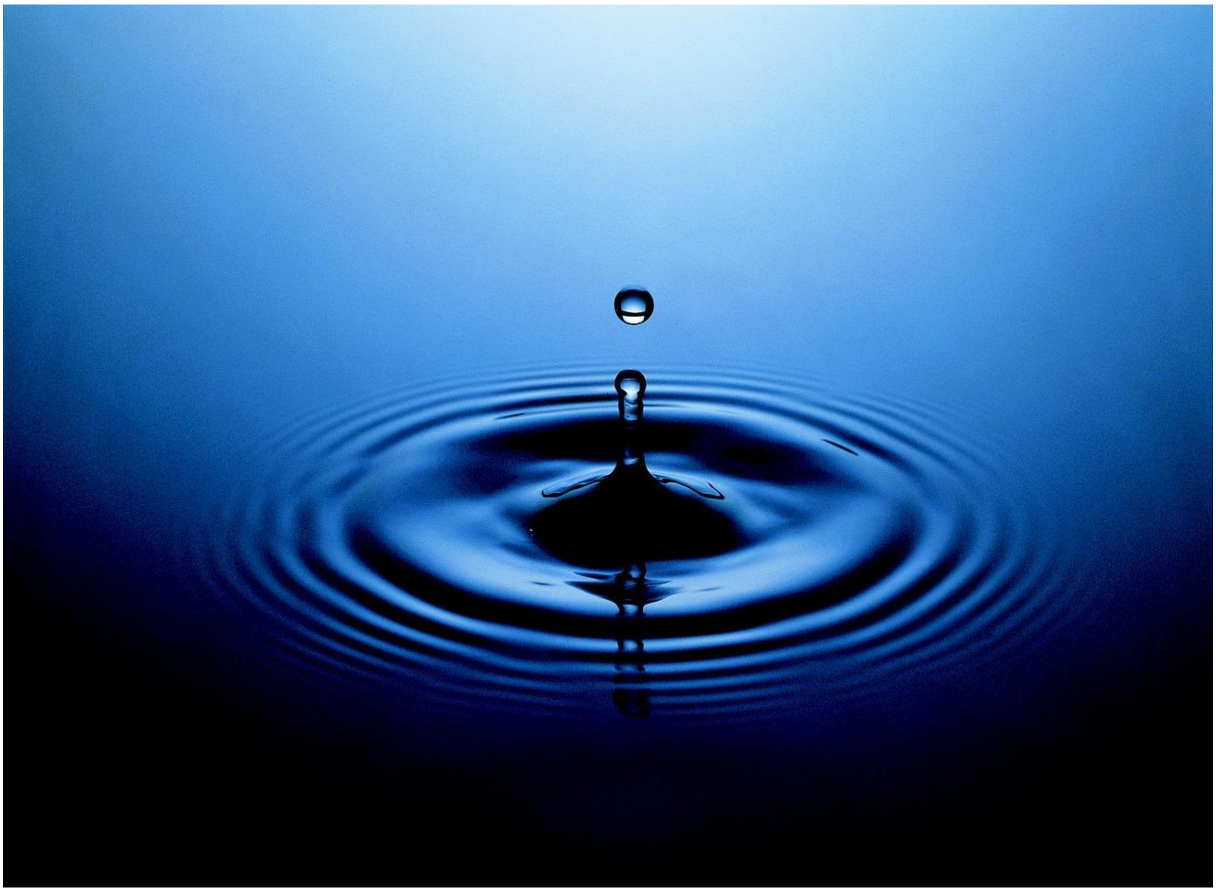
THE EFFECT OF DAMAGES ON A VACUUM SURFACE

THE INFLUENCE OF SCRATCHES AND SURFACE ROUGHNESS ON LEAKS OF A VACUUM SURFACE

FINAL REPORT



VDL Enabling Technologies Group

January 2015

The European Project Semester
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Preface

This report is drafted in order to record the effects of various damages and scratches at different levels of vacuum surfaces, both functionally and visually. The project group participates in the European Project Semester and consists of students with the education of (light packaging) industrial engineering.

This report is intended for Manager Factory Engineering, Ivo Baijens and Process Improvement Engineer Roland Megens. It is also intended for the quality inspectors and possible other interested parties.

The report is structured according to the DMAIC-model. The appendices of the report are supplied separately. Besides the report and the appendices, there are two CDs available containing pictures of different kind of scratches on different kind of vacuum surfaces.

Readers who are primarily interested in the results of the tests can find this in Section 5.2. The functional and visual analysis of the test results are discussed in the analyze phase; these two correlating elements can be found in Section 6.3. Readers who are interested in the suggested improvements can find these in Chapter 7.

The project team is greatly indebted to Mr. I. Baijens and Mr. R. Megens for giving us the opportunity to carry out the project and for their valuable advice. The project team would also like to thank Mr. M. Klootwijk for giving advice during the first period of the project. Finally, we would like to thank Mr. R. Dolstra for leading us during the project.

Eindhoven, 15 January 2015

Juan Carlos del Castillo
Nam van Loon
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Summary

VDL Enabling Technologies Group Eindhoven operates in the business of system integration of mechatronic (sub)systems and modules for OEMs in the high-tech capital equipment industry. As a system supplier, VDL ETG covers the value chain from (co-)engineering through parts production to assembly and testing. In-house production technologies include: machining, high-speed milling, precision grinding, sheet metal production, laser cutting, mechanical and electrical (clean room) assembly, testing, product certification and onsite installation. VDL ETG Eindhoven operates along certified quality management systems, including ISO9001, ISO14001, ISO13485 and AS9100 accreditation.

Several products VDL ETG produces for the customers contain sealing and/or vacuum surfaces. These surfaces are machined (milling and turning machines) and finished by craftsmen for the right roughness and structure. Currently VDL ETG does not have a common or standardized way of working regarding the milling/turning and finishing by craftsmen. Secondly, VDL ETG does not have a common standardized way of working regarding the visual inspection of these surfaces (discussion afterwards between craftsmen and quality inspector) and the inline inspections are not sufficient enough to detect scratches.

VDL ETG has been coping with these problems for several years. Lots of time has been wasted and time equals money. It is therefore important to solve these problems.

The objectives are as followed:

- There should be no discussion about the surfaces of a part between the craftsmen and the quality inspector regarding whether or not a surface is good.
- Record what is the best roughness, machining and material for vacuum surfaces.

On the basis of interviews, carrying out tests and analyzing the test results, the effect of scratches on vacuum surfaces is researched.

The research has yielded the following results:

- Products with aluminum vacuum surfaces are better resistant to leaks than products with stainless steel vacuum surfaces. In fact, the products with aluminum vacuum surfaces had less times the first leak in comparison with the stainless steel vacuum surfaces. However, there are some cases with certain scratches, certain machined vacuum surface and certain roughness where stainless steel vacuum surfaces are better.
- Vacuum surfaces with a roughness of 0.8 is in general clearly the best roughness against leaks. On the other hand, a roughness of 0.4 is clearly the worst roughness against leaks. Actually, according to the results, a roughness of 0.4 was not even once the best roughness against leaks in different tests.
- The polished surface is the best resistant to leaks in an aluminum vacuum surface. Regarding a stainless steel vacuum surface, it is a milled surface. Although a polished surface is not much more vulnerable.

In addition keep the following in mind:

- Every kind of vacuum surface does not leak if it is not damaged.
- Full 90 degrees scratches has the most chance to cause a leak on a vacuum surface.
- During the tests, half external scratches of 90 degrees did not leak on every kind of vacuum surface. The project team even made a half external scratch by hand with full force on aluminum and stainless steel vacuum surfaces and even then it did not leak.
- Centric scratches also did not cause leaks on every kind of vacuum surface during the tests.
- Half internal scratches of 90 degrees did only cause leaks on aluminum as well as stainless steel vacuum surfaces with a roughness of 0.4.
- Scratches on vacuum surfaces made by grain paper do not cause a leak.

The depths and widths of scratches can be measured exactly by means of a mixture of pastes and a microscope. It can then be determined with the depths and widths whether the vacuum surface leaks.

ASML does not accept products with vacuum surfaces that are leaking. They permit scratches up to a maximum of the following dimension:

- Depth: 0.14 mm maximum.
- Width: 0.1 mm maximum.

However, according to the results, scratches are already leaking beneath the permitted dimension.

Differences in scratches on vacuum surfaces are difficult to see. However, a very thin scratch and a very deep scratch are distinguishable. The best method to distinguish different scratches is to use a microscope with 90 times magnify and by eye with flashlight. Investigation verified that if the depth and width of scratches increases, the scratches glint more when aiming the flashlight on the scratches.

For the correlation between the visual evaluation and the functionality of vacuum surfaces, a scratch sample plate can be used. Thus, a vacuum surface can be judged visually whether a surface is good. The scratch sample plate contains the same scratches as the scratches that are made on the vacuum surfaces during the tests. With the scratch sample plate and a flashlight, it is possible to determine in which area of the sample plate, the scratch on the vacuum surface belongs. It can be determined if the scratch either belongs to the green, orange or red area. Nonetheless, most of the time scratches will be hard to determine in which area they belong. A thin scratch that belongs in the green area and a very deep scratch in the red area are easy to distinguish. Scratches that belong in the orange area are hard to determine whether they leak or not. In most of the cases, the scratch has to be measured with a mixture of pastes and a microscope to ensure whether the vacuum surface is leaking. This will only take 15 minutes. Once the depth and widths are measured, it can be determined whether the scratch leaks or belongs in the orange area. If the scratch is in the orange area, the leak tester has to be used. This saves a lot of time, energy and money because the vacuum surface will not be immediately rejected when a scratch is found on the vacuum surface.

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1. Introduction

1.1. The European Project Semester

The students in the project group participate in The European Project Semester (EPS).

1.1.1. What is the European Project Semester

The EPS is a semester-long program, which is designed to train engineering students to work in international teams. The semester is divided into parts:

- A study program comprising courses with subjects like project management, problem-solving techniques, sustainable marketing, sustainable business, sustainable product design and innovation, communication skills, cross-cultural behavior, and languages.
- A real life project on site of and for a Dutch company, performed by a multi-national, multi-disciplinary team of students.

The main objectives are:

- To train students from different countries and different disciplines to work together in multi-cultural and multi-disciplinary groups
- Students work together in order to find a solution for a proposed problem of the company.

1.1.2. The European Project Semester program

The international setting for universities and other institutions of higher education is changing rapidly. Several developments, such as globalization of the economy, the ongoing integration of the European markets and educational systems, have led to more international practices and approaches in education.

Fast technological development leads to faster product shifts on the market. At the same time, the market becomes more global and consequently more competitive. This means that companies should be able to design quality products with a short time-to-market delay. Product development will take place as an integrated process with departments such as engineering, design, planning, production, sales and marketing. The future industry will also have to be increasingly concerned with industrial ecology concepts and must look at sustainable engineering and technology developments.

The future engineer should be able to work with people from other countries and other disciplines, and be able to handle frequent changes. This requires a solid basic engineering knowledge combined with problem-solving and communicative skills. Basic understanding of a broader area of disciplines such as economics, management, communication, languages and solid training in teamwork, will be required, as well as knowledge of other cultures and their habits. Every engineer should be able to plan and run projects effectively, and have the appropriate entrepreneurial and social skills.

