not it would make sense if the feature can be produced by an automatic unscrewing mechanism depends on expected annual volume. According to the theoretical mold cost estimation model such a device in the molds would result in between 200 and 300 hours of extra machining. Given a machining cost of €35/h this would result in an average extra mold cost of at least €8,750. Given such an increase of the mold cost, the cost per part relative to the annual volume during five years can be seen in Figure 48.

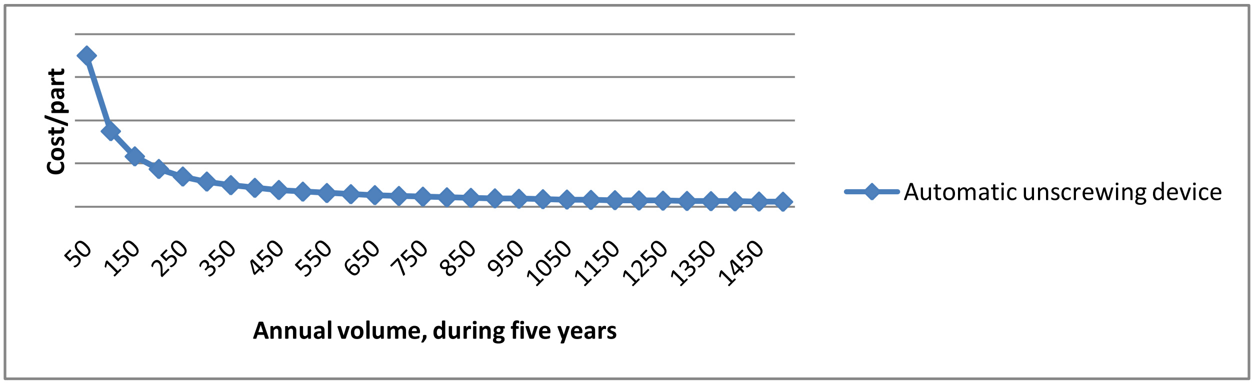


Figure 48 Cost per part when using an automatic unscrewing device in mold.

It may be hard to unscrew part A by hand since the threads are located in a hole. As the material cools it shrinks into the mold, and therefore the part must be unscrewed while it is still relatively warm. Whether or not it is at all possible must be tested to find out.

An insert may also be difficult to use since the wall thickness only is roughly 2mm. It would therefore decrease the flow of the melt. The cost also depends on whether or not the manufacturer has access to an appropriate standard size. If not, it would cost a lot to purchase.

Machining of internal threads for part F costs €3 per part, including machining of the notch. Even though the threaded feature of part A is bigger than that of part F, it can still be used as a reference.

5.3.2.2 Part B and D

Since part B and D are so similar, the analysis is performed on only one of the parts, part D.

The parts B and D can either be produced with injection molding or with thermoforming. Cost estimations of producing part D using the two processes can be seen in Figure 49. Which process is the most appropriate from an economical point of view depends on the annual volume. For very low volumes thermoforming is the most appropriate, and for higher volumes injection molding is preferable. This is due to the high initial fixed cost of injection molding, and the high variable cost of thermoforming.

As mentioned previously, the calculations are made using mold, material, and processing costs, with no consideration to other costs that the manufacturers has to carry the costs for.

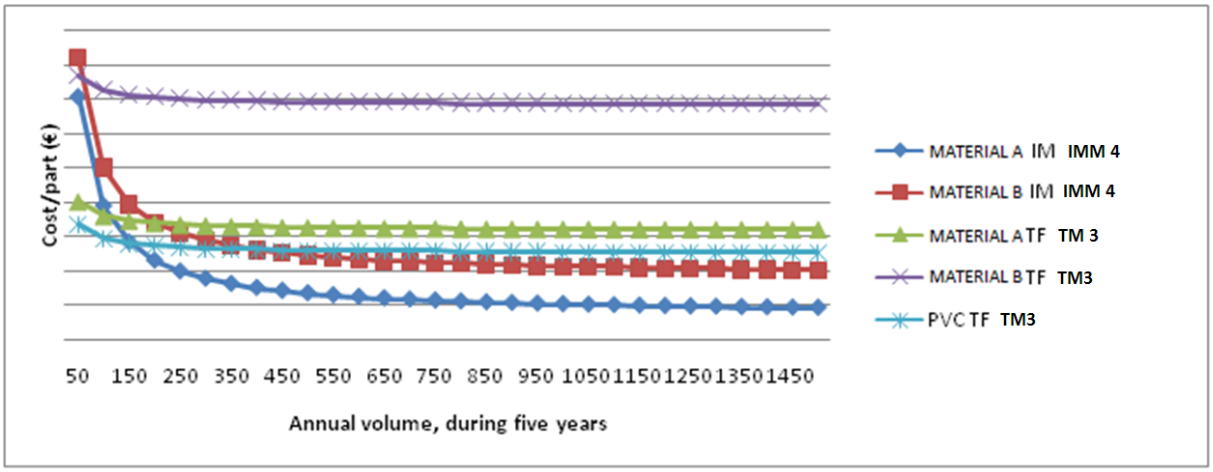


Figure 49 Cost comparison between injection molding and thermoforming for part D.

Since no thermoforming manufacturer was able to give a price estimate of the parts in MATERIAL A or MATERIAL B, the processing cost of part D in PVC have been used to estimate the processing cost without material. Two thirds of the processing cost of PVC, including material, is used as processing cost of producing part D using MATERIAL A and MATERIAL B. To this, the material cost of MATERIAL A and MATERIAL B been added. The material cost is in turn calculated from the cost of purchasing MATERIAL A and MATERIAL B sheets.

None of the injection molding manufacturers has been able to give an estimate of the processing costs of part D including material. Due to this, the processing costs of part C from IMM 5 are used for estimate the processing costs of part D. This can be done since the material usage of both parts should be roughly the same. To be on the safe side, approximately 15% per part has been added to the processing costs of part C.

Even though it has been established that it is possible to thermoform MATERIAL A and MATERIAL B, there are some problems. A large problem is that very few manufacturers have experience from these materials. Therefore the materials have to be test formed. This could be carried out at a low cost since the molds used for thermoforming are relatively cheap from some manufacturers, even though they are rather expensive from some others. However, in this case, the sheets are unusual among the manufacturers, and because of this they do not have sheets of these materials in storage. So to be able to test form the materials the manufacturers need to order the sheets specifically for the test forming. This is expensive since the semi product manufacturers only want to sell sheets in large quantities.

To establish whether or not injection molding can be used to produce parts B and D test molding needs to be carried out. The problems which potentially could occur are warping and short shots due to high flow length to wall thickness ratio. In this case the issue with this test molding is expensive molds. If it is discovered that there is a problem like warpage, it may be solved with increasing the mold temperature or adjusting the mold before hardening to compensate for this. This would increase the cycle time and therefore also the processing costs. However, the margin to the costs of thermoforming is quite large. If warping still occurs, it might be possible to use several gates to mold the parts. This would on the other hand increase the risk of weld lines.

5.3.2.3 Part C

Since part C cannot be manufactured with thermoforming, the only alternative is injection molding. In this case machining is not used as a manufacturing reference since the material wastage would be very high.

If the part is going to be manufactured with injection molding, there are a couple of problems which needs to be cleared out. These are thick walls, undercuts, and potential warpage. The part has very thick walls. This greatly increases cycle time. This will be further analyzed in the design analysis chapter on page 106. The second problem has to do with the undercuts.

There are two suggested mold opening directions. Which is selected affects number of undercuts and mold parting plane complexity. Pros and cons with these cannot be further discussed due to the public nature of this report.

The final problem to analyze is potential warpage due to thick walls and long flow paths. This problem is enhanced since the two potential materials are semi-crystalline. However, the risk of warpage can be decreased by making the part thinner and by selecting glass fiber reinforced MATERIAL B as material.

5.3.2.4 Part E

Part E is only analyzed from an injection molding perspective since thermoforming cannot be used due to geometrical complexity of the part. The costs of machining have only been gathered as a reference. By comparing these estimations to for example the production costs of injection molding part A, it is safe to say that for most annual volumes it would be the most economical alternative to injection mold this part.

5.3.3 Cost Estimation Spread Analysis

There is a spread in some of the gathered cost estimations. The cost difference between the molds of different injection molding manufacturers is at times very large.

By comparing the cost estimations for different molds and manufacturers it is discovered that there are large variations. The difference is large for all parts. The average spread is especially large for part C. Here the difference between the two highest and the two lowest is 83%. In this case it is assumed that a compression mold cost as much as an injection mold. See Figure 50 for an overview of the differences.

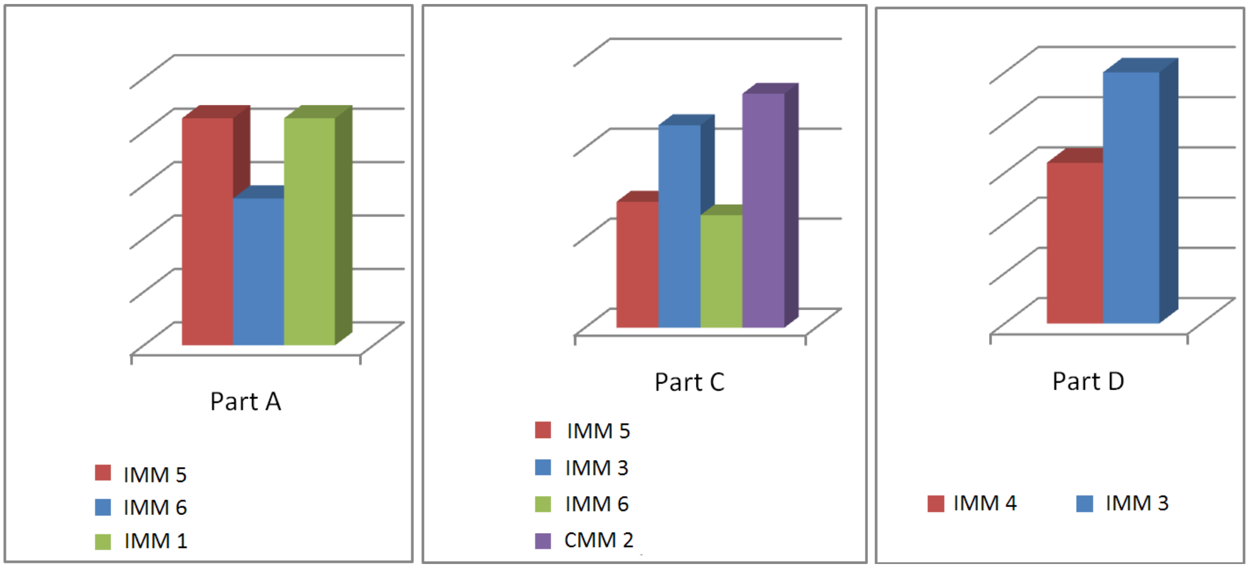


Figure 50 Mold cost (height) estimations for injection molding.

The mold costs estimated by IMM 3 are high both for part C and D, and the costs estimated by IMM 6 are low both for part A and C. However, the costs estimated by IMM 5 seem to be following the majority for both part A and C, at least if only the molds strictly used for injection molding are being considered. Because of this, these mold costs are used in when comparing the costs of injection molding to other processes above. In the case of part D the mold costs estimated by IMM 4 are being used since IMM 3 seems to overestimate the cost of the mold for part C.

These variations could be a result of any of many factors. However, there are four which seem more likely; estimation error, differences in cost structure, different types of steel used, and different margins used. Since none of the estimations are binding and all were done without too much research, it is possible that they simply are somewhat wrong in some cases. However, there seems to be a gap in the estimations, and if the variations only would be a result from estimation errors it would be more probable that they would have a more even distribution. The variations could also be a result of more systematic difference between the companies, such as different cost structures. Since the production cost depends on a large amount of different factors, like salaries of operators, cost of machines, set-up time, machine down time, cost of raw material, wastage, free capacity, et cetera, it is easy to draw the conclusion that the variations in offers simply is due to differences in any of these factors. Furthermore, the cost of the buyer depends on more factors. Overhead must also be covered in the price of the products of a company. Because of this, the variations can also result from different functional structures and levels of offered service to its customers. The third alternative is that the estimations are made for molds made from different types of steel. The less expensive molds may in this case be made from a softer steel, which is more easy to machine. A fourth potential solution could be that some manufacturers simply charge extra for the mold. However, the differences seem to be too large to only have this as a reason.

There are also large variations in the cost estimations of thermoforming molds, which can be seen in Figure 51, and in prices given on the MATERIAL B and MATERIAL A sheets. Both of these variations could be due to the above mentioned factors, and the prices variations of the sheets could also be due to variations in order quantity. The mold estimation from TM 1 is based on an average of the interval given.

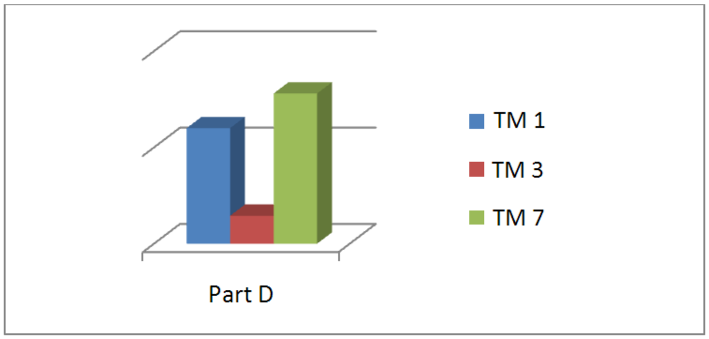


Figure 51 Mold cost (height) estimations for thermoforming.

5.3.4 Considering the Cost of Capital when Selecting Manufacturing Method

When calculating the cost of production the cost of capital should be considered. In a case like when comparing injection molding to thermoforming this becomes extra important since there are big differences in the distribution of costs over time.

In Figure 52 net present value (NPV) cost calculations are made of part D for different annual volumes over a five year period. The three graphs seen are for 20%, 10% and 0% interest rates. The same information is used for these calculations as for the comparison of injection molding costs and thermoforming costs of part D on page 96. By looking at the graph to the right, which shows the 0% interest rate NPV calculations, the same conclusions can be made as by looking at Figure 49. This is that it only would be economically sensible to use thermoforming of MATERIAL A if the annual volume is below roughly 100 parts, and thermoforming of MATERIAL B for volumes below approximately 50 parts per year. Remember that it is costs which are added, and that the NPVs therefore are supposed to be as low as possible.