1.2. The project group

The project group consists of three students from different countries and have a different study background. Juan Carlos del Castillo is 22 years old and comes from Spain. Nam van Loon is 21 years old and comes from the Netherlands. Attila Szűcs is 24 years old and comes from Hungary. All of the students participate in the EPS program of Avans Hogeschool, 's-Hertogenbosch. The language that will be communicated in is English. Also the final report will be delivered in English.

The responsibilities and tasks within the project group are as followed:

Nam van Loon - Industrial Engineer

- Project Manager
- Contact with supervising lecturer

Nam van Loon is doing this project as an internship course.

Juan Carlos del Castillo - Industrial Engineer

- Planner
- Minutes secretary

Juan Carlos del Castillo is doing this project as a final assignment to finish his studies.

Attila Szűcs - Light Industrial Engineer (Paper manufacturing and packaging)

- Quality Manager
- Responsible for improving spelling and grammatical errors in documents

Attila Szűcs is also doing this project as an internship course.

1.3. Introduction of the project

VDL Enabling Technologies Group Eindhoven operates in the business of system integration of mechatronic (sub)systems and modules for OEMs in the high-tech capital equipment industry. As a system supplier, VDL ETG covers the value chain from (co-)engineering through parts production to assembly and testing. In-house production technologies include: machining, high-speed milling, precision grinding, sheet metal production, laser cutting, mechanical and electrical (clean room) assembly, testing, product certification and onsite installation. VDL ETG Eindhoven operates along certified quality management systems, including ISO9001, ISO14001, ISO13485 and AS9100 accreditation.

Several products VDL ETG produces for the customers contain sealing and/or vacuum[1] surfaces. These surfaces are machined (milling[2] and turning[3] machines) and finished by craftsmen for the right roughness (Appendix 1.7) and structure. Currently VDL ETG does not have a common or standardized way of working regarding the milling/turning and finishing by craftsmen. In addition, VDL ETG does not

[1] The definition of the vacuum can be found in the Appendix 1.8.
[2]Milling is the machining process of using rotary cutters to remove material from a work piece advancing (or *feeding*) in a direction at an angle with the axis of the tool.
[3]Turning is a machining process in which a cutting tool, typically a non-rotary tool bit, describes a helical tool path by moving more or less linearly while the work piece rotates.

have a consistent procedure regarding the visual inspection of these surfaces and the inline inspections are not sufficient to detect scratches. This leads to discussions between craftsmen and quality inspectors regarding the quality of vacuum surfaces and results in high costs caused by unnecessarily high quality vacuum surfaces.

VDL ETG has been coping with these problems for several years. Lots of time has been wasted and time equals money. It is therefore important to solve these problems.

The objectives are as followed: There should be no discussion about the surfaces of a part between the craftsmen and the quality inspector regarding whether a surface is good and record what is the best roughness[4], machining and material for vacuum surfaces.

1.4. Company profile

VDL Enabling Technologies Group is a tier-one contract manufacturing partner, operating world-wide. The customers of VDL ETG are leading high-tech Original Equipment Manufacturing companies and users of advanced production lines. The goal of VDL ETG is to outperform customer expectations in delivering mechatronic solutions.

VDL ETG has built their track record in the following markets: semiconductor capital equipment, thin film deposition equipment for photovoltaic solar systems, analytical instruments, medical systems, aerospace & defense parts and systems and mechanization projects.

The services of VDL ETG include prototyping, the prime activity for VDL ETG Research, customer specific factory automation projects, the focus of VDL ETG Projects and series manufacturing of 'high-mix low-volume' products, daily business in all other VDL ETG locations.

Under the Philips flag the company developed to become a worldwide supplier of advanced mechanical components, modules and complete systems.

VDL ETG is committed to supporting their customers wherever they have manufacturing facilities. The sites of VDL ETG in Eindhoven and Almelo (the Netherlands), Singapore and Suzhou (China) are testimony to this.

1.5. Methodology

The methodology that is used for this project is DMAIC. This is an improvement cycle that is commonly used to drive Six Sigma projects whereas can also be used as framework for other projects. It is a structured process for solving problems which consists of five basic phases: Define, Measure, Analyze, Improve and Control.

[4] The definition of the roughness can be found in the Appendix 1.7.

DMAIC – The 5 phases of Lean Six Sigma

The report is written according the DMAIC. The report is structured and will be easier to read and to understand. In Chapter 3, the needs and wishes of the client is mapped out. Different tools are used in order to understand the client at its best. Once the needs and wishes are clear, objectives and expected results can be formulated. It is then clear what is in and what is outside the scope. In the measure phase, a measure plan has to be drafted. The measure plan consists of the required tools that are needed to measure, what is going to be measured and how it is going to be measured. After the measure phase, the test results are examined. In the analyze phase, the test results will be analyzed. Once the test results are analyzed, conclusions can be drawn. Out of those conclusion, solutions can be thought of to implement in the company (improve phase). Solutions will be given for example, on how to improve the inspection of vacuum surfaces on leaks. The final phase is the control phase. In the control phase, an advice is given to implement the solutions and to maintain and improve it.

2. Define

In this chapter the voice of the customer (needs and wishes) are mapped out. Once the needs and wishes of the client are clear, objectives and expected results can be formulated. Different methods and tools are used such as CTQ, SIPOC in order to understand the client at its best.

2.1 Situation sketch

As discussed in Section 1.2, VDL ETG manufactures many high-tech products for different customers. Numerous of those products contain sealing and/or vacuum surfaces that are necessary in the applications of the customers.

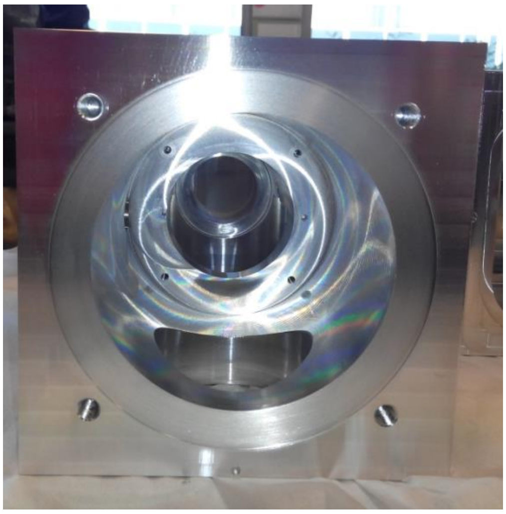


Illustration 1 – Example of a vacuum surface

VDL ETG currently does not have a common standardized way of working regarding the visual inspection of these surfaces which results in discussions between the craftsmen and Quality Inspectors and the inline inspections are not sufficient to detect scratches[5] and damages.

Additionally, these surfaces are machined (milling and turning) and finished by craftsmen to achieve the correct roughness and structure. Currently VDL ETG does not have a standardized method of working regarding the milling/turning and finishing by craftsmen.

2.2 Problem statement

VDL ETG copes with the following problems:

- The inline inspections are not sufficient to detect the problems (scratches, tool marks)
- There is no standard stating which type of scratches/damages causes leaks on a vacuum surface
- Some employees do not have sufficient and adequate knowledge about the vacuum surfaces and they can make scratches on it due to wrong handling

[5]The scratch is type of damage on the suface. The most of the cases it is like a long recess shaped with a certain depth and width. The scratch can be made by any sharpe thing (eg.: tool, grain paper, burr...).

2.3 The objectives

The goal of this work is to test the effect of scratches and damages on vacuum surfaces and to create a procedure which describes how to evaluate the quality of vacuum surfaces. There should be no discussion between the craftsmen and the quality inspector regarding the quality of a vacuum surface. Furthermore, the effect of the surface roughness, type of material and method of machining on the quality of vacuum surfaces is evaluated.

2.4 The expected results

The following results are expected by the company coaches:

- Standardized, proven and unambiguous instructions for testing and validation of sealing and vacuum surfaces
- Improved method to detect failures during inline inspections. Standardized, proven and unambiguous instructions for finishing sealing and vacuum surfaces

2.5 Visualization of the problem and project

There are several methods to visualize a project or problem. First, a planning is made (Appendix 1.1). This section describes several of the methods that are used for this work and refers to the appendices for details on the used methods.

The first method that is used is the mind map diagram. A mind map diagram is used to visually organize information. It is considered as a spider diagram. The reason that a mind map is used is to have a clear view about the scope of the project. The mind map contains subjects such as objectives, the roles on the group, the project tools and the organization of the company. For a clear view of the mind map, see Appendix 1.2.

A mind map functions well for a general overview of a project, although it is not very specific. For that reason a business model is developed. A business model contains the following topics: The problems, the objectives, the key activities, the economic, social, cultural and other aspects. For a clear view of the business model, see Appendix 1.3

After defining the situation, the next step is to consider the needs of the company, which requires that there is no discussion between departments regarding vacuum surfaces. The process of producing and evaluating a surface must be consistent.

A Critical-to-Quality (CTQ) tree is defined as the key measurable characteristics of the process which performance indicators must be met in order to satisfy the needs of the company. The CTQ tree aligns improvement and design efforts with customer requirements. Appendix 1.4 shows the CTQ tree for this project.
After the CTQ, a high-level view of the process-flow of the manufacturing process of a product is created. The best option for this is a SIPOC, which is a tool that summarizes the inputs and outputs of the process. The acronym SIPOC stands for Suppliers, Inputs, Process, Outputs, and Customers which form the columns of the table. The SIPOC is made by using the information from a Production Order Document (POD) of a product. See Appendix 1.5 for the SIPOC overview. The SIPOC overview is a summarized version of the process flow. In Appendix 1.6 the whole process flow of the production process of a product is shown.

3. Measure

In the previous chapter, the needs and wishes of VDL-ETG are mapped out. Out of the needs and wishes of VDL-ETG, objectives and expected results are formulated. Once this is clear, a measurement plan can be drafted.

The goal of this work is to evaluate the effect of scratches and damages on a vacuum surface to the functionality thereof. In this chapter the design of the experiment for this evaluation is described. In section 3.1 the measurement plan is defined including which parameters are of interest and what will be measured. This section also describes the process of designing a test product, the method of testing the products and which assumptions are used for this work. Section 3.2 contains a brief overview of the test results, which are described in further detail in Chapter 4.

3.1 Measurement plan

3.1.1 Requirements

To design a measurement plan, the requested results after measuring the effect of a scratch on a vacuum surface should be taken into account. The following results are needed:

- Which material is best resistant to leaks?
- Which roughness is best resistant to leaks?
- Which kind of machining is best resistant to leaks?
- Which depth and corresponding width of scratches causes leaks?
- Which position of scratches causes leaks?

Which material is best resistant to leaks?

The products with vacuum surfaces are manufactured in two different kinds of material. These materials are:

- Aluminum: Soft, ductile metal and is remarkable for the metal's low density and for its ability to resist corrosion due to the phenomenon of passivation.
- Stainless steel: It does not readily corrode, rust or stain with water as ordinary steel.

The tests are first carried out with aluminum products. The reason for this is that is easier to create scratches due to it being softer and more ductile metal than stainless steel and less pressure on the vacuum surface is required. Afterwards, the tests are carried out with stainless steel products.