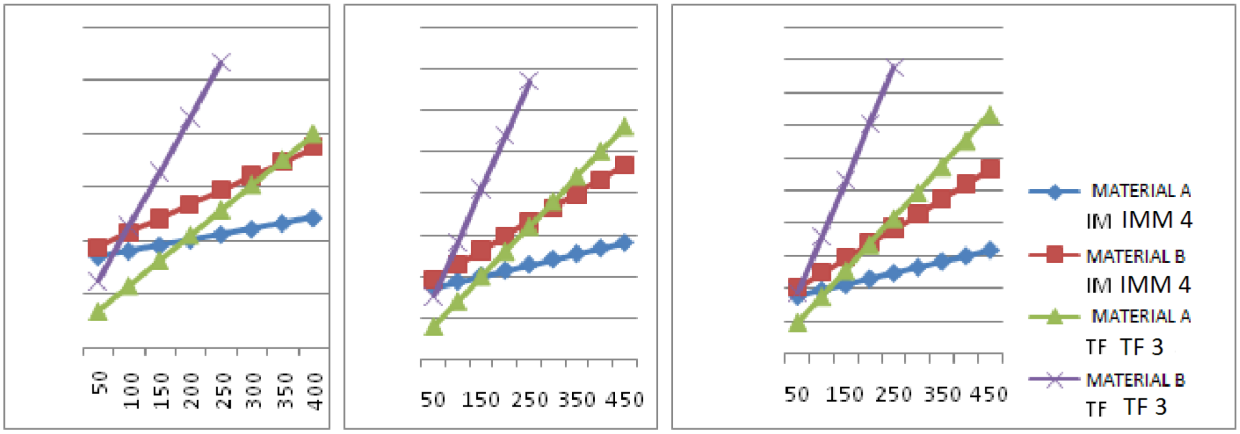


Figure 52 NPV (y-axis, €) cost calculations of part D for different volumes, (x-axis) using 20%, 10%, and 0% interest rate.

By looking in the other graphs, which consider the cost of capital, it is discovered that would be economically sensible to use thermoforming for larger volumes. However, not even using an interest rate of 20% would make it economical to thermoform MATERIAL A over an annual volume of 200 parts.

In Figure 53 the same calculations are made for part A. These are based on the same information as the previous manufacturing calculations which are made on page 94. The graphs show that it is only economical to use machining of MATERIAL A for very low volumes, even if an interest rate of 20% is used. Machining of MATERIAL B is not showed in the graph due to its very high cost.

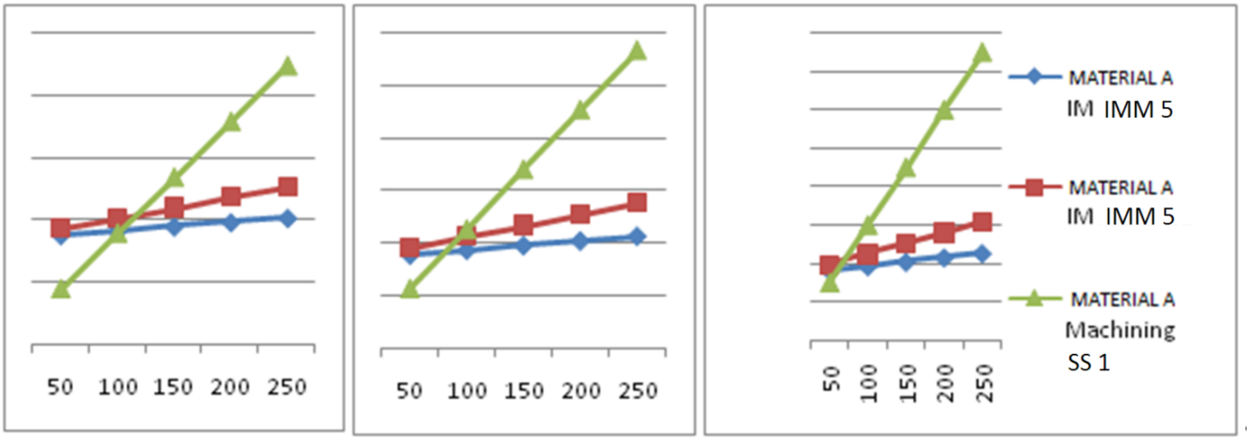


Figure 53 NPV (y-axis, €) cost calculations of part A for different volumes, (x-axis) using 20%, 10%, and 0% interest rate.

Note that no consideration has been made to inflation, changes in material costs, or changes in processing costs, in any of the NPV calculations.

No of these calculations are made for the production of any of the other parts since it is only parts B, D, and A which have an alternative manufacturing process to injection molding.

5.4 Design Analysis

In this chapter the design of part F and the body parts is analyzed from a manufacturing point of view.

5.4.1 Design Alternatives for Part F

In this chapter the design alternatives of part F are being analyzed. The different designs are developed in an iterative way as more and more information was gathered and presented in chronological order. The development of the design is based on that the thermoplastic part F is going to be produced with injection molding, as mentioned above.

The original design of part F has some very thick intersections. This will make it hard to produce this part using any polymer processing technique due to the low thermal conductivity of thermoplastics.

Due to this it would be greatly beneficial if the walls could be thinner, with more even thickness. However, due to product specifications the external geometry must be kept. Because of this, the part must be divided into two separate. A more elaborate discussion cannot be performed due to the public nature of the report.

5.4.1.1 Manufacturing Analysis of the Final Design Suggestion

By examining the theoretical and empirical study there are some things which need to be considered and commented. However, these cannot be discussed here, since this is the public version of this report.

In Figure 54 the cost per product for the injection molding the final design can be seen. These costs are based on the use of aluminum molds, gathered processing costs, MATERIAL B as material, two batches per year, and machining of the notch used for mounting and internal threads. However, it should also be noted that aluminum molds only can be used to produce a few thousand parts. The cost for a steel mold varies depending of type of steel used. The cost could be anything from the same to three times as high.

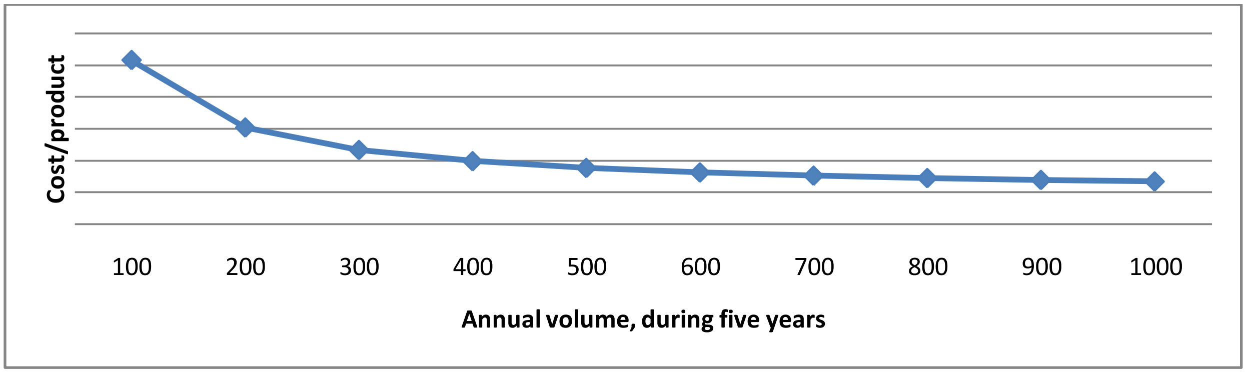


Figure 54 Cost of producing MATERIAL B part Fs with injection molding using aluminum molds.

The cost of injection molding of the final design is far from the cost of machining the product.

5.4.1.2 *Joining of Final Design*

The final design suggestion of part F consists of two parts. These must be joined with the use of some joining method. To be able to select one, the joint should be analyzed using the following factors:

- Functional
- Technical
- Spatial
- Economical

The mechanical requirements on the joint are relatively small. There are no large loads which the any of the two parts must be able to withstand.

The joint must be able to withstand the same chemicals which the material must be able to withstand. Furthermore, the joint cannot leak any liquid into the closed cavity. This is because any liquid in part F would make it wobble. For the same reason the joint itself must provide a balanced solution.

Since part F is going to be coated to improve its resistance wear, the joint cannot interfere with this. However, since there are many coating processes and coating materials the evaluation of joining methods and these two must be carried out together

Part F must be possible to clean. Due to this, the joint cannot prevent this or make it more difficult. Therefore, the joint design cannot include any hidden, rough, or hard to reach features.

When examining different joining processes it is discovered that some of them can be more or less excluded for one or several reasons:

- Laser welding is most often used for sheets, and might therefore be hard to use in this case.
- Gas welding only offers tolerances in the range of ±1mm and since part F needs to be balanced it might not be appropriate to use.
- Even though ultrasonic welding uses a flexible process it is most often used for smaller parts.
- Thermoplastic welding is most often used to join sheets and does probably not offer good enough tolerances.
- The use of mechanical fastening systems would result in making it more difficult to clean part F in the case that for example screws and rivets would be used. Snap fit solutions would on the other hand not give the mechanical strength needed to prevent liquid leakage in to the cavity.

The two joining processes which remain are adhesives and friction welding. However, these might also have potential problems. The adhesive used must have enough chemical resistance, prevent liquids to leak into the closed cavity, and cannot prevent the coating of part F. Whether or not any typical adhesive interfere with a coating process must be tested, and the adhesive used must also be tested for the same chemicals as the material.

Using adhesives to join parts is a very slow process, so even though the adhesives themselves are not expensive, the process might be costly depending on salary costs. Friction welding on the other hand is a rather fast process, but does instead require a larger initial investment. This high speed process does produce some excess material, which needs to be removed and does thereby increase the process costs.

Figure 55 shows estimations of how much it would cost to join part F with adhesives or friction welding for different annual volumes. The fixed costs are spread over the annual production over five years. The estimations are based on the following assumptions:

- The adhesive and primer used are those recommended by JMS 1.
- One glue gun could be used during all five years, but a new nozzle would be attached every time one bottle of adhesive is finished.
- 50ml of primer would last as long as 50ml of adhesive, that is 6.56m.
- The salary of the person applying primer, glue and joining the two parts, is €30 per hour.
- It would take 30 seconds to join the two parts without primer, and 1 minute to join them with primer.
- The diameter of the cylindrical joint is approximately 60mm.
- A low cost fixture for friction welding would cost 42% less than an ordinary fixture.
- Friction welding capacity could be bought from JMS 2.

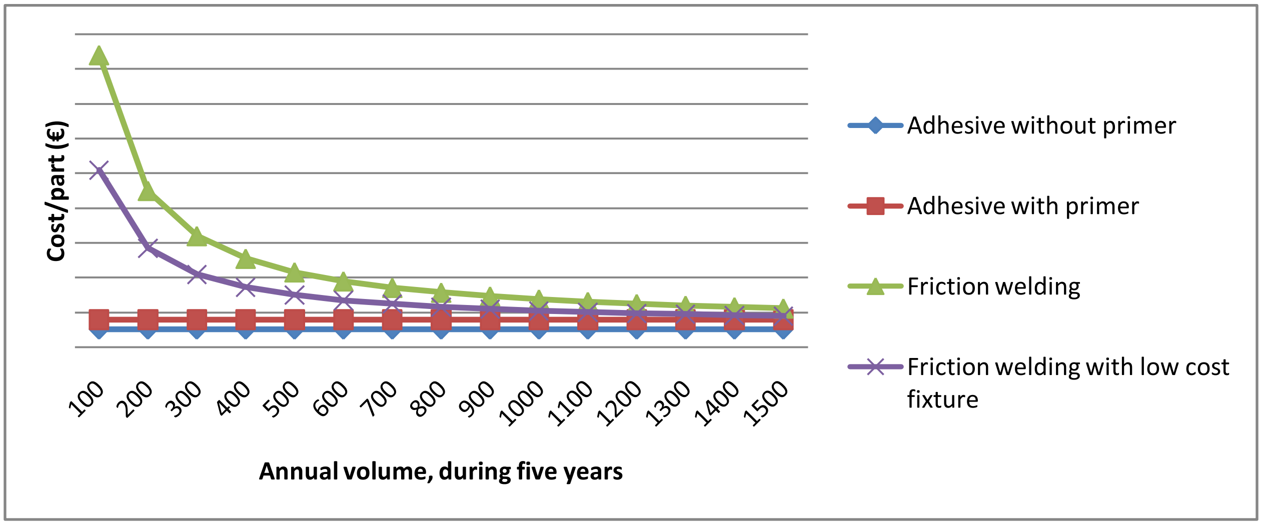


Figure 55 Costs of joining part F with adhesive and friction welding.

It can be seen in the figure that using adhesives, with or without primer, is less expensive than using friction welding, given the above mentioned assumptions. Even though the fixture would be free, the use of adhesives without primer would be the most economical process. In this case the use of adhesives with primer would be a little more expensive. Furthermore, if larger amounts of primer and adhesives would be bought, some discount can most probably be expected, and the joining of part Fs can probably be carried out by a personal with lower salary than €30 per hour.

5.4.1.3 Coatings for Part F

Two selections are to be made regarding the coating of part F; coating process and coating material. Both these selections must be carried out with consideration to substrate material, erosive wear, and conductivity of part F. In this case, the coating does not have to work as a protection against the chemicals since the materials are resistant in themselves, but of course the coating in itself needs to be able to withstand the chemicals.

Before the coating process begins the parts needs to be properly cleaned. This is especially important since part F is going to be injection molded, and because there often are some grease left on the part after molding. To be able to be sure that the coating adheres to the substrate these leftovers needs to be removed.

The substrate material is either going to be MATERIAL B or MATERIAL C. These are relatively soft compared to the substrate materials usually used. This could lead to a problem since it does not matter if the coating is hard as long as the material which is it adheres to is soft. Think of it like a sheet of glass on a bed. If a person would stand on it, it would break. However, in the case of part F, it does not have to be able to withstand any large forces which are perpendicular to the coating surface and focuses on a small area. Because of this, there is no good reason to why it should not work, especially since both MATERIAL B and MATERIAL C are hard materials for being thermoplastics.

MATERIAL B and MATERIAL C could have another problem in the coating process. Some of the coating methods use high temperatures to apply the coatings. However, the substrate temperature should not exceed the melting temperatures of the materials during the coating process.

Part F has previously been manufactured in aluminum which is a good conductor of electricity. Now it is instead going to be manufactured in thermoplastics, which are bad conductors. However, part F needs to be conductive. This can be achieved in a couple of ways. Either carbon fibers can be used in the polymer to lower the electrical resistance or a conductive coating can be applied.