Which roughness is best resistant to leaks?

The products with vacuum surfaces are manufactured with variable levels of roughness. The most used roughness by VDL ETG is Ra[6] 0.8. Within the company there are different opinions about what the best roughness is for the O-ring to fit on the vacuum surface. To evaluate whether a rougher or smoother surface is better for the O-ring, an extreme value under the roughness of 0.8 and an extreme value above the roughness of 0.8 is used.

[6] Ra=Roughness

The following levels of roughness are used during the experiments:

- 0.4 (extreme value under Ra 0.8)
- 0.8 (most used roughness)
- 1.4 (extreme value above Ra 0.8)

Which kind of machining is best resistant to leaks?

To answer this question, it is first required to know what the possibilities are for machining a product with a vacuum surface. Within VDL-ETG, it is possible to machine a vacuum surface by milling and by turning. After machining, some clients specify that the surface requires polishing[7]. For this reason it has been decided to test vacuum surfaces produced by:

- Milling
- Turning
- Polishing

Which depth and corresponding width of scratches causes leaks?

To know which depth and corresponding width of scratch causes leaks, different scratches are evaluated. It is not known in the company or at the customers which depth and corresponding width of scratches causes leaks. The employees can only judge the scratch by eye and roughly say whether the vacuum surface will leak and the judgment is based on experience and feeling. To answer the aforementioned question, it is decided to make scratches using the scratch tool (Illustration 3), starting with low pressure using light weights followed by building the pressure using heavier weights until the scratch causes a leak.

Once it is known which depth and corresponding width of scratch leaks, it is necessary to make a deeper and wider scratch to ensure that a deeper and wider scratch also leaks.

[7]It is a kind of surface treatment. In this case the most used tool to polish is the grain paper. This method makes smoother surface on the vacuum grooves. The polishing makes lines on the vaccum surface in the direction of the O-ring and it keeps the vacuum in perfect order. It can be found in the Appendix 2.4.

Which positions of scratches cause leaks?

The position of the scratch is an important variable regarding leaks. For instance, a narrow and shallow scratch on the internal side of the O-ring[8] will leak and the same scratch on the external side of the O-ring will not leak.

To understand better what is meant by the different and positions of scratches, see the following illustration:

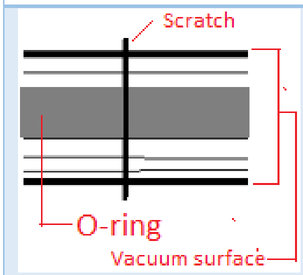
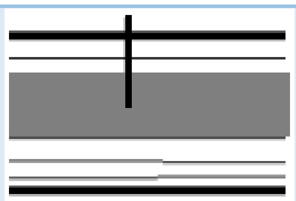
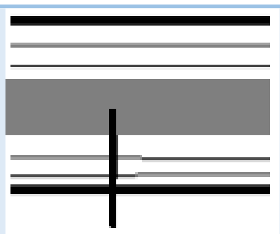
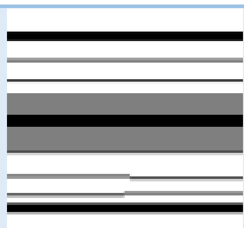
Full scratch 90 degrees	Half external scratch 90 degrees	Half internal scratch 90 degrees	Centric scratch
			

Table 1 – Different positions of the scratch

3.1.2 Design of the test product

With the defined requirements, a test product has to be designed. There are two different designs available of the test product. The reason for this is because when the first design was finished, an employee suggested another design that was easier and cheaper to produce. The first design is made in SolidWorks. It is also available in CAD. The design is shown in Appendix 2.2. The second design is shown in Appendix 2.3. The second design was used for the tests because of the low manufacturing costs and its simplicity.

The following requirements for the test part are taken into account for the design of the test part:

- The test part is manufactured in aluminum and stainless steel
- The test part consists of a roughness of 0.4 or 0.8 or 1.4
- The test part is machined by milling and turning
- Different depths and widths and types of scratches (internal, external, grain paper, by hand) must be made on the vacuum surface of the test part

Design 1

After talking with the factory engineer about what is required from the test part, a test part is drawn in SolidWorks (Appendix 2.2).

[8] The definition of O-ring can be found in the appendix 1.9.

Design 2

The second design was suggested by another factory engineer. It is a disc with two sides; on both sides are three vacuum surfaces with different levels of roughness. One side of the disc can be milled and the other side can be turned (Appendix 2.3).

Advantages and disadvantages of design 1 and design 2

	Design 1	Design 2	Conclusion
Ra	1	3	Design 2 is better because it consists of two additional different roughness
Machining	Milled or turned	Milled and turned	Design 2 is better because it has a machined and turned side
Number of vacuum surfaces	1	6	Design 2 is better because it consists of 5 more vacuum surfaces
Material	Aluminum or stainless steel	Aluminum or stainless steel	Both designs are equal
Different kind of scratches	1	1	Both designs are equal
Number of test parts that has to be manufactured	144	24	Design 2 is better because there are 120 test parts less needed

Table 2 – Advantages and disadvantages of design 1 and design 2

Design 2 is clearly the best option and is chosen as the design for the test part. Because using 24 test parts is expensive to manufacture, it was decided to re-mill and re-turn the test parts. Consequently, the number of test parts is reduced to 6 test parts.

Performing the test

Once the design has been chosen and the requirements for the desired results are clear, a plan of how to carry out the test has to be made. To answer the question ''Which depth and corresponding width of scratches causes leaks?'', the permitted depth and width of scratches by ASML are considered[9]:

[9] Generic standards of ASML: Leak testing: Helium vacuum method

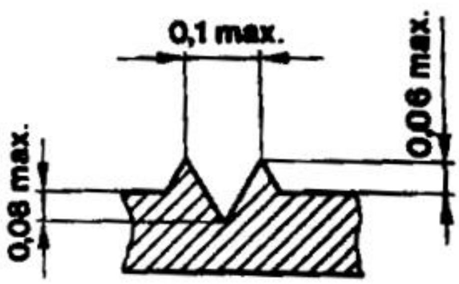


Illustration 2 – Permitted damages by ASML

During the tests, the depth of the scratch is measured from the deepest point until the highest point.

- Depth: 0.08+0.06=0.14 mm
- Width: 0.1 mm

VDL ETG does not have a method of making scratches with a specific depth. Hence, for this project, a tool is designed to make scratches and carry out the tests. Different weights can be used on the scratch tool to vary the depths and widths of scratches that can be made. The scratch tool is a very simple tool that consists of a plate with three legs. One of these legs is connected to a pen with a sharpened head. If the scratch tool moves, the sharpened head makes a scratch as long as required. It is possible to put different weights on the scratch tool. Depending on the weight, the scratch tool can make scratches with different depths and widths. The design of the scratch tool is shown in the following illustration:

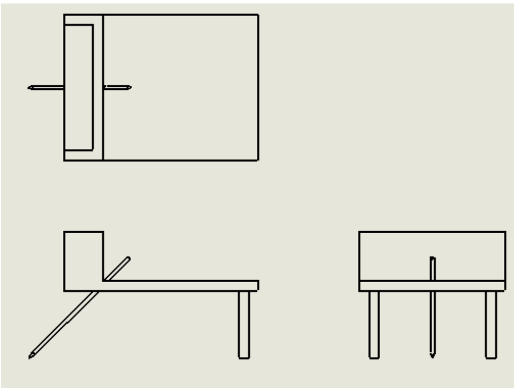


Illustration 3 – Design of the scratch tool

It is possible to measure the depth of a scratch with a mixture of two components of pastes by means of a microscope. The method to measure the depth and width of each scratch can be found in Appendix 2.5. From the results it is possible to know which kind of scratches leaks.

Three test parts of aluminum and three test parts of stainless steel are manufactured. Each test product has 3 different levels of roughness on each side of the product. One side is machined by milling and the other side by turning. As mentioned above, the test parts will be re-milled and re-turned.

Once the test products are manufactured they are directly tested on leaks. It is then known whether a milled or turned vacuum surface leaks. After the test products are tested on leaks, the tests with scratches on the surfaces can be performed.

The planning of how to carry out each step is shown in Appendix 2.1.

3.1.3. Assumptions

During the tests, there are certain factors that could not be investigated. Therefore, there are some assumptions made for an efficient investigation. The assumptions:

- The pump, the leaking tester and the helium gun[10] are in perfect conditions.
- The O-ring and the plates are always dirty and must be cleaned.
- There is no scratch on the vacuum surface of the female plate (counterpart). For a visual view of the female plate, see Appendix 2.3.
- Half internal and half external scratches have to cross the O-ring from the side of the vacuum surface until the middle. (Table 1)
- The plates are concentric and the O-ring is in the middle of the grooves.
- The roughness after being machining is equal to the specified roughness.
- After polishing, the surface has to be concentric and smooth.
- The method of measuring the depth and width with a mixture of pastes are accurate.
- A leakage with a value of $10^{-8}$is because of the dust on the O-ring or helium that is stuck in the O-ring or the dust on the grooves of the female part.
- It is considered a leak when the leaking tester changes from a tight value (10^{-9}-10^{-8}) into a value under 10^{-7}

3.2. Test results

At the beginning of the tests, very thin scratches were made on the vacuum surface, those are scratches that are certainly not leaking. Constantly, more weight is put on the scratch tool to increase the depth and width of a scratch until a point when it starts to leak. Therefore, the depth and width of the scratch that starts to leak can be accurately pinpointed.

The last deepest scratch that does not cause a leak will be measured. Therefore, scratches with a lower depth and width than the last deepest scratch will not cause a leak. Also the first two scratches (after the last deepest scratch that does not cause a leak) that are causing a leak will be measured. The reason for measuring the first two scratches that are causing a leak, is to ensure that a deeper scratch than the first leak scratch also causes a leak. Hence, a vacuum surface can leak due to dirt on the ring. The scratches were measured with the help of a microscope and a mixture of pastes.

It is decided to divide the depth of scratches into three categories:

- Green (No leak): This category contains depths and widths of scratches where it is certain that it does not leak.
- Orange (High chance leak): This category contains depths and widths of scratches where it is not 100% accurate to say that the depths of scratches is leaking. Although the chances are high.
- Red (Leak): This category contains depths, widths of scratches where it is certain that the depths of scratches leak.

[10]It is a connected device to the helium tank what is pistol shaped. The trigger by pulling is opening the way of the helium from the tank.