Part F has some vey sharp edges. Due to this either the coating applied needs to be very uniform or the coating needs to very thin to save the geometry of the edges. For example, a 1mm thick coating which is not uniform would simply ruin the geometry of the part.

By examining the theory of the coating materials and processes, it is discovered that some coatings are more appropriate to use in the case of part F than others. For example, paints and polymers are mostly used as coatings to protect the substrate from corrosion. Furthermore, since the selection of thermoplastic materials for the substrate is so restricted, the list of potential polymer coating materials would not be much longer than the list for substrate materials.

Coating materials which are usually used as hard coatings are metals, composites, and ceramics, and these can be applied by the use of for example physical vapor deposition (PVD), chemical vapor deposition (CVD), thermal spray coating (TSC), and electroless plating (ElsP). If metals coatings are o be applied on to a thermoplastic material this can be done by using ElsP, TSC, or some vapor deposition process. Electro plating (EP) can also be used, but then must a first conductive layer of copper and nickel be applied using ElsP. The benefit of metal coatings is that they are conductive, and the benefit using EP or ElsP is that complex shapes can be coated. However, metal materials are not as hard as the other coatings materials which can be used. For example solgel and silicone coatings are much harder and are also possible to apply at low temperatures on complex shapes. Diamond and ceramic coatings are also very hard. However, these could be more difficult to apply on polymer substrates because of higher process temperatures.

High temperatures should not be a problem if TSC is used, but the coatings would probably need to be thicker since it is more difficult to create a uniform thickness using the process. Therefore it might be more appropriate to use PVD despite that it would be more expensive, since this process can apply thin coatings at rather low temperatures. The uniformity on complex shapes could perhaps be a problem for sputtering though, but with good process control it should be possible. CVD on the other hand uses somewhat higher temperatures. So if a chemical coating process is to be used, PACVD is probably more appropriate. The problem with long cycle times could be solved by coating several parts at once.

Because there is a large amount of special coating materials and processes, and the selected coating material and process must be based on a commercial solution, the rest of the analysis is based on the empirical study. However, since this is the public version of this report, this analysis is left out.

5.4.2 The Body

Below, the geometry of the body parts is analyzed. The analysis is based on that part A, C, and E are going to be injection molded, and that part B and D are either going to be injection molded or thermoformed.

5.4.2.1 Part A

The outer surface of part A must remain smooth to ease cleaning. So as long as these specifications are kept, this geometry is allowed to be changed. However, since the internal geometry is mostly locked, and the wall thickness is to be kept as constant as possible, there is no reason to change the outer geometry.

Focusing on the inner geometry instead, there is one feature of the part which has a much thicker intersection than the rest of the part. It would be good to change this thick intersection into a ribbed structure instead. The result of this would be shorter cycle time in production, and reduced risk of warpage.

To be able to injection mold the part, there need to be some draft of surfaces which are parallel to the mold opening direction. This is especially important for internal cavities, such as the hole in part A. Therefore, an at least 1 degree draft is required on these surfaces and is preferable for the outer surfaces.

5.4.2.2 Part B and D

Both parts have an even wall thickness, which is good for all plastic processing methods, and both parts would preferably need some draft to ease the demolding process for both injection molding and thermoforming. However, other design features are discussed below from a process specific point of view.

5.4.2.2.1 Design analysis from an injection molding point of view

The parts have a very high thickness to flow path ratio, and this increase the risk of warpage and short shots. However, by increasing the mold temperature during injection this problem may be possible to solve, even though this also would result in an extension of cycle time.

Another potential way to handle the problem would be to use several gates. The drawback of this solution in an increased mold cost and risk of weld lines

5.4.2.2.2 Design analysis from a thermoforming point of view

With thermoforming it is not possible to produce the same complex geometries as with injection molding. This does that for each of the extra features which are incorporated in to the design there is often some machining required after the actual forming process. So is the case here as well.

The special stepped overlap which part B and D has with each other needs to be machined. It would be possible to form the step of part D in the forming process if a 1mm bump would be acceptable on the surface of the body. However, since this would make it more difficult to clean it, this is not acceptable. Therefore, the overlap must be machined after forming. Some other features which must be machined after forming are the holes which are close to the bottom plates.

Despite that both parts have shapes with large radius; the geometry is too complex for regular thermoforming with MATERIAL A as material. To be able to produce these parts with thermoforming, vacuum is not enough, but air pressure must be applied from the other side as well.

5.4.2.3 Part C

Part C is has walls with a thickness of up to a centimeter. This is the most crucial design problem, and it would be greatly beneficial if the structure could be ribbed out. How the ribs would be located depends upon selected mold opening direction.

When a ribbed structure is created, this may leave less material around holes to for examples screws. However, this may be somewhat solved by strategic placement of the ribs or by a dedicated ribbed structure around the holes.

It is not only the area around holes which then to be weakened, but the entire structure. Because even though a ribbed structure offers better strength to weight ratio than a solid structure, part C would get weaker. This could be solved by selecting a material which has better mechanical properties. Another potential drawback is that molds for ribbed structures are more expensive, since they are more complex. However, in this case it cannot be avoided since a one centimeter thick wall would take a very long time to cool, and therefore extend the cycle time very much. Furthermore, when creating the ribbed structure, remember that it is the thickest intersection which determines the cycle time. It is therefore no use to rib one section of the part, if another section still has thick walls. A cost comparison between a thick and a thin design of part C can be seen in Figure 56.

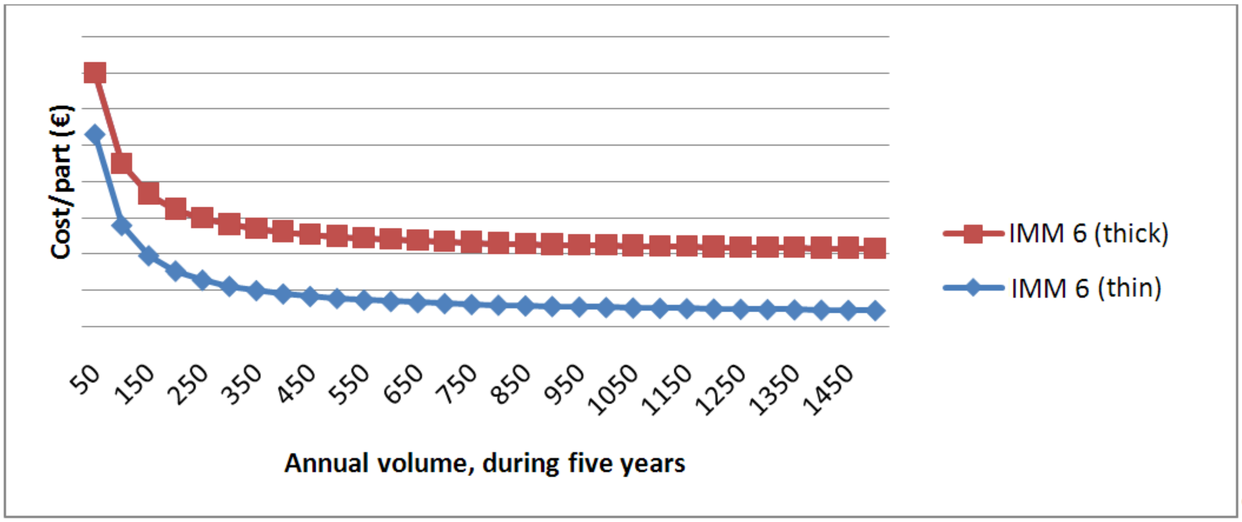


Figure 56 Cost comparison between thick and thin design of part C.

5.4.2.4 Part E

Part E does not have a uniform wall thickness. It would be preferable if for example a ribbed structure could be created to decrease the cycle time. The ribs could either be located internally or externally dependant on geometric specifications.

5.4.2.5 *Joining Parts B, C, and D*

These parts can be joined in many ways. However, since it must be possible to disassemble the parts, no permanent joining method can be used. This leaves out all welding techniques and usage of adhesives. The only joining types which remain are mechanical fastening systems which are not permanent. Therefore, non-permanent and semi-permanent mechanical joining system suggestions have been developed and will be analyzed by the use of the following factors:

- Functional
- Technical
- Spatial
- Economical

The joining alternative suggested when the project started was the use of extra hooks which were to be fastened onto parts B and D by the use of some permanent joining method. The idea is then that these hooks are to be inserted into the holes on the side of part C and work like a snap fit solution. This alternative involves extra parts; something that was established in the DFA analysis was unnecessary. Its mechanical properties very much depend on its design, but since it is located within the cover parts no special material is required of the hooks. The economy of such a joint also depends on the design, however, the extra machining of the holes on part C and the joining of the hooks on part B and D would probably cost at least €3.85 per product. This is based on:

- A processing and assembly cost of €70 per hour.
- It would take 15 seconds to glue each of the four hooks to parts B and D. This means two hooks for part B and two hooks for part D.
- It would take 30 seconds to machine all of the holes on part C.
- Each hook would cost €0.4
- An assembly time of 5 seconds.

Another solution which would require extra parts is the use of screws. Holes, just like the one which is used to fasten the cascade could be created with a low extra cost. The holes in part B and D could also be created in the molding process if they are going to be injection molded, but needs to be machined if these parts are thermoformed. If screws are to be used, the joint definitely would be strong enough. However, consideration would have to be taken to the material of the screw so that it does not react with the solvents, and since the screw heads would show it would be more difficult to clean the body. Given the estimations below, the cost of using screws would be roughly €1.17 if parts B and D are thermoformed and €0.58 if they are injection molded.

- A processing and assembly cost of €70 per hour.
- If would take 30 seconds to machine four holes; two on part B and two on part D. this is only necessary if the parts are thermoformed.
- Creating the holes in parts B, C and D with injection molding would cost nothing extra.
- If would take 30 seconds to assemble the parts.
- There would be no cost for the screws.

The third potential solution would require that part B and D are injection molded. The idea is similar to that of the first suggested hook alternative. The difference is that this alternative uses a snap fit hooks which are created in the injection molding process. The solution is illustrated in Figure 57 and is numbered one. Please note that the creation of these features requires no undercuts. This decrease the cost of the mold, but since the features are located on the outer side of the joined parts, cleaning would be hard. This could be helped by locating the solution in the inside of the parts instead, just as it is illustrated by the twos in the same figure. However, this would require undercut creation.

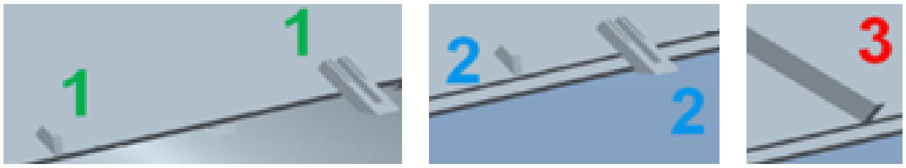


Figure 57 Joining alternatives part B, C, and D.

When designing any of these solutions, the designers must be thinking of which part the hook is located. Since part D is overlapping part B, less elastic deformation is required if the hooks is located on part D if the external snap fit solution is selected. If the internal solution, on the other hand, is desired, the hooks should be located on part B to minimize the risk of permanent deformation. There is also a risk that the mechanical strength of the hooks is going to be low due to weld lines.

The total cost per product of these solutions can be estimated to €0.10 for the external solution, and €1.16 for the internal. These estimations are based on the following assumptions:

- A processing and assembly cost of €70 per hour.
- Assembly of the parts would take 5 seconds for both alternatives.
- The mold cost would not be increased by creating the external snap fit solution.
- Each of the four undercuts required for the internal solution would increase the mold cost by €1000.
- Expected annual volume.
- The cost of the mold for part C would not change.

Since the annual volume is somewhat uncertain, and because the internal undercut creation requires increased initial investments, a sensitivity analysis can be seen in Figure 58. It shows that the cost per product is drastically decreased as the volume is increased.

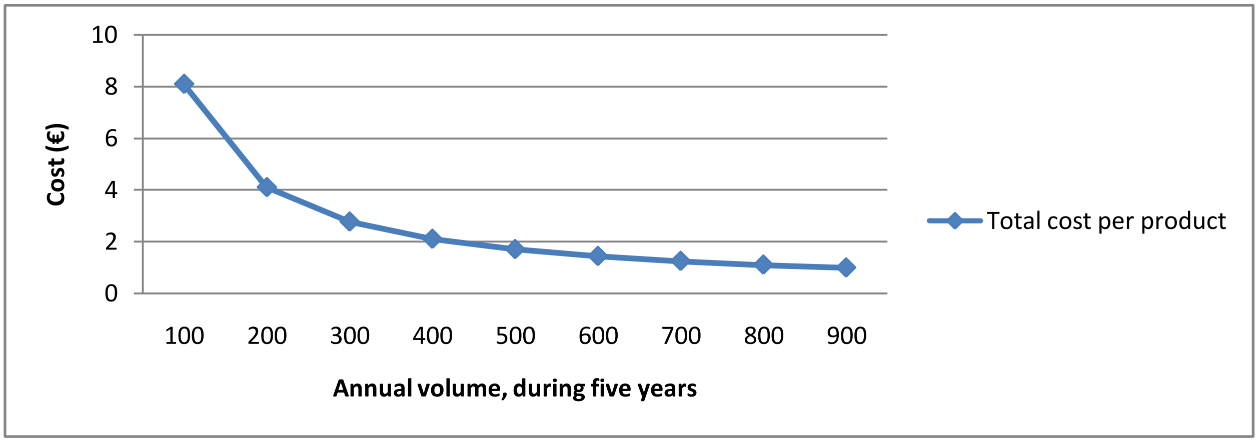


Figure 58 Total cost per product when using the internal snap fit solution which is created in the injection molding process.

A fourth joining alternative, which also is based on that the parts are injection molded can be seen in Figure 57, and is there numbered three. By the use of ribs on part B and D and a hollow track on part C the parts can be located to each other and locked in place by the bottom plates. This alternative requires the removal of the bottom plates, and therefore the removal of the robotic tool from the robot, to enable disassembly.

The cost of this joining alternative can be estimated to €0.29 given the following assumptions:

- A processing and assembly cost of €70 per hour.
- No extra cost for mold.
- Assembly would take 15 seconds.

It should also be mentioned that disassembly and assembly when service is required would take longer than 15 seconds since the removal of the bottom plates is necessary. However, during first assembly the bottom plates are being joined in the same way for all joining alternatives. Therefore, the time necessary to assemble the bottom plates has not been included in the joining alternative cost.

The fifth and final joining suggestion is also a snap fit solution. An illustration of the alternative can be seen in Figure 59, the notches are just colored red to enhance features in the picture. By creating small notches on the edge of the joined part B, C, and D the parts can be locked to each other. The features can either be created in the injection molding process or be created when milling of the edges is done if the parts B and D are to be thermoformed.

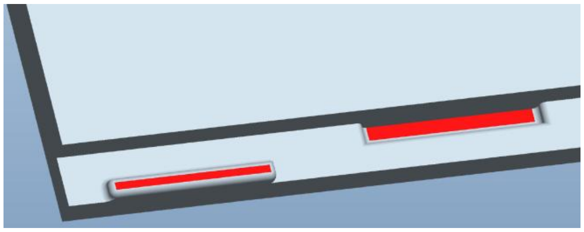


Figure 59 Snap fit solution.

Some special considerations have to be made if the parts B and D are to be injection molded:

- The thickness of the notch, which can be seen as a small rib, should preferably be two thirds of a millimeter to minimize the risk of sink marks.
- By locating the negative notch in the same place, but on the opposite side, as the positive notch on the part which is to be located in between the other cover part and part C, the wall thickness can be kept constant. In the present design this would be part B. For example, if part D has a positive feature which fixates it to part B, part B has a positive feature which fixates it to part C. Part B would in this case have a negative feature which is matched by the positive feature of part D, and a positive feature which is matched by a negative feature of part C. Please note that part B has both a negative and a positive feature. These should be located in the same place, but on opposite sides of the wall, to keep the wall thickness constant.

The product cost of this solution can be estimated to €0.63 if all parts are injection molded with the expected annual volume, and €1.10 if part B and D are thermoformed. These estimations are base on the following assumptions:

- A processing and assembly cost of €70 per hour.
- No extra cost for the mold which is used to produce part C.
- If parts B and D are injection molded, the positive features of these can be created without sliding cores, simply by the use of a dedicated ejection system at no extra cost.
- The negative features on part B is created by the use of 2 sliding cores at the cost of €1000 each.
- Assembly would take 5 seconds.
- Extra complications of the trimming of the edge if parts B and D are thermoformed involve an extra cost of €1.

To examine the costs of creating the features with injection molding at different annual volumes, the sensitivity analysis showed in Figure 58 can be used. The cost can simply be divided by two.

5.5 Comments to Qualitative Design Guidelines

The opinions are divided whether or not qualitative guidelines should be used or not. In this analysis, they are used in a complementary way to ensure that no aspect of the DFMA analysis is forgotten. In the case where a motivation or a comment is necessary or in some other way is appropriate, it is given below. All guidelines are not used.

- Minimise production steps.

By the use of injection molding near-net-shapes can be created, this minimizes the number of production steps. The manufacturing analysis above also shows that it would be economical to use this process relative to machining and thermoforming for most annual volumes.

The creation of part F is somewhat special. The final proposal seems to involve a fair amount of production steps. First two parts are created, and then coated and joined. Furthermore, if sharp edges are wanted, some machining is most likely needed. However, the analysis also shows that this is the most economical and appropriate way to produce it.

- Use standard components, processes and procedures whenever possible.

The only opportunity there is to use standard components is the screw or hooks when joining parts B, C, and D in the case that they are going to be joined in this way. However, when producing the parts, standard injection molding can most likely be used. Special processes of injection molding, such as RHCM and microcellular molding can be evaluated as a second step. To be able to process MATERIAL A sheets in thermoforming a process with over pressure is required. This is not some special process in this case, but is the most simple thermoforming process which can process MATERIAL A.

- Do consider using stock items when you need only a small quantity of components

The total annual volume of any of the products is relatively low, and the use of machined stock items is considered. However, the volume expected is still too large to make it economical to use this alternative.

- Materials and methods of fabrication must be the cheapest acceptable.

MATERIAL A is a much less expensive material than MATERIAL B, and MATERIAL B is much less expensive than MATERIAL C. Which material can be used, partly depends upon the chemical testing.

Regarding manufacturing, an economical analysis of several appropriate manufacturing methods is done above.

- Manual processes should be reduced to a minimum.

There are a few manual processes which could be needed in the production of the robotic tool. These are for example, assembly of parts B, C, and D, potential unscrewing of treaded injection molded parts such as part A and part F, and drilling of undercut holes. In each case where manual processes are presented an economical analysis is performed to motivate a decision.

- Design a base component to reduce the need for jigs and fixtures.

Part C can be seen as a base component onto which other parts are mounted. This does that this part is relatively complex and has many undercuts.

- If symmetry cannot be achieved, exaggerate asymmetry features to facilitate orienting.

All parts are either symmetrical, like part A around the central cavity axis, or greatly asymmetrical.

- To achieve a high level of reliability the designer must consider the use of well tried and tested components and materials, rather than new and uncertain ones.

This is not true in the case of new part F. The material is new, the process is new, the design is new, and an adhesive is used. There are many new things with the new part F, but this is the point. The purpose of the development is to find out whether or not a thermoplastic part F can be created, and this involves a lot of uncertainty and new challenges.

- Make sure disassembly is equally practicable as assembly.

If the joining alternative which uses ribs is selected, the assembly of the parts B, C, and D is easier than disassembly. However, this option is evaluated using quantitative methods relative to other assembly alternatives.

- Design castings so as to minimise the cost of flash removal.

The sharp edge of part F increases the risk that flashing will occur. However, since the edge and the design of it is essential, this cannot be avoided.

- Use the widest possible tolerances and finishes on components.

The only tolerances which are given are the diameter of part F and one for the mounting of part F. All the other measurements are less important. For example, the body parts only need to be possible to assemble.

The surface finish of the surface of part F needs to be smooth. However, whether or not special efforts needs to be made in order to improve the surface finish relative to the regular result of injection molding needs to be tested. The surface finish attained using regular injection molding and thermoforming is enough for the body parts.

5.6 General Analysis of Short Series Processing of Thermoplastics

Trying to lower the costs for short series production of thermoplastics is a complex matter. There are no easy solutions or fixed processes to follow in order to succeed. However, there are ways it can be achieved. By understanding how the processes used works a new product development team can also understand how a product should be designed for manufacturing and assembly. This is important to avoid complex and expensive solutions to problems which could have been avoided. Furthermore, by collaborating with the manufacturer which is going to produce the part, the design can be adapted to their capabilities and competences. Since the capabilities of all companies differ due to different machines and suppliers, and competences differ due to different level of experience, each manufacturer must be treated individually. The tight link between competence and experience is because of the empirical nature of polymer processing. Most information available is based on a specific material processed by a specific machine using specific process parameters into a specific geometric shape. Since most individual cases are unique, and because it is not possible to totally rely on simulation software, it is very hard to say what is possible and what is not if it not based on similar empirical results. However, it should also be mentioned that there are some factors which affect the production cost which are universal for each process. These are described in the following chapters.

The cost of production also differs between manufacturers due to already mentioned factors. This results in that the cost of producing parts varies for those whom use them as suppliers as well. As illustrated in the chapter Cost Estimation Spread Analysis on page 97, costs for injection molding and thermoforming molds can vary greatly.

So, something that all manufacturing processes for thermoplastics have in common is that the selection of supplier should be made with care, and that the design of the product should be carried out with the help of that manufacturer.

5.6.1 Injection Molding

The cost of producing parts with injection molding can be divided into processing costs and costs for the mold. There are also other costs such as overhead and set-up costs, but the processing and mold costs are those which are affected by part design.

There are a lot of factors which determine the cost of producing a part with injection molding. The most important are listed and commented below:

- The geometric complexity of the part

The geometric complexity both affects the processing costs and mold costs. The more complex the part is the more machining time is required to create the mold, and the more machining time which is required, the more the mold costs. Complex shapes also required more preparations before machining, such as gate analysis, runner design, CAM preparation, flow analysis, and ejection system analysis. Processing costs are also increased due to increased complexity by for example extended holding times during cooling or more problematic filling. Complex parts may also require more complex runner systems which might result in increased material spillage and trimming costs.

If undercuts exists in the design, this does further increase both processing and mold costs. Cycle times are extended because of the extra steps in the demolding process which are required as the moving parts in the mold retract. How much the mold costs are increased by an undercut, depends on the type of it. For example while a simple side pull mechanism may add €1000 to the mold cost. An unscrewing mechanism adds much more.

The parting plane of the molds is also determined by the geometric complexity of the part, and the more advanced the parting plane is the more expensive does the mold get.

- The size of the part

The size of the part also affects both the processing and mold costs. A large part requires a large mold base, which is more expensive than a small, and requires more machining. The increased processing costs are for example due to longer filling time and more required material. Furthermore, a larger machine may also be needed because of larger shot size and injection pressure.

- Cost of poor quality due to part design

By considering the limits and opportunities of the process when designing parts the cost of poor quality can be greatly decreased. One of the most typical guidelines is to try to keep the wall thickness constant since this eases the filling of the cavity and reduces the risk of receiving warped parts. The wall thickness should also be relatively thin; roughly 2mm to 3mm. The usual way by with keeping the wall thickness thin and constant is to use ribs to give mechanicals strength to the part. These ribs should be somewhat thinner than the regular wall thickness to reduce the risk of sink marks. How much thinner depends on the viscosity of the material, but approximately two thirds is recommended.

To further ease the flow of material, variations in wall thicknesses should be smooth and sharp edges preferably avoided. Sharp edges should also be avoided since these features wear most quickly in the mold.

The risk of weld lines can be reduced by thinking of this and the location of the gate when designing the part. By strategic positioning of the gate, the flow distance of two flow fronts can be reduced, and by reducing the distance the temperature of the fronts can be kept as high as possible. The same applies to the design of runner systems. Furthermore, both gate and runner design should be made with general consideration to flow paths.

If the parts have flash after the injection molding process, this must be removed. At best the flash can simply be ripped off, but if the part has high tolerances it must most often be machined. Either way, flash removal adds costs to the production of the part, and can be viewed as an extra step in production. By simply considering the risk of flashing when designing the part the risk can be reduced, and extra costs might be avoided.

- Miscellaneous

With injection molding it is possible to produce both tight tolerances and special surface requirements. However, the tighter the tolerances and the smother surfaces which are required the higher the processing and mold costs. Because of this, surface and tolerance specifications should not be selected without thought and proper motivation.

5.6.1.1 The Use of Special Processes to Lower Costs for Short Series Production

In the theoretical framework some of the available special processes for injection molding are described. Many of them require a higher initial cost than conventional injection molding, like for example gas-assisted injection molding, overmolding, microinjection molding, injection-compression molding, and thin-wall molding. However, all of the mentioned offer special capabilities that may lower the total production cost. Because of this, they should not be discarded without proper consideration.

A few of the processes offer the possibility to use less pressure in the process. These processes are structural foam injection molding, microinjection molding, microcellular molding, and low-pressure injection molding. Because less pressure can be use when using these processes, they enable the opportunity to use less expensive molds. However, whether or not the increased costs for using special processes can be outweighed by the lowered costs for the molds still remains to be examined.

Insert molding is a process which might have increased initial costs for a mold compared to conventional injection molding. However, inserts can be used to create geometric features like for example threads, which otherwise might have been to be machined or created by automatic unscrewing mandrels at very high costs.

5.6.1.2 Special Ways of Lowering Mold Costs

One of the largest problems when producing short series with injection molding is the high cost of the mold. Even though it might be preferable to use this process despite the high initial investment, due to its capabilities to produce near-net-shaped complex parts at low cycle times, there are methods by which the cost of the mold can be decreased.

Much effort has been focused on trying to standardizing mold sizes. The benefit of this is that off-the-shelf base mold solutions can be bought at lower cost and shorter lead times than customized sizes. As a result the mold might be a little too big, but since standardized support and ejection systems can be acquired, the pros often outweigh the cons. However, the use of standard sized base molds is not a way to lower the costs of customizing the cavity or the ejection system of a mold, and since between 60% and 70% of the cost of a mold is due to machining, a large portion of the cost still remains.

In some special cases, one customized mold can be used to produce several parts. If a number of parts have similar geometric features, a generic cavity with exchangeable mold inserts can be used. By switching these inserts, different parts can be produced with only one large investment. This is something which should be considered when designing the parts.

When the parts which are to be produced are dissimilar, like the case often is, there are other ways to decrease the initial investment. The reason why the machining costs are so high is that steel is so hard and therefore also hard to machine. How hard steels are necessary depends on level of wear on the mold and the number of parts which are to be produced. By selecting the type of steel which cover the specification but not overshoot them, the mold cost can be adapted to the occasion.

A problem with the selection of appropriate steel is that there often lacks the information needed to properly make a decision. This is because it is hard to foresee both wear and demand. Estimating level of wear is difficult since the production of each part is unique, partly due to unique design, and simulation models are not 100% reliable. The difficulty by which the total demand, and thereby also the annual production and length of the product life cycle, can be predicted varies. For entirely new to the market products it can be very hard, but for a redevelopment of an old product it will probably be much easier.

Two of the reasons why steel is used as mold material are the level of wear and large pressure used. By decreasing the viscosity of the melt, both of these can be decreased. Using special injection molding processes like microcellular molding and RHCM this can be achieved. However, both of these processes are still relatively new and they do require specially trained operators and dedicated equipment. Because of this, the processing costs are relatively high compared to regular injection molding. Furthermore, since they still are new it is even harder to estimate level of wear to select an appropriate type of steel.

Another way to try to lower the mold costs is to select aluminum as material for the mold. Aluminum is less hard and it is therefore possible to produce fewer parts with such a mold. However, if the expected annual volume is low enough, it might be worth considering. How much fewer parts depend on a lot of factors and can be hard to estimate. As a best case scenario over a million parts can be produced, and at worst only a few hundred. To increase the number of parts which an aluminum mold is able to produce, it can be coated. However, since the coating process is expensive, it is most often more sensible to use regular steel molds in this case instead. How much cheaper an aluminum mold is than a steel mold differs. Generally it can be said that the more complex the geometry of the cavity is going to be, the more is saved by using aluminum. At best the cost of an aluminum mold is one third of the cost of corresponding steel mold. Even epoxy molds are used to lower the cost of the molds, but they are mostly used for very low volume prototyping purposes.