Weight (g) / Depth and width (mm)		ALUMINIUM Full scratch of 90º								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH no Leak	weight	323,1	463,5	601,4	323,1	694,2	463,5	832,9	1378,6	1654,7
	width	0,053	0,063	0,053	0,065	0,071	0,04	0,073	0,078	0,095
	depth	0,011	0,026	0,018	0,015	0,021	0,017	0,015	0,02	0,018
SCRATCH Leak	weight	463,5	601,4	694,2	463,5	832,9	601,4	909,9	1511,8	1834,9
	width	0,063	0,07	0,091	0,069	0,083	0,057	0,093	0,101	0,104
	depth	0,033	0,027	0,031	0,018	0,025	0,024	0,022	0,025	0,026
SCRATCH Leak	weight	601,4	694,2	832,9	601,4	200	694,2	1142,4	1654,7	2065,6
	width	0,065	0,091	0,084	0,079	0,079	0,063	0,094	0,116	0,104
	depth	0,028	0,027	0,024	0,02	0,035	0,027	0,026	0,027	0,031

Table 3 – Depth and width results – Aluminum – Full 90 degrees scratch

Weight (g) / Depth and width (mm)		STAINLESS STEEL Full scratch of 90º								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH no Leak	weight	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7
	width	0,12	0,143	0,147	0,145	0,158	0,141	0,142	0,147	0,139
	depth	0,028	0,036	0,036	0,029	0,035	0,036	0,026	0,028	0,022
SCRATCH LEAK	weight	1142,4	1378,6	1378,6	1142,4	1794,5	1925,8	1142,4	1834,9	1834,9
	width	0,057	0,062	0,05	0,057	0,066	0,064	0,073	0,069	0,062
	depth	0,023	0,021	0,017	0,015	0,022	0,018	0,02	0,016	0,02
SCRATCH LEAK	weight	1378,6	1925,8	1654,7	1511,8	1925,8	2065,6	1279,3	2065,6	2065,6
	width	0,061	0,067	0,051	0,056	0,089	0,075	0,098	0,072	0,07
	depth	0,023	0,024	0,019	0,015	0,015	0,024	0,023	0,022	0,024

Table 4 - Depth and width results – Stainless steel – Full 90 degrees scratch

Only the full 90 degrees scratch is highlighted in the aluminum and stainless steel vacuum surfaces. For the other types of scratches can be found in Appendix 2.7.

The green, orange and red areas are represented in the following charts that represent the values of Table 3.

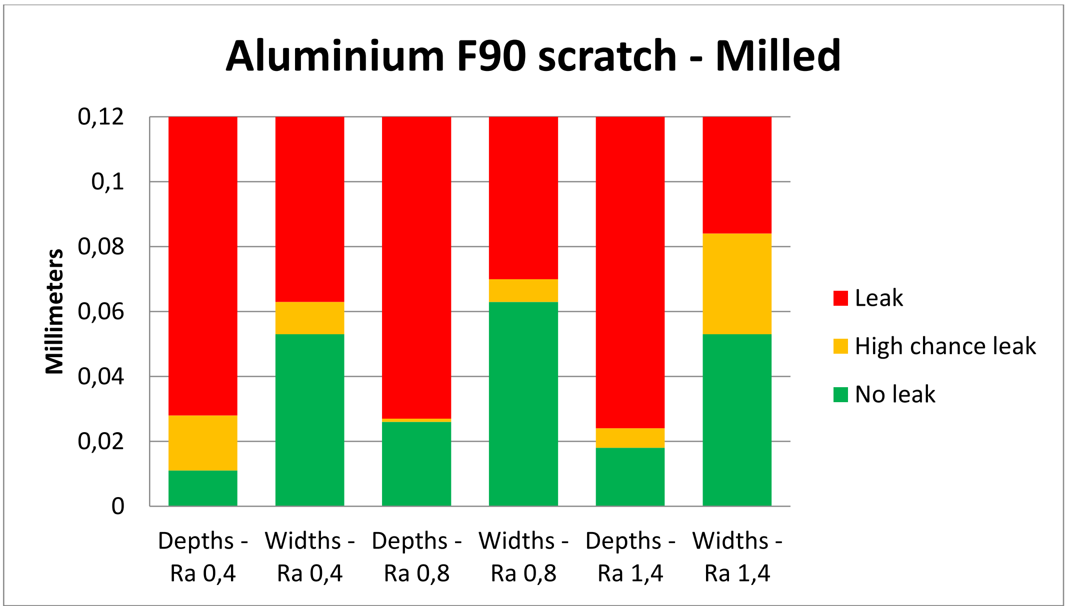


Illustration 4 - Depths and widths bands: Aluminum – Full 90 degrees scratch - Milled

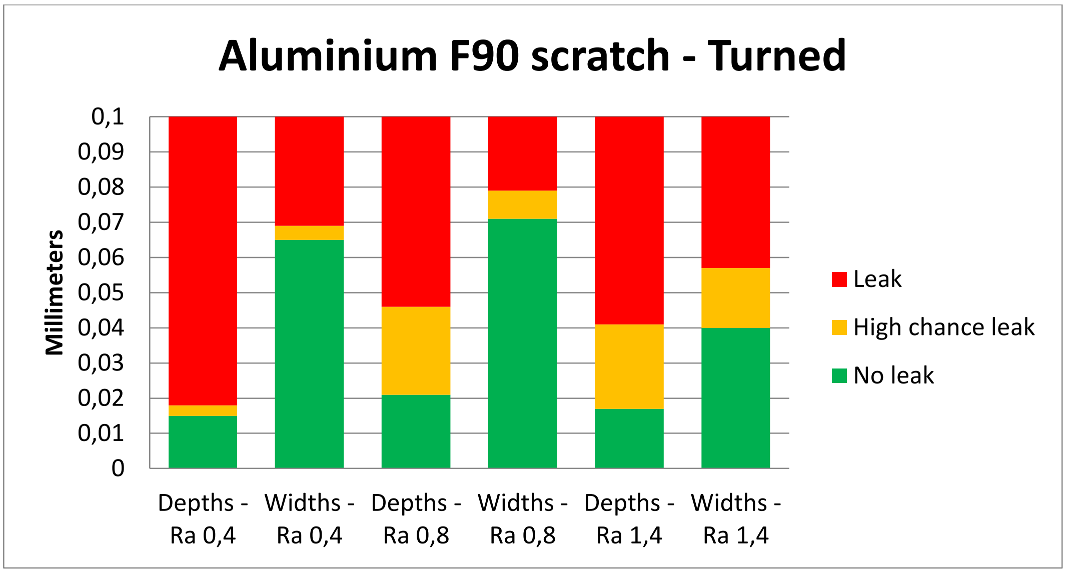


Illustration 5 - Depths and widths bands: Aluminum – Full 90 degrees scratch – Turned

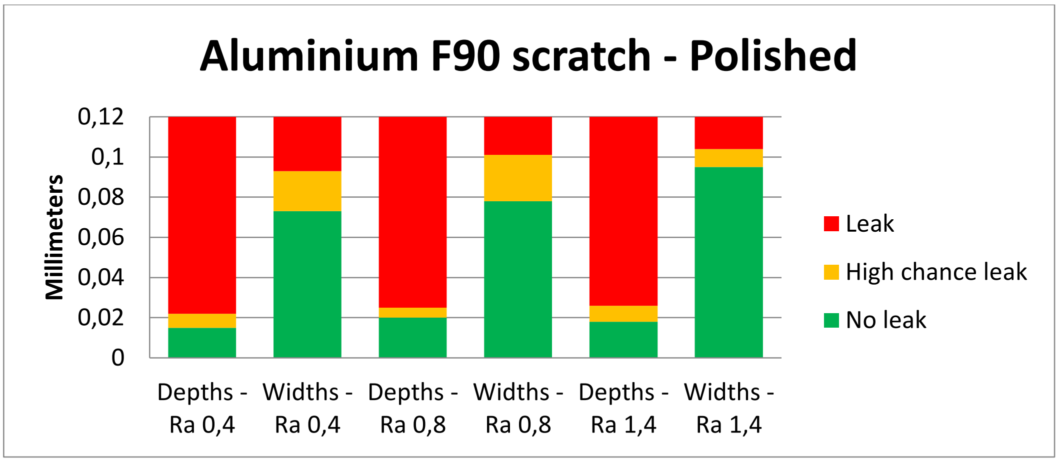


Illustration 6 - Depths and widths bands: Aluminum – Full 90 degrees scratch - Polished

3.3. Visual evaluation

Tools for the visual evaluation of the investigation:

- Microscope – It is a magnifying device that is connectible to a computer. During the test it is used with the maximal 90 times magnification. The distance was approximately 5 cm between the plate's surface and the lens of the microscope. The tool has an integrated LED light.
- Phone – Camera of the mobile phone is an 8 megapixel object glass. The photos were taken from the surface between 4-5 cm.
- Flashlight – It is a simple flashlight with LED system what the inspector uses for the investigation.
- Storage of pictures – The photos were saved on the computer in separate folders.

Types of images: (There are three different types of images of one scratch. All photos were taken from above whereas with different illuminations)

- Microscope – The lens and the LED light were aimed at the same point. The angle was 90 degrees.

- Phone I. – These pictures were taken in a room with indoor lights.
- Phone II. – These pictures were taken in a dark room with flashlight. The angle of incidence of the light was 15 degree perpendicular to the scratch.

Taking into account of the available tools and possibilities, these three different devices were the best choice reflecting the reality most effectively.

4. Analyze

After the test results are acquainted, the results have to be analyzed. It is important to know which level of roughness, which kind of machining or which material is the best solution in certain circumstances regarding damages/scratches on the vacuum surface. This is the functional part of the investigation. It is also important to analyze how this functional part correlates to the visual evaluation. This means that if an employee inspects the vacuum surface, he can already conclude what effect the damages on the vacuum surface have without testing the vacuum surface on leaks.

Test results:

After the results of the tests are obtained, the following aspects can be analyzed:

- Which material is best resistant to leaks?
- Which roughness is best resistant to leaks?
- Which kind of machining is best resistant to leaks?
- Which depth and corresponding width of scratches causes leaks?

This is the functional part of the results. After the functional part is analyzed, the following step is to link the outcome to the visual aspect of the evaluation.

4.1 Functional analysis

In this section the question is answered about the connection between the damages and vacuum surface. Illustrations and graphs show the interactions. At the end of this section, it is clear which material, roughness and kind of machining is best resistant to leaks.

During the tests, the weight on the scratch tool was increased. For the chart of the relation between the weight on the scratch tool and the depth of the scratch, see Appendix 3.1.

4.1.1 Which material is best resistant to leaks?

Aluminum and stainless steel materials are considered. This section is divided into a turned, milled and a polished surface part. The results will show which material which material leaks first as the depth or width of the scratch will rise. Based on this it can be concluded which material is best resistant to leaks.

- <u>**No scratch:**</u> Aluminum and stainless do not leak without a scratch at all levels of roughness and all kinds of machining.
- <u>**Full 90 degrees scratch (Table 1):**</u> Stainless steel is the most vulnerable material in case of a full 90 degrees scratch on the vacuum surface.
- <u>**Half external 90 degrees scratch (Table 1):**</u> Aluminum and stainless steel do not leak with different scratches at all roughness and all kinds of machining.
- <u>**Half internal 90 degrees scratch (Table 1):**</u> Aluminum is the most vulnerable material in case of a half internal 90 degrees scratch on the vacuum surface. However it must be mentioned that with a roughness of 1.4 with a turned surface the aluminum only starts to leak with a significant, really deep scratch.
- <u>**Centric scratch (Table 1):**</u> Aluminum and stainless do not leak with different scratches at all roughness and all kinds of machining.
- <u>**Full power external scratch by hand:**</u> Aluminum and stainless steel do not leak with different scratches at all roughness and all kinds of machining.

In the following chart it is shown how many times the aluminum or stainless steel surfaces leak first:

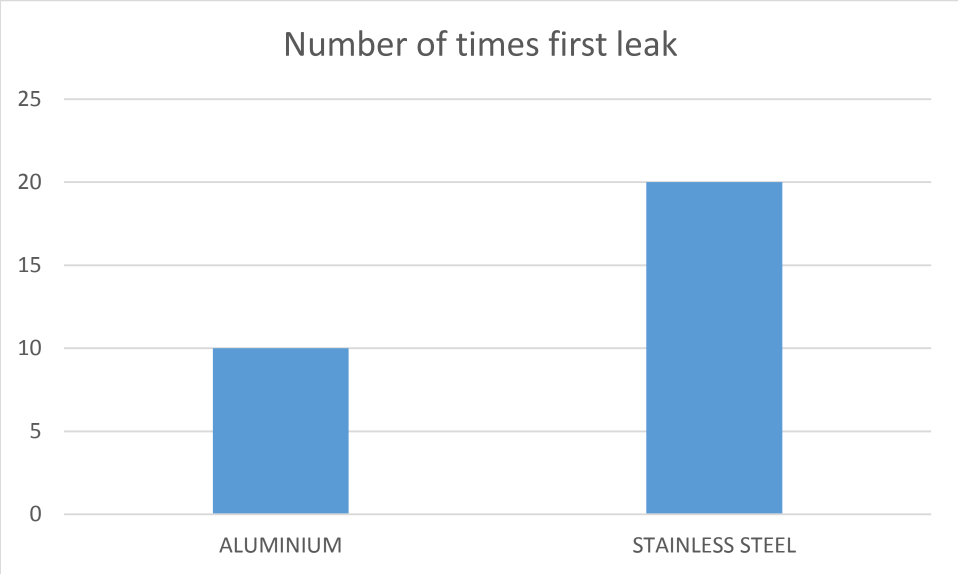


Illustration 7 – Best resistant material - Number of times first leak

From this, it can be concluded that an aluminum surface is the better material for preventing leaks compared to a stainless steel surface in the different kinds of machined surfaces. For further details on the values and test results that are used, see Appendix 3.2.1.

Which kind of material (aluminum or stainless steel) is the best resistant to leaks?

- **Aluminum.**

4.1.2 Which roughness is best resistant to leaks?

To answer this question the test results are examined. It concerns the roughness of 0.4, 0.8 and 1.4. The results will show which levels of roughness leak first as the depth and width of the scratch will rise. Based on this it can be concluded which levels of roughness is most vulnerable for leaks and which levels of roughness is best. The following charts will represent this:

- **No scratch:** In the previous paragraph it is stated that in case of a vacuum surface without scratches there are no leaks. For this reason there will be no winner designated in this category.

- **Full 90 degrees scratch:** There are leaks identified with scratches of full 90 degrees. The measure results will be plotted in a chart to decide which levels of roughness for a vacuum surface is the best for a milled, turned or polished vacuum surface. For the exact depths and corresponding widths of the scratches, see Appendix 2.7.

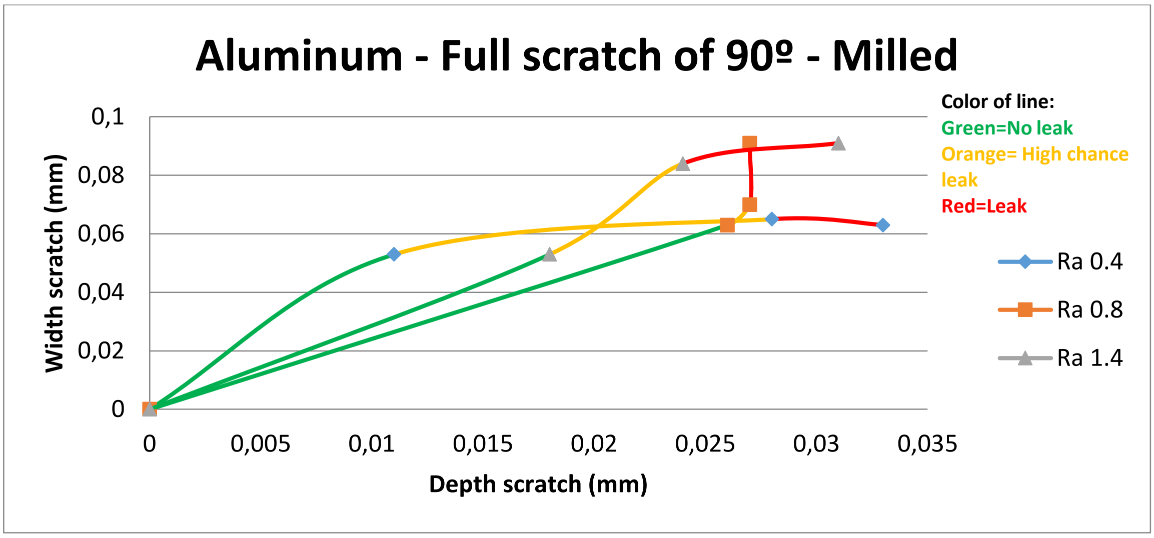


Illustration 8 - Best resistant roughness: Aluminum – Full 90 degrees scratch - Milled

Conclusion: A milled vacuum surface with a roughness of 0.8 is best resistant to leaks. It is clearly the best one in comparison with the other levels of roughness. The roughness of 0.4 is the most vulnerable for leak.

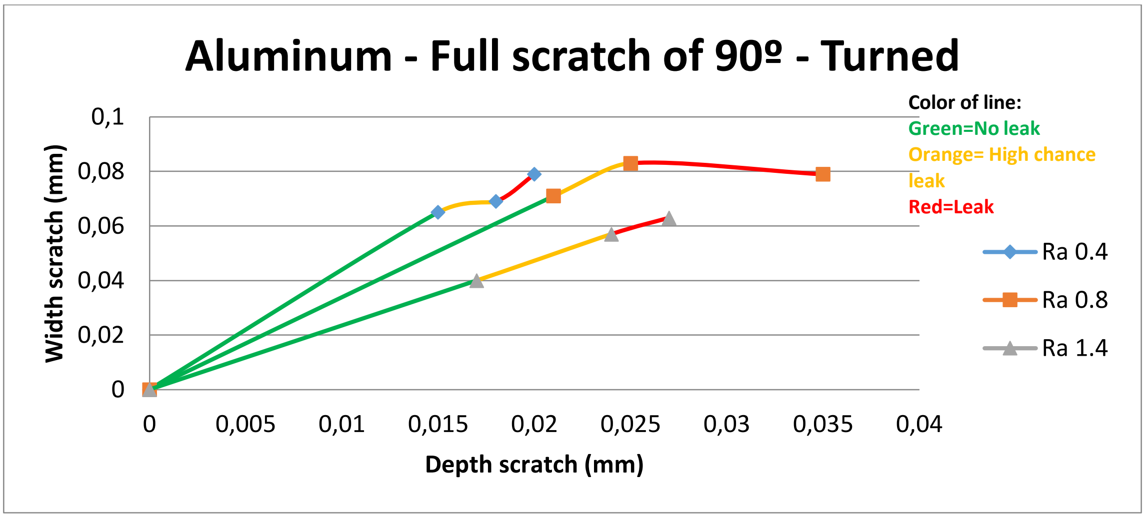


Illustration 9 - Best resistant roughness: Aluminum – Half internal 90 degrees scratch - Turned

Conclusion: A vacuum surface with a roughness of 0.8 is clearly the best resistant to leaks again. The best roughness after 0.8 is respectively 0.4 and 1.4.

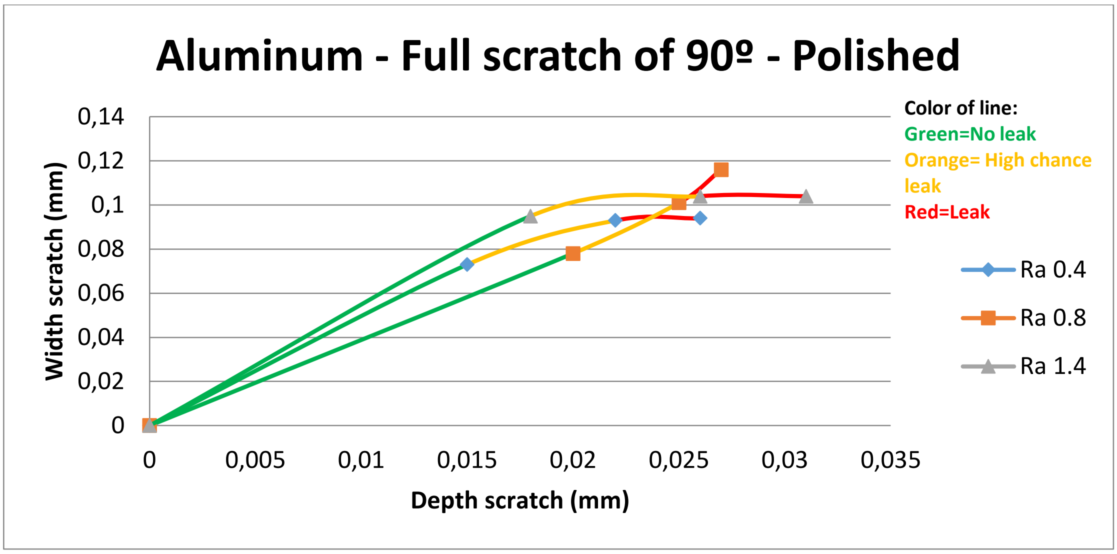


Illustration 10 - Best resistant roughness: Aluminum – Half internal 90 degrees scratch - Polished

Conclusion: There is no clear winner in this category. However, it shows that a roughness of 0.4is the least resistant. There is no clear winner because a roughness of 0.8 has a high chance of leaking at a scratch with a depth of 0.02 mm and a width of 0.078 mm, and a roughness of 1.4 has a high chance of leaking at a scratch with a depth of 0.018 and a width of 0.095 mm.

Aluminum – Milled, turned, polished

General conclusion: With much certainty, it can be said that a roughness of 0.8 is the best and a roughness of 0.4 is the most vulnerable for leak.