Using aluminum molds offer other advantages than just lower costs. For example aluminum builds up less stress during machining. This enables even faster machining of molds. Another pro is that aluminum molds heats faster and easier to control the temperature of. This does that the cycle time can be reduced. However, the usage of this type of molds also leads to other cons than decreased life time. The mold temperature cannot be as high as for steel molds, since aluminum start to anneal at lower temperatures. Furthermore, since these molds cannot withstand the same pressures, the operators controlling the injection molding machines must have a special education. Due to this, aluminum molds are not entirely interchangeable to steel molds. As a final con it can be mentioned that due to the inferior mechanical strength of aluminum, thin ribs in the cavity are not able to withstand the flow front of the melt. So in able to create these features can copper inserts be used.

An interesting finding was made in the empirical study. According to the manufacturing company IMM 3, the cost difference between aluminum and steel molds is next to none it both are produced using high speed milling in China. This should be a result of the lower salaries and less expensive machines of the country. Also IMM 6 suggested that the cost difference between low strength steel molds and aluminum molds is not so big.

5.6.1.2.1 Machining of Steel and Aluminum Molds

The unmodified aluminum molds are more expensive than steel molds. However, the ready to use aluminum molds are less expensive. This cost difference between the modified steel and aluminum molds differs; partly due to level of part complexity and partly due to type of steel used. The more complex a part is, the longer it takes to machine it. Because of this, an aluminum mold may be much less expensive than a steel mold if the geometry of the part which is to be produced is complex, since aluminum takes less time to machine.

According to the empirical study, the cost of a steel mold can differ by a factor three depending of type of steel used. Since 60 to 70% of the cost of a mold can be derived from the machining of the mold, a large portion of this difference must be in the difference of machinability. When comparing the maximum material removal rate from the two steel types Unimax and Vanadis 10, both of which are used for injection molding and are supplied from Uddeholm tooling, a more than threefold difference is found. The material removal rate of Unimax is between 4,800 and 6,000cm^3/min and that of Vanadis 10 is between 1,200 and 1,600cm^3/min. The numbers are valid when a solid carbide tool with TiCN-coating of a diameter of between 10 and 20mm is used. The information used can be found in Table 2 on page 31.

Because the cost of different steel molds differ, the relative cost difference between steel and aluminum molds also varies. The difference between a steel mold which is used to produce low volumes and an aluminum mold is according to the empirical study almost none. This suggestion is supported when comparing the material removal rate of aluminum to a steel type which is used for low volumes, such as Unimax. Given that the axial depth of cut and the radial width of cut both are 8mm and that the speed used is between 610 and 900m/min when machining aluminum, the material removal rate is between 3,904 and 5,760cm^3/min. This is fairly close to that of Unimax, and therefore almost three times the removal rate of Vanadis 10.

The final cost of the modification of a mold, such as machining the cavity, depends on the cost structure of the company as discussed above. However, the time necessary to adapt a mold largely depends on the material removal rate which is possible to use. Due to this, the cost of a mold is also largely dependent of the material removal rate.

Another reason to why steel molds are more expensive than aluminum molds is that they do not require any hardening after milling, and furthermore no final modifications after hardening either. However, there are new steel types which do not require hardening, but they are also rather soft and are mostly be used for lower volumes.

5.6.1.3 Theoretical versus Empirical Cost Estimations

In the theory it is presented a theoretical model which can be used to estimate the cost of injection molding molds. In this chapter the result of this model is compared to the result of the empirical study.

Assumptions and calculations cannot be shared due to the public nature of this report. However, some rather rough assumptions were made when estimating the complexity of the parts, especially for parts C and D. Despite this, given a machining cost per hour of $50, the cost estimations for parts A, C, and D, are fairly accurate, at least if compared to the higher empirical mold estimations. The reason to why the theoretical estimations are high might be that most often are harder steels used for injection molding. However, in this case, the steels used can be softer because of the low volume which is to be produced with them. Consideration to this is taken for the empirical cost estimations but not for the theoretical. The empirical cost estimations for part F are based on molds produced from aluminum. This explains why the empirical costs are much lower. Furthermore, it might be discussed if a machining cost of $50/h is a good estimate for the companies examined, but what should be noticed is that there seems to be a correlation between the empirical and theoretical mold cost estimations. This can be seen in Figure 60.

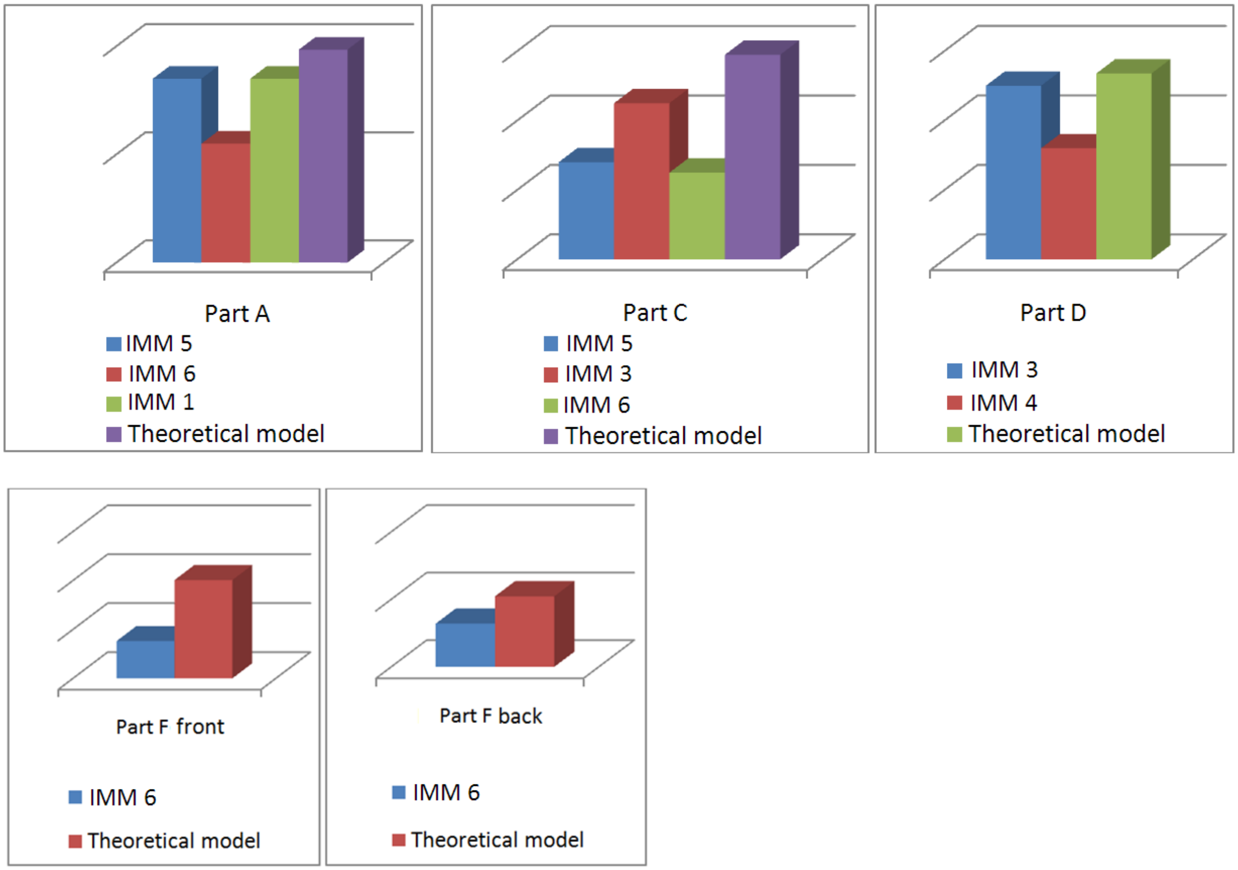


Figure 60 Comparison between theoretical and empirical injection molding mold estimations.

5.6.2 Thermoforming

There are a few oblivious differences between thermoforming and injection molding. To start with does the molds cost much less. This is because they must not be able to withstand the same pressures and therefore often are made from aluminum, and because of the fact that only one mold is necessary. How much less varies, both between manufacturers and between parts. To further decrease the cost of the mold, wooden and epoxy molds are used for prototyping purposes.

Even though the initial costs are lower for thermoforming than injection molding, the variable costs are usually higher due to longer cycle times and because the materials used already are processed. Cycle times are usually around minutes. A rule of thumb is that the cycle time increases with a minute for each millimeter of wall thickness the finished part has. However, this general rule should be used with caution since the cycle time varies with the type of material used, and because cooling time increases exponentionally with wall thickness.

The other large reason to why thermoforming has higher variable costs is because the material already is processed. The product of the extrusion machine is the raw material in the thermoforming process. The situation is even worsened by the fact that the part needs to be trimmed after forming. The rate of material which is thrown away after trimming is usually between 25% and 75%. Since the material has much less value as scrap than as sheets, this can be very expensive. It is especially expensive if the thermoplastics is somewhat more advanced and therefore cost more. For example, like the case is for MATERIAL B sheets in the case study. This is probably one of the reasons to why a lot of companies have little experience from certain thermoplastics like MATERIAL A, MATERIAL B, and MATERIAL C. It simply involves too high variable costs to make it economically sensible to use thermoforming instead of injection molding.

There are also large differences between thermoforming and injection molding in terms of which geometries can be created. Since the raw material is a sheet which is drawn into a shape with the use of only one mold, the result has to be a part with a rather uniform wall thickness. On the other hand cannot the tolerances be too high of the level of uniformity of the wall thickness. The walls are always a little thicker or thinner in some places even though prestretching procedures are taken. Prestretching can also be used to increase how deep draw can be made. However, there are of course limits to which H:D ratios can be achieved in one processes step. If the depth which is to be draw is too deep, sometimes it might be possible to divide the process into two steps, with increased manufacturing costs as a result.

Designers should also think of that there are standard sizes of sheets, and by doing so trying to adapt the size of the parts in an attempt to reduce the wastage after trimming. This might be less important when producing short series compared to long series, but since the difference could be very large it might be worth a try. It should also be remembered that some very large parts might be more expensive to produce since there are no standard sheets large enough to produce them. However, this is most often not a problem.

In general it can be said that when designing a part which is to be produced with thermoforming, the designers should always think of the limits and possibilities of the process, but also which material that are easily accessible and appropriate for the process. It this is not done, the production of the parts might be carried out with large spillage, high trimming costs, and extra machining after the forming.

5.6.3 Compression Molding

Compression molding is mostly used as a process to produce parts in thermosets, but it can also be used for thermoplastics. In the PRIMA selection matrix, showed in Appendix 1 – PRIMA Selection Matrix, it is for example recommended as a process for thermoplastics for volumes between 100 and 100,000 parts. However, the empirical results show that there is no cost difference between the molds used for compression molding and those used for injection molding. Because of this, much longer cycle times, and more manual handling there is no reason to use compression molding as a thermoplastic processing method for short series due to economic reasons. The situation is not helped by the fact that there seem to be very few manufacturers which have experience from thermoplastic processing using compression molding. This does probably only decrease competition and increase prices.

When it comes to geometric considerations, the same features can be created with compression molding as with injection molding, even though the parts which are produced with compression molding often is less complex. This could be the reason to why the cost estimated for the compression molding mold in the case is more expensive than any injection molding mold; simply lack of experience.

However, there is a benefit with producing parts with compression molding compared to injection molding. The parts produced with compression molding have better dimensional stability.

5.6.4 Machining of Semi-Products

Machining of semiproducts has two of the same economic problems that thermoforming has; the raw material is already processed and the material wastage is large. Because of this the material used is much more expensive than regular granulates used in the injection molding process, and more of that expensive material has to be recycled at low economic value. Machining is also in most cases a much slower process than injection molding. However, it is a very flexible process in the sense that it is possible to produce a large variety of geometric shapes using it, with next to none initial investments. Due to this it could be an alternative to use machining if annual volumes are low or very hard to anticipate.

5.6.5 Rapid Prototyping Processes

With rapid prototyping processes very complex structures can be created without any initial investments. This makes it very appropriate to use these processes when only a few products or prototypes are to be produced. If larger volumes are to be produced however, it does often make economical sense to use another thermoplastic manufacturing process since its production rate is very low and its variable costs are very high relative to injection molding. For example, a variable cost of €2.6/cm^3 can be used as a reference of producing polycarbonate parts with FDM, and this material is the least expensive.

Even though the high variable cost it may in some special cases be suitable to use some of the processes for production. For example, SLA offers some economies of scale since the building of each extra layer does not take a lot more time even though several parts are produced at once, and small thin walled parts might be possible to produce in an economical way since the material usage is low.

Unfortunately there are other drawbacks with these processes. The amounts of available materials are few, and there is often some roughness of the surface of the produced parts. The roughness of the surfaces depends on the layer building principle of the processes, so this can be somewhat avoided if thought of when deciding the orientation of the parts during building. If this case, smooth surfaces might be possible to produce thanks to the good tolerances of the processes.

6 Conclusion and Recommendation

In this chapter the conclusions and recommendations of the robotic tool case study and the general survey of short series production of thermoplastics is presented.

6.1 Case – The Robotic tool

In this chapter conclusions and recommendations are presented for the robotic tool case.

The development during this project has been carried out by a multifunctional team where design, market, business, material, and production functions have been represented. Environmental aspects have not been considered this time.

The DFMA analysis shows that all the parts should and must be kept separate. However, the joining of parts B, C, and D can and should be integrated into the parts joined, and not result in additional parts.

6.1.1 Part F

There are two potential materials for the thermoplastic part F. These are MATERIAL B and MATERIAL C. In the analysis the pros and cons of the different materials are weighted against each other, and since the least expensive material which fills the product specifications should be selected, this should be MATERIAL B. However, when fiber reinforced MATERIAL B is processed with Injection molding the surface may be rough due to the fibers. The problem becomes more severe when the material is machined. So if the edge is to be machined, which it has to since it cannot be created in the injection molding process, the result may be rough.

The next problem is that MATERIAL B without glass fiber is most often not processed with injection molding, partly because of large shrinkage and partly because it is rather brittle. The brittleness is not a problem for the application of part F, but it would require extra care in the processing of it. The large shrinkage on the other hand may cause problems if it is unpredictable. Furthermore, since MATERIAL C and MATERIAL B have different levels of shrinkage, both cannot be processed using the same mold during prototype production. One alternative could be to process the material with the least shrinkage first and then expand the mold cavity by further machining.

The final selection also depends on the result of the chemical tests which are being carried out. If MATERIAL B does not have the chemical resistance needed it cannot be used as material. The only alternative left in this case is MATERIAL C.

There are two manufacturing alternatives for part F. One is machining and the other is injection molding. When comparing the costs of the two, injection molding is preferable for most volumes, even though consideration is taken to the joining of the two injection molded parts.