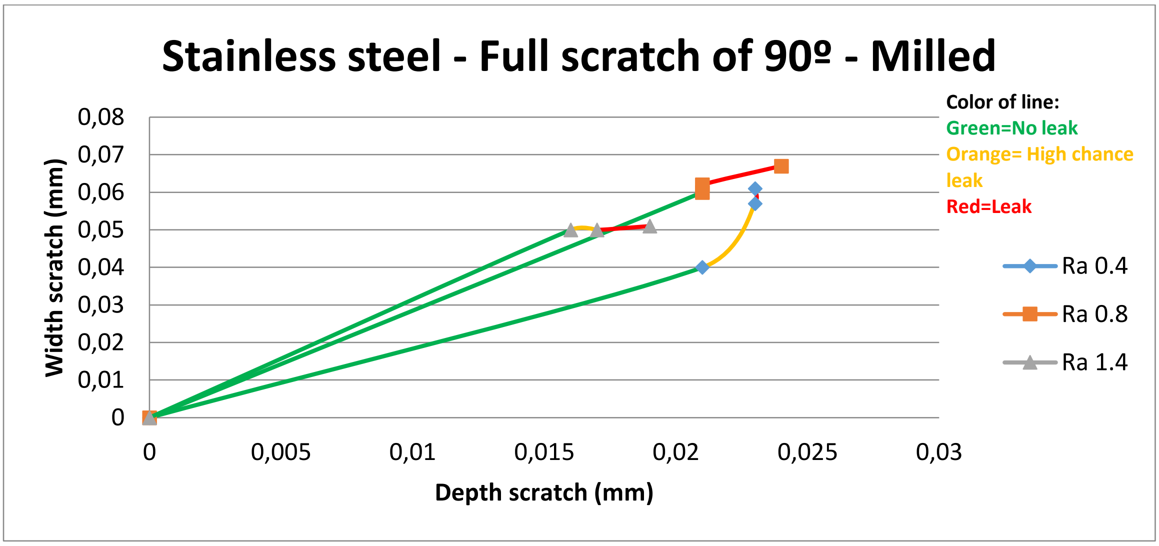


Illustration 11 - Best resistant roughness: Stainless steel – Full 90 degrees scratch - Milled

Conclusion: A vacuum surface with a roughness of 0.8 is with no doubt the best resistant to leaks. Between a roughness of 0.4 and 1.4 it is hard to decide which one is better, because a roughness of 0.4 leaks with a lower width of scratch than a roughness of 1.4 although does not leak with a higher depth of scratch than a roughness of 1.4.

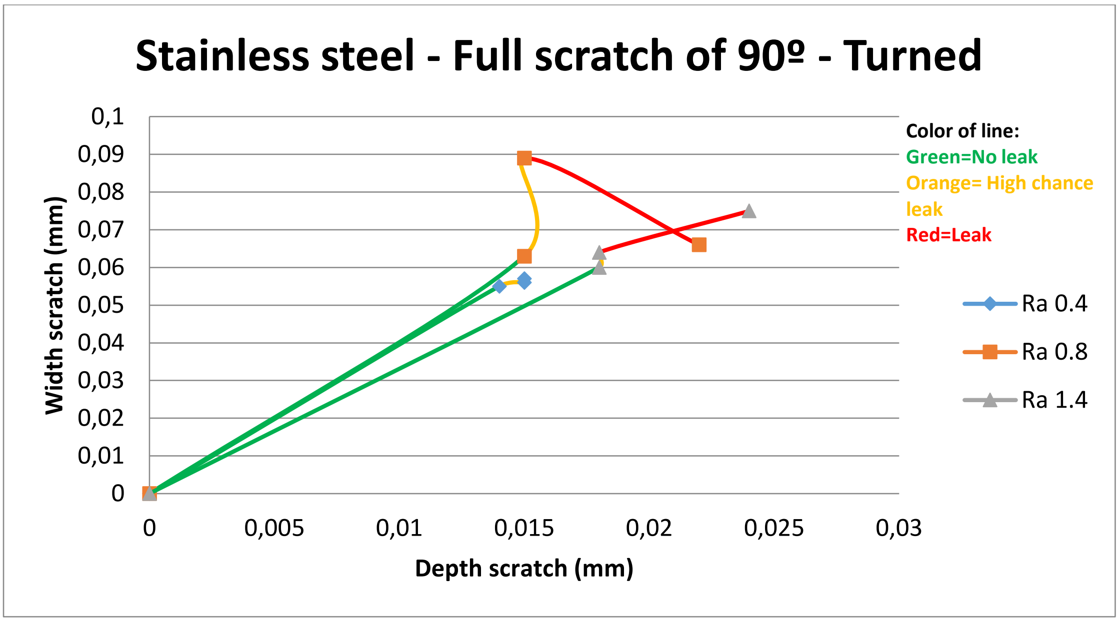


Illustration 12 - Best resistant roughness: Stainless steel – Full 90 degrees scratch - Milled

Conclusion: A roughness of 0.4 is the most vulnerable for leaks. The best roughness in this category is 1.4, although it can be concluded that they are roughly the same.

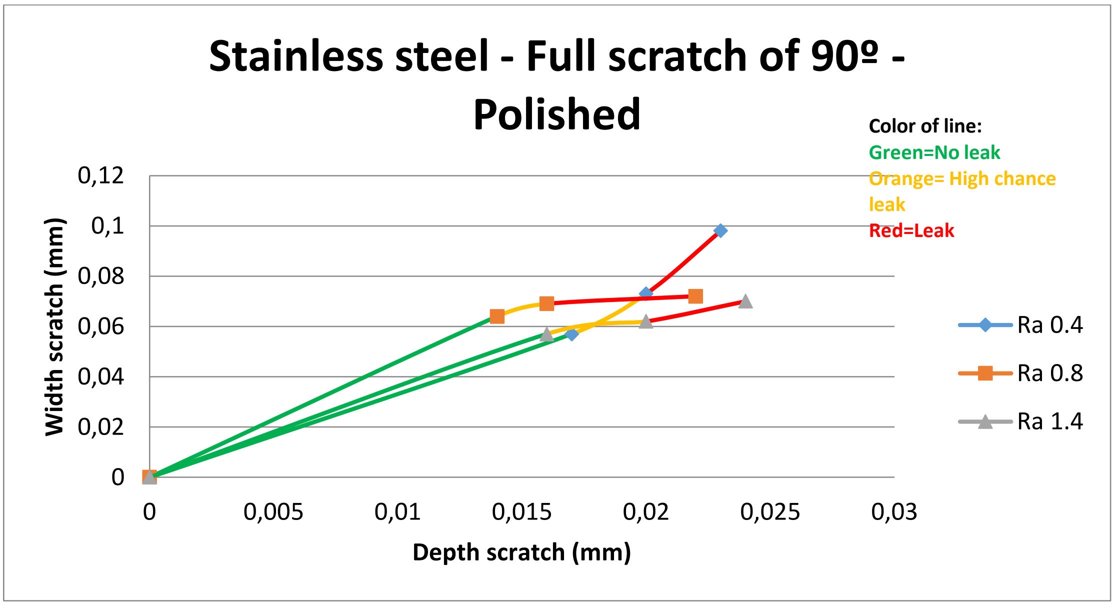


Illustration 13 - Best resistant roughness: Stainless steel – Full 90 degrees scratch - Milled

Conclusion: The differences in chances on a leak are rather small to draw a winner out of it.

Stainless steel – Milled, turned, polished
General conclusion: A roughness of 0.8 is slightly better than the rest.

To analyze the other type of scratches, the measure results are plotted in a chart (Appendix 3.2.2.) For the exact depths and corresponding widths of the scratches, see Appendix 2.7.
In the following table, the different levels of roughness in each kind of machining are compared. In every kind of machining, a total of ten points can be divided over the three roughness. The roughness with less points than the others, means that it leaks with a lower depth and width in comparison to the other roughness. So, the roughness that is best resistant to leaks receives the most points.

		Aluminum – Which roughness is best? (10 points can be divided)								
		Milled			Turned			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
Type of scratch	F90º	1	6	3	3	6	1	2	4	4
	Half internal 90º	0	5	5	1	7	2	1	5	4
	Half external 90º	NO LEAKS WERE FOUND								
	Centric	NO LEAKS WERE FOUND								
	Total	**1**	**11**	**8**	**4**	**13**	**3**	**3**	**9**	**8**

Table 5 – Which roughness is best resistant to leaks? – Aluminum

In the following data it is shown the smallest and the biggest scratches that do not leak. These scratches were measured during the tests in each kind of scratch and in each kind of machining.

Full 90 degrees scratch: (These scratches do not leak)

- Milled:
  - Smallest scratch: Ra 0.4 - depth: 0.011mm // width: 0.053 mm
  - Biggest scratch: Ra 0.8 - depth: 0.026 mm // width: 0.063 mm
- Turned:
  - Smallest scratch: Ra 1.4 - depth: 0.017 mm // width: 0.04 mm
  - Biggest scratch: Ra 0.8 - depth: 0.021 mm // width: 0.071 mm
- Polished:
  - Smallest scratch: Ra 0.4 - depth: 0.015 mm // width: 0.073 mm
  - Biggest scratch: Ra 1.4 - depth: 0.018 mm // width: 0.095 mm

Half internal 90 degrees scratch: (These scratches do not leak)

- Milled:
  - Smallest scratch: Ra 0.4 - depth: 0.015mm // width: 0.089 mm
  - Biggest scratch: Ra 0.8 - depth: 0.026 mm // width: 0.111 mm
- Turned:
  - Smallest scratch: Ra 1.4 - depth: 0.015 mm // width: 0.056 mm
  - Biggest scratch: Ra 0.8 - depth: 0.036 mm // width: 0.149 mm
- Polished:
  - Smallest scratch: Ra 0.4 - depth: 0.015 mm // width: 0.073 mm
  - Biggest scratch: Ra 0.8 - depth: 0.033 mm // width: 0.152 mm

Half external 90 degrees scratch: (These scratches do not leak)

- Milled:
  - Biggest scratch: Ra 1.4 - depth: 0.047 mm // width: 0.144 mm
- Turned:

Biggest scratch: Ra 0.8 - depth: 0.055 mm // width: 0.144 mm

- Polished:
  Biggest scratch: Ra 0.8 - depth: 0.059 mm // width: 0.155 mm

Centric scratch: (These scratches do not leak)

- Milled:
  Biggest scratch: Ra 1.4 - depth: 0.036 mm // width: 0.147 mm
- Turned:
  Biggest scratch: Ra 0.8 - depth: 0.035 mm // width: 0.158 mm
- Polished:
  Biggest scratch: Ra 0.8 - depth: 0.028 mm // width: 0.147 mm

	Ra 0.4	Ra 0.8	Ra 1.4
Total	**8**	**33**	**19**

Table 6 – Which roughness is best resistant to leaks? - Aluminum

Conclusion: In every kind of machining, the roughness of 0.8 is the best resistant to leaks.
The roughness of 0.4 is clearly the most vulnerable for leaks with only ten points.
Remarkably, the half external of 90 degrees and the centric scratch did not cause a leak during the tests.

Which roughness is the best resistant to leaks in an aluminum vacuum surface?

- **The roughness of 0.8 (Ra 0.8)**

		Stainless steel – Which roughness is best? (10 points can be divided)								
		Milled			Turned			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
Type of scratch	F90º	2	6	2	1	4	5	NO CLEAR WINNER		
	Half internal 90º	0	5	5	0	5	5	0	5	5
	Half external 90º	NO LEAKS WERE FOUND								
	Centric	NO LEAKS WERE FOUND								
	Total	**2**	**11**	**7**	**1**	**9**	**10**	**0**	**5**	**5**

Table 7 - Which roughness is best resistant to leaks? – Stainless steel

In the following data it is shown the smallest and the biggest scratches that do not leak. These scratches were measured during the tests in each kind of scratch and in each kind of machining.

Full 90 degrees scratch: (These scratches do not leak)

- Milled:
  Smallest scratch: Ra 1.4 - depth: 0.016 mm // width: 0.05 mm
  Biggest scratch: Ra 0.8 - depth: 0.021 mm // width: 0.06 mm
- Turned:
  Smallest scratch: Ra 0.4 - depth: 0.014 mm // width: 0.055 mm
  Biggest scratch: Ra 0.8 - depth: 0.015 mm // width: 0.063 mm

- Polished:
  - Smallest scratch: Ra 1.4 - depth: 0.016 mm // width: 0.057 mm
  - Biggest scratch: Ra 0.8 - depth: 0.014 mm // width: 0.064 mm

Half internal 90 degrees scratch: (These scratches do not leak)

- Milled:
  - Smallest scratch: Ra 0.4 - depth: 0.021 mm // width: 0.07 mm
  - Biggest scratch: Ra 0.8 - depth: 0.033 mm // width: 0.103 mm
- Turned:
  - Smallest scratch: Ra 0.4 - depth: 0.015 mm // width: 0.072 mm
  - Biggest scratch: Ra 1.4 - depth: 0.028 mm // width: 0.102 mm
- Polished:
  - Smallest scratch: Ra 0.4 - depth: 0.014 mm // width: 0.066 mm
  - Biggest scratch: Ra 0.8 - depth: 0.026 mm // width: 0.087 mm

Half external 90 degrees scratch: (These scratches do not leak)

- Milled:
  - Biggest scratch: Ra 0.4 - depth: 0.024 mm // width: 0.083 mm
- Turned:
  - Biggest scratch: Ra 0.4 - depth: 0.031 mm // width: 0.1 mm
- Polished:
  - Biggest scratch: Ra 0.8 - depth: 0.024 mm // width: 0.088 mm

Centric scratch: (These scratches do not leak)

- Milled:
  - Biggest scratch: Ra 0.8 - depth: 0.036 mm // width: 0.081 mm
- Turned:
  - Biggest scratch: Ra 1.4 - depth: 0.026 mm // width: 0.075 mm
- Polished:
  - Biggest scratch: Ra 0.4 - depth: 0.026 mm // width: 0.092 mm

	Ra 0.4	Ra 0.8	Ra 1.4
Total	3	25	22

Table 8 - Which roughness is best resistant to leaks? – Stainless steel

Conclusion: The roughness of 0.8 is the best resistant to leaks with 25 points. The roughness 0.4 is the most vulnerable for leaks with only 3 points.

Which roughness is the best resistant to leaks in a stainless steel vacuum surface?

- **The roughness of 0.8 (Ra 0.8)**

4.1.3 Which kind of machining is most vulnerable for leaks?

As mentioned in Section 3.1.1. there are three different types of machining for a vacuum surface:

- Turning
- Milling
- Polishing

There are also five types of scratches as mentioned before:

- No scratch
- Full 90 degrees scratch
- Half internal 90 degrees scratch
- Half external 90 degrees scratch
- Centric scratch

- **No scratch:** There is no leak when there is no scratch on the vacuum surfaces of a turned, milled and polished vacuum surface with roughness of 0.4, 0.8 and 1.4.

- **Full 90 degrees scratch:** There are leaks identified with scratches of full 90 degrees. The measured results will be plotted in a chart to decide which kind of machining for a vacuum surface is the best at the roughness of 0.4, 0.8 and 1.4. Only the chart with a roughness of 0.8 is shown. For the exact depths and corresponding widths of the scratches, see Appendix 2.7.

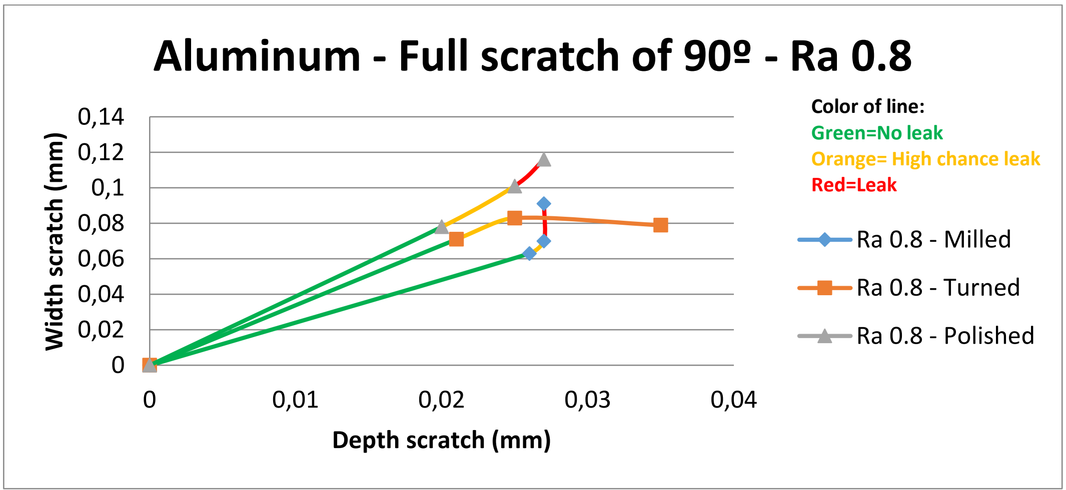


Illustration 14 – Best resistant machining – Aluminum – Full 90 degrees scratch – Ra 0.8

Aluminum – Ra 0.8

Conclusion: In this category there is no clear winner. A polished vacuum surface and a turned vacuum surface are again, pretty similar. There is no clear winner since the milled vacuum surface leaks with a lower width of scratch than the rest and does not leak with a higher depth of scratch than the rest.

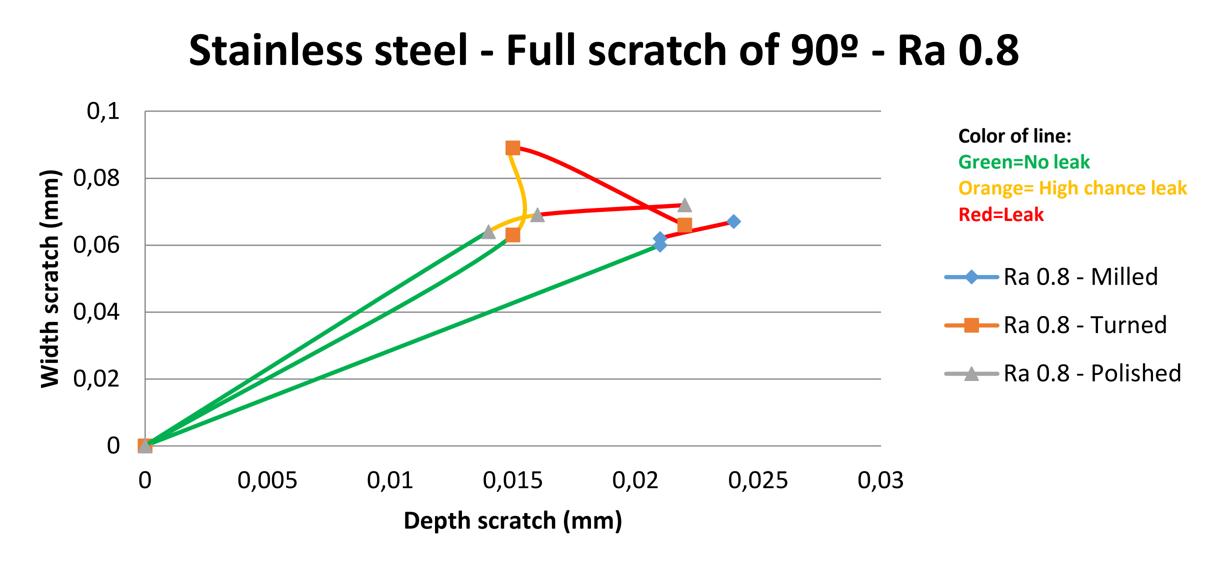


Illustration 15 - Best resistant machining – Stainless steel – Full 90 degrees scratch – Ra 0.8

Stainless steel – Ra 0.8

Conclusion: Remarkably a milled vacuum surface is in this situation the best surface. The turned and polished vacuum surfaces are similar to each other.

To analyze the other type of scratches, the measure results are plotted in a chart (Appendix 3.2.3.) For the exact depths and corresponding widths of the scratches, see Appendix 2.7.

In the following table, the different kind of machining in each different levels of roughness are compared. In every level of roughness, a total of ten points can be divided over the three kind of machining. The kind of machining with less points than the others, means that it leaks with a lower depth and width in comparison to the other kinds of machining. So, the kind of machining that is best resistant to leaks receives the most points.

		Aluminum– Which kind of machining is best? (10 points can be divided)								
		Ra 0.4			Ra 0.8			Ra 1.4		
		Milled	Turned	Polished	Milled	Turned	Polished	Milled	Turned	Polished
Type of scratch	F90º	2	4	6	3	3	4	3	2	6
	Half internal 90º	3	2	5	5	5	0	**7**	**1**	**2**
	Half external 90º	NO LEAKS WERE FOUND								
	Centric	NO LEAKS WERE FOUND								
	Total points	5	6	11	8	8	4	10	3	8

Table 9 – Which kind of machining is best resistant to leaks? – Aluminum

	Milled	**Turned**	**Polished**
Total points	23	17	23

Table 10 - Which kind of machining is best resistant to leaks? - Aluminum

Conclusion: The milled and polished surfaces, with 23 points, are better that the turned surface. In the full 90 degrees scratch, that is the most critical scratch, the polished surface is the best in every level of roughness.

Which kind of machining is the best resistant to leaks in an aluminum vacuum surface?

- **The milled and polished surface**

		Stainless steel – Which kind of machining is best? (10 points can be divided)								
		Ra 0.4			Ra 0.8			Ra 1.4		
		Milled	Turned	Polished	Milled	Turned	Polished	Milled	Turned	Polished
Type of scratch	F90°	3	3	4	4	2	2	2	5	3
	Half internal 90°	5	3	2	NO LEAKS WERE FOUND					
	Half external 90°	NO LEAKS WERE FOUND								
	Centric	NO LEAKS WERE FOUND								
	Total points	**8**	**6**	**6**	**4**	**2**	**2**	**2**	**5**	**3**

Table 11 - Which kind of machining is best resistant to leaks? – Stainless steel

	Milled	**Turned**	**Polished**
Total points	14	13	11

Table 12 - Which kind of machining is best resistant to leaks? – Stainless steel

Conclusion: The milled vacuum surface, with 14 points, is the best resistant to leaks. Remarkably, the polished surface is the most vulnerable for leaks. However, the differences in points between the different levels of roughness are not really big.

Which kind of machining is the best resistant to leaks in a stainless vacuum surface?

- **The milled surface**

4.2. Correlation between the visual evaluation and functionality of vacuum surfaces

The correlation between the visual analysis and the functional analysis of the vacuum surface is very important. Therefore, the company will save a lot of time and money if a vacuum surface can already can be judged visually whether a surface is good. For example: The quality inspector looks at a scratch on a vacuum surface and can determine whether the vacuum surface is leaking without even using the leak tester. It is hard to see differences between scratches because the deviations (width, depth, length) are small. Therefore, a scratch sample plate is provided for the company. The scratch sample plate contains the same scratches as the scratches that are made on the vacuum surfaces during the tests. With the scratch sample plate, it is possible to determine in which area of the sample plate, the scratch on the vacuum surface belongs. It can be determined if the scratch either belongs to the green, orange or red area. However, if it is not clear in which area the scratch belongs, measure the scratch with the mixture of pastes. Search the depth and the width in Appendix 3.7 to determine whether the vacuum surface leaks or not.