An injection molding analysis of the design of part F is made. Considerations have here been taken to evening of the wall thickness, minimize sharp edges, and balancing of the two parts. This is the general design which is recommended to produce with injection molding.

If the final design is to be produced there are some features which are more troublesome than others, for example the small notch and the internal treading. For low volumes these features should be produced with machining after the molding process. The creation of these undercut would require substantial extra initial investments, and before the demand of the product is established, it is simply a risk which can and should be avoided.

Another problematic feature is the edge of part F and the tight tolerances of it. Whether or not it is possible to create this in the molding process needs to be investigated during test molding. If it is not possible, the cavity can be enhanced to allow the edge to be machined afterwards.

After molding and necessary machining the two parts are to be joined. Two different permanent joining processes have been further evaluated, and these are friction welding and the usage of adhesives. The friction welding alternative may be better from a mechanical and functional point of view, but it is much more expensive and requires a high initial investment. Whether or not the recommended adhesive from JMS 1 is resistant to the chemicals used and if they have the mechanical strength needed must be tested. If a primer is needed, which also needs to be tested, the chemicals need to be tested as well. Friction welding can most likely be used since this alternative involves no other materials.

The final problem has to do with the combination of joining method and coating. Some coating processes are carried out in vacuum and if the joining of the parts is done before coating, they will explode. Furthermore, if adhesives are selected as joining method, they may interfere with the coating process, for example by reacting with chemicals used. If the coating is carried out on the two parts individually, however, the joining of them might be made impossible. A potential solution could be to assemble the two parts before coating, but not properly join them. The small gaps between the two parts would work as ventilation holes but he surfaces which are to be joined are kept uncoated.

6.1.1.1 Recommended Next Steps

To further examine the possibility to use injection molding to produce part Fs, some prototypes should be produced using an aluminum mold. This can be done by IMM 6. This manufacturer should be selected due to their short lead time and experience from prototype molding. They have experience from molding both MATERIAL B and MATERIAL C using aluminum molds. As material MATERIAL B or MATERIAL C should be selected, depending on the results in the chemical study and whichever has the lowest amount of shrinkage. If the chemical results for MATERIAL B are good, the material with the lowest shrinkage can be produced first, and then the cavity can be expanded to enable the production of the other material. Recommendations regarding specific grades have to be left out due to the public nature of this report.

In order to be able to produce these prototypes, a proper CAD design and a mechanical analysis of it has to be made.

In order to be able to use adhesives to join the two part F parts the recommended adhesive and primer, both from JMS 1, should be tested for the listed chemicals.

The edge can either be machined as a second step when the first round of tests have been performed, or machined on the first batch of prototypes. Which is preferred depends on whether or not a thermoplastic part F without the characteristic edge also could be interesting from a market and business point of view.

6.1.2 Body

The materials available for selection for the exposed body depends on the result of the chemical resistance study of MATERIAL A and MATERIAL B. If MATERIAL A is chemically resistant enough it is the economically best alternative sine it is much less expensive than MATERIAL B. For the body parts which are not exposed, like part C and E, the materials available for selection is more open. A mechanical analysis, a production analysis, and an economical analysis should be made in order to decide which thermoplastic material is most appropriate.

Which processes should be selected largely depends on anticipated annual volume of the robotic tool. This will be further discussed for each of the parts. However, the machining and rapid prototyping processes alternatives can be discarded due to them being too uneconomical for all volumes over 100 parts per year.

6.1.2.1 Part A - Recommended Next Steps

Regarding the design of part A it should be investigated if it is possible to adjust the design like suggested in the analysis to even the wall thickness. Consideration has to be taken to internal parts and mechanical strength.

Injection molding is the most appropriate manufacturing alternative for part A. However, the creating of the threads does cause a problem. During the first year, it is probably beneficial to machine the treads after molding, to minimize the risk that a too large of an initial investment is made before the demand has been properly established. Alternatively the threads may be possible to create in the process without a too large investment if the parts can be unscrewed from the mold manually, but this has to be discussed with the specific manufacturer. It could be tested, and if it does not work the threads could be machined away from the mold.

If the annual demand is established to be high enough to invest in a mold with an unscrewing mechanism after a year or two, this decision can be made then.

The alternative to produce the threads using an insert is unlikely since the specific manufacturer would have to have an insert with the right dimensions and which has thin enough walls not to interfere with the flow of the melt. However, this alternative can and should be discussed with the manufacturer selected.

6.1.2.2 Part B and D - Recommended Next Steps

The material selection for part B and D partly depends on the chemical resistance study as previously mentioned, but it also depends on which materials are possible to use for which processes. For example if MATERIAL A parts cannot be produced with injection molding it is still more economical, given most annual volumes, to use MATERIAL B in combination with injection molding than using MATERIAL A with thermoforming.

To find out whether or not it is possible to produce either MATERIAL A or MATERIAL B with injection molding, a simulation of this should be performed at the internal Polish manufacturing center. This should help decide whether or not it is at all possible. If the results are promising it would probably be a good idea to test form some low viscous grade of MATERIAL A and MATERIAL B with good dimensional stability in a similar mold. Based on these results a decision can be made if it would be possible to manufacture these parts with injection molding.

If it is not be possible, it could be an option to search for a manufacturer which has experience from compression molding of thermoplastics, since compression molding offers better dimensional stability than injection molding. However, it is unlikely that a compression molded with experience from MATERIAL A and MATERIAL B given the geometries of these parts will be found. Because of this it would be hard to say if it would be possible to produce the parts with compression molding before tests have been carried out. Since these tests would involve large initial investments as well, it would be a gamble.

The last alternative is to manufacture the parts with thermoforming, at approximately three times the price compared to injection molding given that the mold cost of thermoforming is as low as estimated by TM 3. The high variable cost is mainly due to large trimming costs since the edge is stepped, large amount of wastage, and expensive sheets. Especially the MATERIAL B sheets are expensive. However, if thermoforming is selected or have to be selected as manufacturing alterative despite the high costs, the sheets still need to be test formed. This can either be done at TM 7, which has wide experience from thermoforming, or at another thermoforming manufacturer which offers molds at lower costs. If a manufacturer with lower experience is selected there is a risk that the total costs will be much higher than if TM 7 is selected since they have to experiment more, or that they will simply not be able to produce the parts at all.

6.1.2.3 Part C - Recommended Next Steps

The design as it is today has very thick walls. It would be greatly beneficial if the wall thickness could be decreased uniformly by using a ribbed structure. However, to be able to change the geometry of the part to a ribbed structure, a mechanical strength analysis of the part has to be made using a CAD tool. Whether or not e part has the mechanical strength needed greatly depends on the selected material as well. So this analysis has to be made for several materials until the least expensive applicable material is found. When selecting the material, considerations should also be taken to the risk of warpage when molding the part.

When changing the design to a ribbed structure, extra care should be taken to the holes. By creating circles around the holes such as suggested in the analysis, and by strategic placement of the ribs, the strength of the holes can be enhanced.

The preferable process is injection molding, and warpage should not be a problem since an amorphous material can be selected. The holes are most economical to produce in the injection molding process for all volumes over 200 parts per year.

6.1.2.4 Part E - Recommended Next Steps

Part E should be injection molded in a material which would provide enough mechanical strength to the purpose of the part. Which material is suitable should be analyzed in a in a CAD tool. At the same time it should be analyzed if the part could get a more ribbed structure and thereby reduce the cycle time and the risk of warpage.

6.1.2.5 Joining of parts B, C, and D - Recommended Next Steps

The joining of the parts B, C, and D does not require the involvement of any other parts. Integrated solutions would be easier to achieve if the parts are produced with injection molding than thermoforming, since it is possible to produce more complex geometries with this process.

The joining alternative selected is most likely going to have to be an internal solution because the increased risk of contamination, due to increased difficulty of cleaning, if an external solution is selected. Since the cost of contamination is so high, the alternatives which use screws or external snap fit solutions are probably not applicable. This leaves internal joining solutions.

The ribs alternative is an internal and integrated joining alternative which could be created directly in the injection molding process. However, it requires that the bottom plates are removed when disassembly is needed, and to do this it is required that the robotic tool is removed from the robot. Whether or not this can be accepted depends on how often this procedure is required. It is therefore up to the design team, which has the market knowledge to determine if this is an appropriate alternative.

The type of internal snap fit solution depends on the type of process selected. If injection molding is selected as process, the snap fit solutions which could be used are the notch and integrated hook alternatives. The hook alternative could be created in the process, but at a higher initial cost and with a risk of weld lines. To discover if this would be possible, a flow analysis of this can be performed at the same time as the flow analysis of parts B and D is made. If the notch alternative is selected, these should also be included in a flow analysis. Furthermore, a mechanical analysis should be made to ensure that no liquid leaks into the body.

If thermoforming is selected as process extra hooks can be used. They can be glued on to the parts B and D. The result would be a higher cost than any of the other alternatives, and the strength of this solution is questionable. To properly determine the strength of the solution a mechanical analysis must be performed. However, when designing the solution consideration should not only be taken to the strength of the joint, but also to if off-the-shelf hooks can be used since the creation of custom parts would result in even higher costs.

The other alternative if thermoforming is selected as process is the machining of the notches. In this case a mechanical strength analysis should be performed for the same reason as mentioned above.

6.2 Short Series Production of Thermoplastics

In the analysis of short series production of thermoplastics the capabilities and limits of different thermoplastic processes are analyzed. Large emphasis is put on injection molding due to the fact that it is the most versatile process of the examined processes. The key findings of the analysis are presented below as a comparison between the processes investigated and as guidelines of how to lower the costs of production, especially during product development.

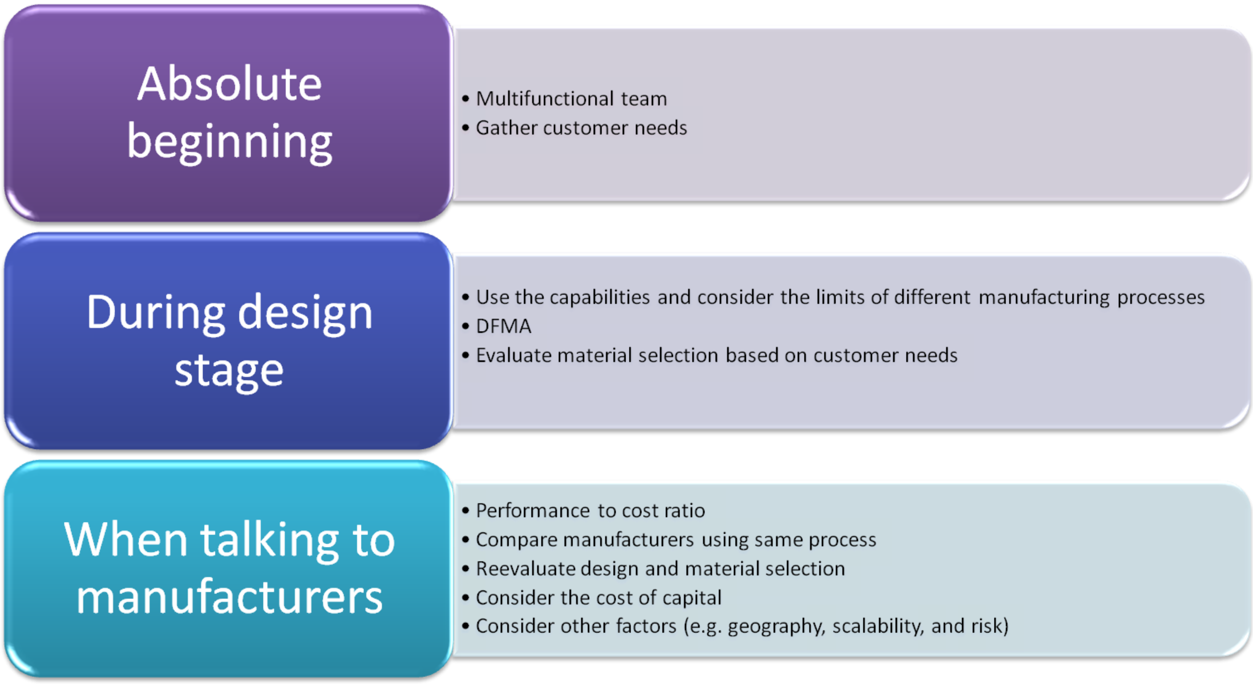
6.2.1 Comparing the Manufacturing Processes

When comparing the different manufacturing methods a few things can be noted:

- Injection molding offers the possibility to produce near-net-shaped in complex geometric shapes which enables the opportunity to reduce the number of parts, and thereby ease assembly. The opportunities which can be found in injection molding are because of this unmatched by any of the other examined thermoplastic manufacturing processes.
- If consideration is taken to the capabilities and limits of the injection molding process during design, it is possible to produce parts with a high rate and in a relatively economical way even for low volumes. To decrease the initial mold cost, the theoretical model described to estimate the mold cost can be used as reference to understand how different part designs affect the initial cost.
- In the case that only one or very few parts are to be produced, it is often most economical to use any of the rapid prototyping processes. For somewhat larger volumes machining is more likely to be more appropriate, and for larger volumes injection molding is most often most suitable. Thermoforming can be used if the geometry of the part allows it. If so, it is most often economical for lower volumes than injection molding. However, to be able to answer the question exactly for which volumes each process is to prefer, more information, like material selected, general design, tolerances, et cetera, is needed.

6.2.2 Guidelines of How to Lower the Costs of Production during Product Development

The conclusion of the general survey of how low volume products in thermoplastics should be developed and produced is presented below as recommendations. The recommendations are given for the different stages of the product development process, see Figure 61.



Absolute beginning

- Multifunctional team
- Gather customer needs

During design stage

- Use the capabilities and consider the limits of different manufacturing processes
- DFMA
- Evaluate material selection based on customer needs

When talking to manufacturers

- Performance to cost ratio
- Compare manufacturers using same process
- Reevaluate design and material selection
- Consider the cost of capital
- Consider other factors (e.g. geography, scalability, and risk)

Figure 61 Short series production of thermoplastic guidelines.

6.2.3 Absolute Beginning

In the absolute beginning of a new product development process there are two things which are especially important. The first is that the project team must have representatives from a lot of different functions, and the second is that the development must be based on customer needs.

The main purpose of having many functions represented is to get their input as early as possible in the development process. This is important because when inputs are received late, it most often takes much more time to take consideration to it. The reason to why it takes more time if inputs are received late is that most often work has to be redone based on these inputs. The result is longer time-to-market and higher development costs. While considering this, remember that it is just as important to attempt to reduce developments cost as any other initial cost, such as the cost of a mold.

The reason to why it is so important to gather customer needs is to make sure that the development decisions of the new product is based on something that is valuable to the customer. An example of this is that the customer does not care if the product is made from MATERIAL B or MATERIAL C as long as the performance is the same. In this example one material should not be selected before the other only based on the material type, but based on the effect on performance.

6.2.4 During Design Stage

The design stage stretches over a long period of time. As soon as concept sketches are being made, the preliminary design begins to take shape. At this stage it is important to have representatives from manufacturing to makes sure that feasible designs are not discarded as impossible, and that complicated and expensive designs are not assumed to be simple and inexpensive. During the entire process when the design is established, it is important to understand and consider the limits of processes, but perhaps most important, to use the capabilities which processes offer. For example, injection molding does offer the capability to produce parts at much higher rate, with less waste, and much more complex geometries than thermoforming. Because of this it might be worth to use it despite the higher initial cost.

DFMA analysis is another which should be used to guide the design team to a more effective design. By for example reducing the number of parts a product consists of, and the number of process steps used to produce one part, the cost of manufacturing can be greatly decreased. DFMA should be used as soon as concept sketches are being made to improve the design, and must be carried out as a cross functional collaboration.

As the example above described, the material selection should not be made on assumptions but on what is valuable to the customer, and therefore on customer needs. The reason is that if it is not valuable to the customer, it is not valuable to the company which produces the product.

6.2.5 When Talking to Suppliers

When talking to manufacturers it is important not only to discuss costs, but also what is given at that cost; the performance to cost ratio. In the case of injection molding for example, the cost of the molds can differ by a factor three dependent on the type of steel used for the mold. So in this example it is important to specify which material is going to be used, how many parts are going to be produced, and the geometry of the part, so that the manufacturer can understand the need.

It should also be noted that different manufacturers using the same manufacturing processes has different capabilities to fulfill the needs. The differences could for example be due to different cost structures, level of experience, resources, or capabilities. Due to this, offers from several manufacturers should be gathered to make sure that the needs cannot be fulfilled in a better way by someone else. The gathered information should then be compared to the cost estimations given by each company.

Since the possibility to fulfill needs and specifications is not only process specific, but also company specific, it is important to reevaluate the selection of design and materials given the company at hand. This requires a close collaboration between the development team and manufacturers.

The different thermoplastic manufacturing processes do have rather different cost structures. Injection molding does for example have higher initial cost than thermoforming, but thermoforming has higher variable costs. These differences makes is important to consider the cost of capital when selecting process, since the influence of high initial investments is higher when this is done. Just as it should since every company has limits in the amount of accessible capital.

Finally, there are many other factors which are important to consider when collaboration with a manufacturer has begun. For example, where are the parts and products going to be produced if that manufacturer is selected, is the manufacturer able to scale up production if demand increases, and what risk is involved in that manufacturer? Geographical distances does for example result in increased lead time and higher logistics cost. The manufacturer's ability to scale up production is also important. If a small manufacturer is primarily selected, maybe an entirely new manufacturer has to be used if demand increases. This could result in that the demand cannot be filled for a period, which may result in the risk of losing business to competitors.

When selection a manufacturer it is important to consider other risks as well. For example if the manufacturer is known for having problems with delivering on time, has economical problems and may go bankrupt, may leak information to competitors, or may have a high cost of poor quality.

7 Discussion

There are three things which would be appropriate to discuss a little more freely. Firstly, as always it is interesting to read the writer's own comments regarding the findings and conclusions of the study. Secondly; there are other, more strategic, decisions to consider when deciding by whom and where the production is to be carried out. These have to do with the implications of insourcing, outsourcing, and offshoring of production. Thirdly; the different cost structures of manufacturers could have to strategic decisions made by them.

7.1 Comments to Conclusions

The overall purpose of this thesis was to find ways to lower the costs for low volume production of thermoplastics. It is interesting, and rather natural, to discover that many of the same procedures which are used to lower the costs for short series can be used for long series as well. These are for example to minimize the number of parts, use multifunctional teams, and consider the limits of manufacturing processes when developing the design. However, even though the procedures are the same, the focus lies elsewhere.

High initial costs may feel extra troublesome if the volume produced is low since there are fewer products to spread the cost among. Meanwhile, high variable costs are problematic if the produced volume is large because of the effect these have on the total costs. What may be forgotten is, that the absolute cost of for example an injection mold is the same for high volume products, but since it is spread among a lot of products, it simply does not feel so high. However, since high volume products, like most consumer goods, often are sold with lower margins than low volume industrial goods, the pay-back time can be just as long. The point is that it is not the initial investment that matters; it is the NPV of the investment.

Another aspect of the preparation of production of low volume products which should be commented has to do with the use of hard technical and soft intangible solutions to economical issues. What is meant by hard technical solutions is for example the use of the proper type of steel in the mold, proper gating, and the gathering of the right process parameters when preparing a product for production. By soft intangible solutions is meant the use of the right procedures, like for example the right constellation of the development team and the use of DFMA analysis. One might think that the technical solutions outweigh the intangible solutions by importance. This is not the case. The analysis shows and the conclusion describes the major importance of the soft intangible solutions, since for example the technical solutions would arrive at a too late a stage in the development process or simply be discarded if not the team would be multifunctional. The technical and intangible solutions are mutually dependant.

7.2 Insourcing, Outsourcing, and Offshoring of Production

The question whether or not a company should insource or outsource the production is a frequent problem. The issue is even further extended by the question if the company should offshore. These questions do perhaps not have anything to do with the preparation of an individual product for production, but it has to do with if ABB can gain some competitive advantage by using any of them.

By insourcing the production of thermoplastic parts, ABB can start to develop technologies which can be used to produce them with a lower initial coast using injection molding. If they outsource the production, there is no use to use of developing technologies to the manufacturers since competitors also could use them. Insourced production also offers other benefits like better control of quality and intellectual property. However, it also involves drawbacks since it would no longer be possible to use the world class capabilities of specific manufacturers nor would be possible to switch manufacturers to be able to get the lowest cost.

When a company has made the decision if it should insource or outsource, the question still remains if it should offshore. It may be a little hard to determine what actually outsourcing is for a multinational company like ABB, which it active and has markets all over the world. However, if offshoring due to low cost reasons is considered, the question is rather if ABB should produce their parts in low cost countries like China or Vietnam. This option would have other benefits than just reduced costs, like for example access and proximity to markets, but could also result in lower quality, increased logistics cost, increased lead times, and increased risk of intellectual property leakage.

The question whether or not ABB should use insourcing or outsourcing, possibly in combination with offshoring remains. Since ABB does not primarily sell products but rather technology within power and automations, it is not within their core competence to develop technologies which can be used to for example lower the initial cost of injection molding on their own. There are a lot of other companies which are much better than ABB at specialized production, and ABB have no reason to compete with them. However, since ABB has a lot of know-how which can be used when developing new production methods, strategic alliances might be advantageous if signed with the right companies.

7.3 Business Implications of Process Choice

It has been discussed of how the cost structures of different manufacturers vary. However, what not have been mentioned is that these differences could be self-chosen. For example if a manufacturer wants to strive for production flexibility and specialist services it is only logical that they get paid for delivering something that a high volume low cost manufacturer cannot deliver. The term flexibility in this case is broad and could have to do with everything from short lead times to variation in parts produced.

It not only has to do with that these flexible companies charge for thing which others cannot deliver, but also on the fact that they cannot deliver products to the same low cost as the high volume producers can. This is because their production is not flexible in the sense that is can produce a great variety of parts in both high and low volumes at low cost. They can only deliver what they are good at, at a relatively low cost. The high volume producers, however, have highly dedicated production facilities to produce a certain type of high volume products. It is simply a business implication of a process choice that they have made.

ABB is a high-tech company which use advanced engineering thermoplastics in extreme conditions. They cannot expect to use manufacturers with the same cost structures as companies with less demand on competence and flexibility on their manufacturers. What they need is manufacturers which can supply the service they need. Since more flexibility and service result in a lower production rate and larger overhead for the manufacturers, the result is higher costs spread among fewer parts.

8 Suggestions for Continual Analysis and Improvement

In this chapter suggestions for continual studies, analysis, and improvement are presented for the robotic tool and for the more general case of short series production of thermoplastics. The suggestions are structured by the time perspective needed when pursuing them.

8.1 The Robotic tool

8.1.1 Short Term

Here are ideas which could be pursued as a next step:

- Depending on the result of part F prototypes, manufacturers which have experience from RHCM and microcellular molding can be contacted as a next step. According to information gathered, RHCM can be used to produce parts with big variations in wall thickness and to produce small features. Therefore it might be possible to produce a thick walled part F with characteristic edge using this process. The edge cannot have the initial geometry since such a mold cannot be milled, so some compromises would have to be made. However, microcellular molding reduces the viscosity of the material and might therefore be appropriate to use to produce a sharp characteristic edge.
- By the use of a generic mold and a few mold inserts, part Fs of several sizes could be produced using only one mold.

8.1.2 Long Term

Here are ideas which could be pursued as a next step:

- A DFMA analysis could be performed of the entire robotic tool, not only the body parts. This will probably result in a simplified structure and a reduction of production costs.
- Depending on the result of part F prototypes, part F could be redesigned to better fit the capabilities of injection molding. This might make it possible to produce it using only one mold and make joining processes obsolete.

8.2 Short Series Production of Thermoplastics

8.2.1 Short Term

Here are ideas which could be pursued as a next step:

- A more elaborate study can be made of the differences between producing injection molding molds in typical offshoring counties and producing them in countries like for example Sweden, Germany, or USA. The differences should cover quantitative data like costs and lead time, but also more qualitative data like quality and different types of risks.
- A study can be made of how many parts an aluminum mold can produce given material used, geometry of the part produced, and process parameters. This study can then be compared to a similar study made for softer mold steels.

8.2.2 Long Term

Here are ideas which could be pursued as a next step:

- Better simulation tools can be made developed to estimate the level of wear on a mold, given type of mold material, thermoplastic used, geometry of the part, and process parameters. This could then be used to optimize the mold material selection, and thereby minimize the initial investment required.
- New processes with low initial investment for thermoplastic parts can be developed to suit the need of producing parts with varying shapes.

9 Contradictions in sources

Footnote number 3:

ABB's five divisions are Power Products, Power systems, Automation Products, Process Automation and Robotics, according to ABB annual report, and, Power Products, Power systems, Low Voltage Products, Process Automation and Discrete Automation and Motion, according to Reuters Finance and ABB's webpage. However, a coworker at ABB Corporate Research explained this as the recent change of functional structure. Therefore, the information given in the annual report was correct at the time, but not anymore.

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10.5 People

Alessandro Mattozzi, ABB Corporate Research and Development, Västerås

Furthermore, there have been interviews with several suppliers and other contacts. These are listed in the chapters Material Suppliers, Cost estimations how much it would cost to purchase MATERIAL B sheets have been gathered but cannot be reviled due to the public nature of this report.

Manufacturing Suppliers, Joining Method Suppliers, Cost estimations of how much it would cost to join the two parts using adhesives have been gathered, but cannot be reviled due to the public nature of this report.

Coating Suppliers, and Other sources, on page 67, 69, 81, 83, and 86, respectively.

10.6 Figures

Figure 1 Illustration of concurrent engineering:
Modified version from Ståhl, Jan-Eric (2009) *Industriella Tillverkningssystem del II*. Industriell Produktion vid Lunds Tekniska Högskola. Second Edition. Lund.. The aspects are translated from Swedish by the writer.

Figure 2 Typical steps taken in the use of DFMA:
Boothroyd, Geoffrey (1994) *Product design for manufacture and assembly*. Computer-Aided Design. Volume 26, Issue 7. Page 505-520

Figure 3 Time to market with and without DFMA:
Own creation with inspiration from Boothroyd, Geoffrey (1994) *Product design for manufacture and assembly*. Computer-Aided Design. Volume 26, Issue 7. Page 505-520

Figure 4 Simplify overall design vs. simplify individual parts:
Boothroyd, Geoffrey (1994) *Product design for manufacture and assembly*. Computer-Aided Design. Volume 26, Issue 7. Page 505-520

Figure 5 through Figure 9
Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

Figure 10 Manufacturing process selection:
Somewhat modified version from Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition. The figure is standing in the book, but is here lying to save room. Nothing else is changed.

Figure 11 through Figure 12:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 13 and Figure 14:
Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

Figure 15 and Figure 16
Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

Figure 17 (a) Cold-runner two-plate mold, (b) cold-runner three-plate mold, and (c) hot-runner mold:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 18 Number of surface patches:
Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

Figure 19 (a) Undercuts created by the use of stripper plate, (b) collapsible core, and (c) split core:
Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

Figure 20 and Figure 21:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 22 Overmolding processes:
Osswald, T.A., Turng, L.-S. & Gramann, P.J. (2002) *Injection Molding Handbook*. Carl Hanser Verlag. First Edition. Munich.

Figure 23 A mold temperature comparison between RHCM (1) and conventional injection molding (2):
Wang, G., Zhao, G., Li, H. & Guan, Y. (2009) *Research on a New Variotherm Injection Molding Technology and its Applications on the molding of a large LCD Panel*. Polymer-Plastics Technology and Engineering. Volume 48. Page 671-681.

Figure 24 Different thermoforming processes:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 25 H and D in negative thermoforming:
Schwarzmann, P. & Illing, A. (2001) *Thermoforming – A Practical Guide*. Hanser Publishers. First Edition. Munich.

Figure 26 Prestretching in mixed thermoforming
Schwarzmann, P. & Illing, A. (2001) *Thermoforming – A Practical Guide*. Hanser Publishers. First Edition. Munich.

Figure 27 Male and female mold:
Own creation with inspiration from Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9.

Figure 28 An undercut in thermoforming (demolding direction is up):
Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9.

Figure 29 Twin-sheet thermoforming:
Throne, J.L. (1997) Advances in Thermoforming. Rapra Review Reports. Report 93, Volume 8, Number 9.

Figure 30 (a) Fused-deposistion modeling, (b) stereolithography, and (c) selective laser sintering:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 31 through Figure 37:
Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition.

Figure 38 The effect of selection of coating material and process on the coating properties:
Own creation with inspiration from Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

Figure 39 Electroplating:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 40 Solgel coating processes:
Illustrations taken from internal document at ABB created by Harald Martini, ABB Corporate Research, Västerås

Figure 41 Left: Thermal wire spray, Right: Plasma spray:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 42 The physical vapor deposition process (vacuum deposition)
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 43 The sputtering process, Figure 44 The ion plating process
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 44 The ion plating process:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Figure 45 The chemical vapor deposition process:
Kalpakjian, S. & Schmid, S. (2006) *Manufacturing, Engineering and Technology*. Prentice Hall. Fifth Edition. Singapore.

Other figures are created by the author.

10.7 Tables

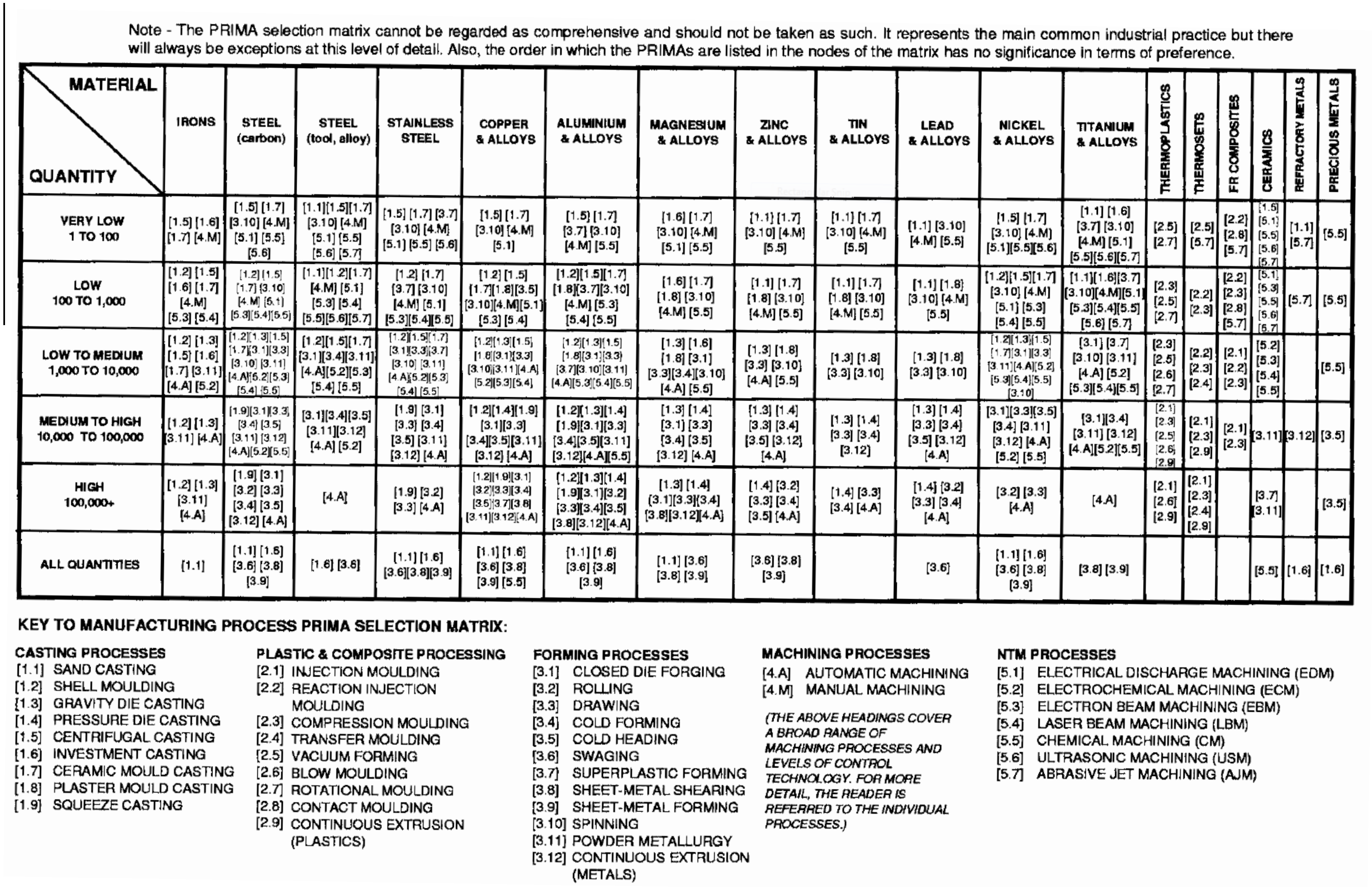
Table 3 and Table 4:
Boothroyd, G., Dewhurst, P., & Knight, W.A. (2001) *Product Design for Manufacture and Assembly*. CRC Press. Second Edition. New York.

Table 5 Coating material and processes candidates based on type of wear and corrosion:
Bunshah, Rointan F., et al. (2001) *Handbook of Hard Coatings*. Wiliam Andrew publishing. First Edition. Norwich.

Other tables are created by the author.

Appendices

Appendix 1 – PRIMA Selection Matrix[194]



Note - The PRIMA selection matrix cannot be regarded as comprehensive and should not be taken as such. It represents the main common industrial practice but there will always be exceptions at this level of detail. Also, the order in which the PRIMAs are listed in the nodes of the matrix has no significance in terms of preference.

MATERIAL / QUANTITY	IRONS	STEEL (carbon)	STEEL (tool, alloy)	STAINLESS STEEL	COPPER & ALLOYS	ALUMINIUM & ALLOYS	MAGNESIUM & ALLOYS	ZINC & ALLOYS	TIN & ALLOYS	LEAD & ALLOYS	NICKEL & ALLOYS	TITANIUM & ALLOYS	THERMOPLASTICS	THERMOSETS	FR COMPOSITES	CERAMICS	REFRACTORY METALS	PRECIOUS METALS
VERY LOW 1 TO 100	[1.5] [1.6] [1.7] [4.M]	[1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.1][1.5][1.7] [3.10] [4.M] [5.1] [5.5] [5.6] [5.7]	[1.5] [1.7] [3.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.5] [1.7] [3.10] [4.M] [5.1]	[1.5] [1.7] [3.7] [3.10] [4.M] [5.5]	[1.6] [1.7] [3.10] [4.M] [5.1] [5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [3.10] [4.M] [5.5]	[1.5] [1.7] [3.10] [4.M] [5.1][5.5][5.6]	[1.1] [1.6] [3.7] [3.10] [4.M] [5.1] [5.5][5.6][5.7]	[2.5] [2.7]	[2.5] [5.7]	[2.2] [2.8] [5.7]	[1.5] [5.1] [5.5] [5.6] [5.7]	[1.1] [5.7]	[5.5]
LOW 100 TO 1,000	[1.2] [1.5] [1.6] [1.7] [4.M] [5.3] [5.4]	[1.2] [1.5] [1.7] [3.10] [4.M] [5.1] [5.3][5.4][5.5]	[1.1][1.2][1.7] [4.M] [5.1] [5.3] [5.4] [5.5][5.6][5.7]	[1.2] [1.7] [3.7] [3.10] [4.M] [5.1] [5.3][5.4][5.5]	[1.2] [1.5] [1.7][1.8][3.5] [3.10][4.M][5.1] [5.3] [5.4]	[1.2][1.5][1.7] [1.8][3.7][3.10] [4.M] [5.3] [5.4] [5.5]	[1.6] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.8] [3.10] [4.M] [5.5]	[1.2][1.5][1.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5]	[1.1][1.6][3.7] [3.10][4.M][5.1] [5.3][5.4][5.5] [5.6] [5.7]	[2.3] [2.5] [2.7]	[2.2] [2.3]	[2.2] [2.3] [2.8] [5.7]	[5.1] [5.3] [5.5] [5.6] [5.7]	[5.7]	[5.5]
LOW TO MEDIUM 1,000 TO 10,000	[1.2] [1.3] [1.5] [1.6] [1.7] [3.11] [4.A] [5.2]	[1.2][1.3][1.5] [1.7][3.1][3.3] [3.10] [3.11] [4.A][5.2][5.3] [5.4] [5.5]	[1.2][1.5][1.7] [3.1][3.4][3.11] [4.A][5.2][5.3] [5.4] [5.5]	[1.2][1.5][1.7] [3.1][3.3][3.7] [3.10] [3.11] [4.A][5.2][5.3] [5.4] [5.5]	[1.2][1.3][1.5] [1.8][3.1][3.3] [3.10][3.11][4.A] [5.2][5.3][5.4]	[1.2][1.3][1.5] [1.8][3.1][3.3] [3.7][3.10][3.11] [4.A][5.3][5.4][5.5]	[1.3] [1.6] [1.8] [3.1] [3.3][3.4][3.10] [4.A] [5.5]	[1.3] [1.8] [3.3] [3.10] [4.A] [5.5]	[1.3] [1.8] [3.3] [3.10]	[1.3] [1.8] [3.3] [3.10]	[1.2][1.3][1.5] [1.7][3.1][3.3] [3.11][4.A][5.2] [5.3][5.4][5.5] [3.10]	[3.1] [3.7] [3.10] [3.11] [4.A] [5.2] [5.3][5.4][5.5]	[2.3] [2.5] [2.6] [2.7]	[2.2] [2.3] [2.4]	[2.1] [2.2] [2.3]	[5.2] [5.3] [5.4] [5.5]		[5.5]
MEDIUM TO HIGH 10,000 TO 100,000	[1.2] [1.3] [3.11] [4.A]	[1.9][3.1][3.3] [3.4] [3.5] [3.11] [3.12] [4.A][5.2][5.5]	[3.1][3.4][3.5] [3.11][3.12] [4.A] [5.2]	[1.9] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A]	[1.2][1.4][1.9] [3.1][3.3] [3.4][3.5][3.11] [3.12] [4.A]	[1.2][1.3][1.4] [1.9][3.1][3.3] [3.4][3.5][3.11] [3.12][4.A][5.5]	[1.3] [1.4] [3.1] [3.3] [3.4] [3.5] [3.12] [4.A]	[1.3] [1.4] [3.3] [3.4] [3.5] [3.12] [4.A]	[1.3] [1.4] [3.3] [3.4] [3.12]	[1.3] [1.4] [3.3] [3.4] [3.5] [3.12] [4.A]	[3.1][3.3][3.5] [3.4] [3.11] [3.12] [4.A] [5.2] [5.5]	[3.1][3.4] [3.11] [3.12] [4.A][5.2][5.5]	[2.1] [2.3] [2.5] [2.6] [2.9]	[2.1] [2.3] [2.9]	[2.1] [2.3]	[3.11]	[3.12]	[3.5]
HIGH 100,000+	[1.2] [1.3] [3.11] [4.A]	[1.9] [3.1] [3.2] [3.3] [3.4] [3.5] [3.12] [4.A]	[4.A]	[1.9] [3.2] [3.3] [4.A]	[1.2][1.9][3.1] [3.2][3.3][3.4] [3.5][3.7][3.8] [3.11][3.12][4.A]	[1.2][1.3][1.4] [1.9][3.1][3.2] [3.3][3.4][3.5] [3.8][3.12][4.A]	[1.3] [1.4] [3.1][3.3][3.4] [3.8][3.12][4.A]	[1.4] [3.2] [3.3] [3.4] [3.5] [4.A]	[1.4] [3.3] [3.4] [4.A]	[1.4] [3.2] [3.3] [3.4] [4.A]	[3.2] [3.3] [4.A]	[4.A]	[2.1] [2.6] [2.9]	[2.1] [2.3] [2.4] [2.9]		[3.7] [3.11]		[3.5]
ALL QUANTITIES	[1.1]	[1.1] [1.6] [3.6] [3.8] [3.9]	[1.6] [3.6]	[1.1] [1.6] [3.6][3.8][3.9]	[1.1] [1.6] [3.6] [3.8] [3.9] [5.5]	[1.1] [1.6] [3.6] [3.8] [3.9]	[1.1] [3.6] [3.8] [3.9]	[3.6] [3.8] [3.9]		[3.6]	[1.1] [1.6] [3.6] [3.8] [3.9]	[3.8] [3.9]				[5.5]	[1.6]	[1.6]

KEY TO MANUFACTURING PROCESS PRIMA SELECTION MATRIX:

CASTING PROCESSES
[1.1] SAND CASTING
[1.2] SHELL MOULDING
[1.3] GRAVITY DIE CASTING
[1.4] PRESSURE DIE CASTING
[1.5] CENTRIFUGAL CASTING
[1.6] INVESTMENT CASTING
[1.7] CERAMIC MOULD CASTING
[1.8] PLASTER MOULD CASTING
[1.9] SQUEEZE CASTING

PLASTIC & COMPOSITE PROCESSING
[2.1] INJECTION MOULDING
[2.2] REACTION INJECTION MOULDING
[2.3] COMPRESSION MOULDING
[2.4] TRANSFER MOULDING
[2.5] VACUUM FORMING
[2.6] BLOW MOULDING
[2.7] ROTATIONAL MOULDING
[2.8] CONTACT MOULDING
[2.9] CONTINUOUS EXTRUSION (PLASTICS)

FORMING PROCESSES
[3.1] CLOSED DIE FORGING
[3.2] ROLLING
[3.3] DRAWING
[3.4] COLD FORMING
[3.5] COLD HEADING
[3.6] SWAGING
[3.7] SUPERPLASTIC FORMING
[3.8] SHEET-METAL SHEARING
[3.9] SHEET-METAL FORMING
[3.10] SPINNING
[3.11] POWDER METALLURGY
[3.12] CONTINUOUS EXTRUSION (METALS)

MACHINING PROCESSES
[4.A] AUTOMATIC MACHINING
[4.M] MANUAL MACHINING

(THE ABOVE HEADINGS COVER A BROAD RANGE OF MACHINING PROCESSES AND LEVELS OF CONTROL TECHNOLOGY. FOR MORE DETAIL, THE READER IS REFERRED TO THE INDIVIDUAL PROCESSES.)

NTM PROCESSES
[5.1] ELECTRICAL DISCHARGE MACHINING (EDM)
[5.2] ELECTROCHEMICAL MACHINING (ECM)
[5.3] ELECTRON BEAM MACHINING (EBM)
[5.4] LASER BEAM MACHINING (LBM)
[5.5] CHEMICAL MACHINING (CM)
[5.6] ULTRASONIC MACHINING (USM)
[5.7] ABRASIVE JET MACHINING (AJM)

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[194] Swift, K.G. & Booker, J.D. (2001) *Process Selection*. Elsevier Ltd. Second Edition.

Appendix 2 – Chemical resistance chart[195]

Due to the public nature of this report, this informations cannot be released.

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[195] Harald Martini, ABB Corporate Research and Development, Västerås