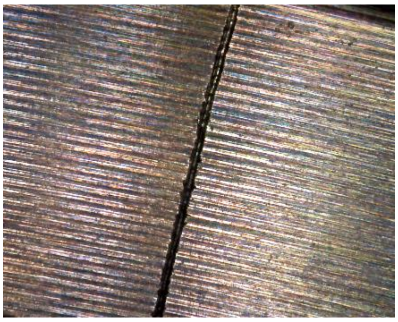
It is important to mention that comparing the scratches is still a subjective evaluation. Most of the time scratches will be hard to determine in which area they belong. A thin scratch that belongs in the green area and a very deep scratch in the red area however, are distinguishable. Scratches that belong in the orange area are hard to determine whether they leak or not. In most of the cases, the scratch has to be measured to ensure if the vacuum surface is leaking. Nevertheless, measuring a scratch only takes 15 minutes. This takes much less time than to reject the product and re-mill and re-turn it.

Different methods are used for taking pictures of the scratches. The best tools for identifying a scratch is with a microscope, by eye and by eye with a flashlight. The scratches are the most distinguishable when using a microscope. However for large products, it is hard to use a microscope. Using a flashlight is the best option in that case.

Example (three different photos of one scratch):

1. Microscope, aluminum, turned, 1.4 roughness, full 90 scratch, weight 694.2 g, leaking
2. Above, aluminum, turned, 1.4 roughness, full 90 scratch, without flashlight, weight 694.2 g, leaking
3. Above, aluminum, turned, 1.4 roughness, full 90 scratch, flashlight, weight 694.2 g, in dark room, leaking

1.



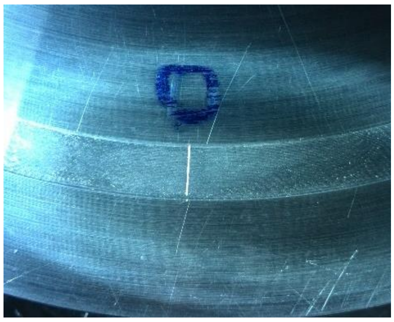
Microscope

(90 times magnification)

2.

Phone I. (Indoor lights)

3.



Phone II.

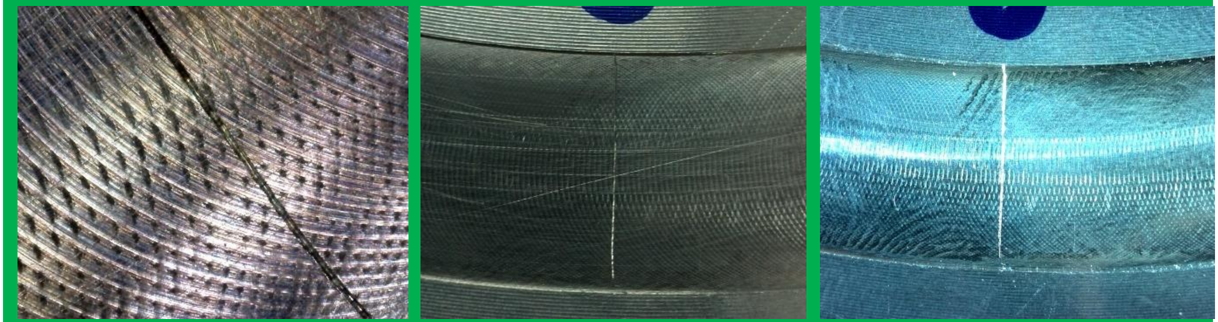
(In dark room with flashlight)

Comparison of pictures on Ra 0.8 (dimension of the widths and depths are in millimeters [mm] and the weights are in grams [g]). Comparison of the pictures with roughness 0.8 on stainless steel can be found in Appendix 4.2. The scratches are the most visible on the Ra 0.4 because it is the smoothest surface where the scratches are well separated by the surface. Even so, to see the difference between the scratches it is very difficult with the naked eye because the depths and widths of the scratches are almost the same. The following examples are the scratches of roughness 0.8 on every type of surface. This roughness is the most commonly used at the company.

Details: Aluminum, not polished, full 90 degrees scratch, milled surface, roughness 0.8

Microscope	Photo I.	Photo II.

Green area (no leak)

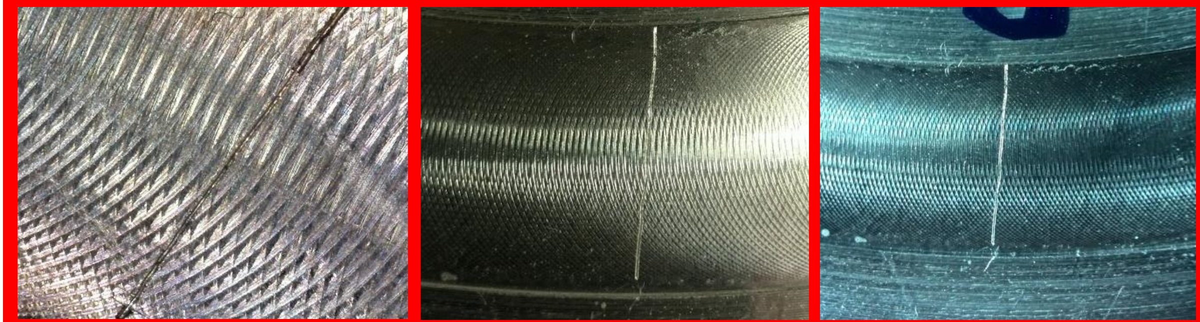


Weight 323,1

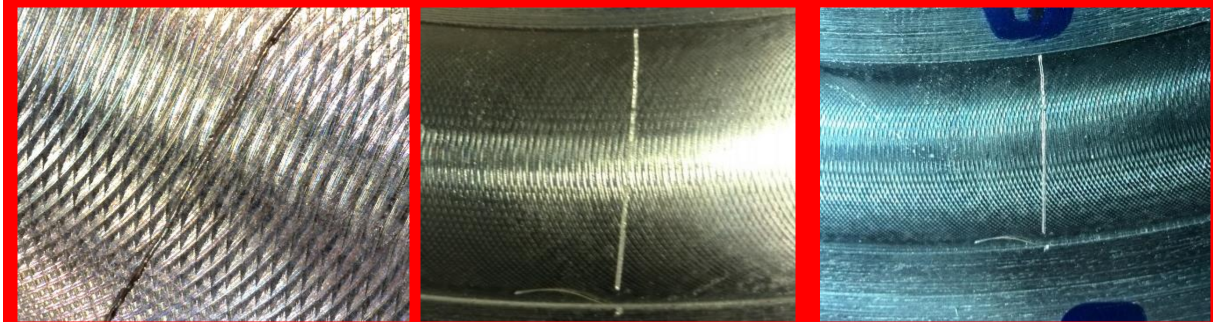
Orange area (high chance leak)

Scratches between the green and red area have a high chance of leaking.

Red area (leak)



Weight 601.4 – width 0,07 – depth 0,027



Weight 694,2 – width 0,091 – depth 0,024

In the first row the lowest scratch can be found (this is the same in the next six comparisons), which was made with a weight of 323.1 gram. Another two scratches were made with about two times bigger weights.

1. Details: Aluminum, not polished, full 90 degrees scratch, turned surface, roughness 0.8.
   Microscope Photo I. Photo II.

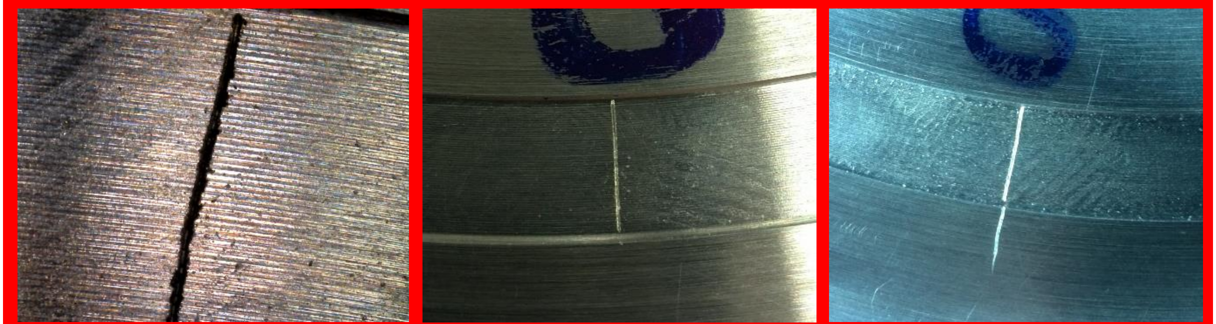
Green area (no leak)

Weight 323,1

Orange area (high chance leak)

Scratches between the green and red area have a high chance of leaking.

Red area (leak)



Weight 832,9 – width 0,083 – depth 0,025

Weight 909,9 – width 0,079 – depth 0,035

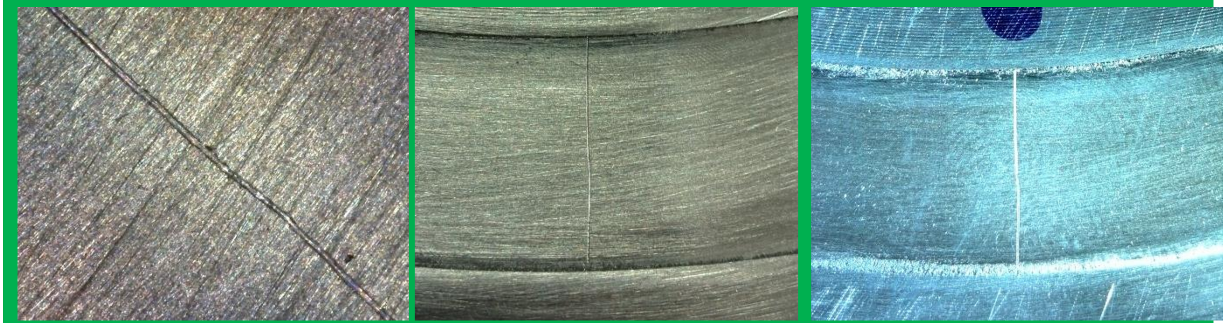
These scratches are more visible on the turned surface than on the milled because the machining of turning causes a more flat surface. With the microscope the disparity is very well distinguishable.

The difference between the scratches are the most visible on the photos which are made by the phone I. and phone II, because the exterior[11] light and flashlight glint on the walls of the scratches at the second and third row surfaces.

2. Details: Aluminum, polished, full 90 degrees scrath, roughness 0.8.

Microscope Photo I. Photo II.

Green area (no leak)



Weight 323,1

Orange area (high chance leak)

Scratches between the green and red area have a high chance of leaking.

Red area (leak)

Weight 1511,8 – Width 0,101 - Depth 0,025

Weight 1654,7 – Width 0,116 - Depth 0,027

[11] TL lamps in the roof of the room

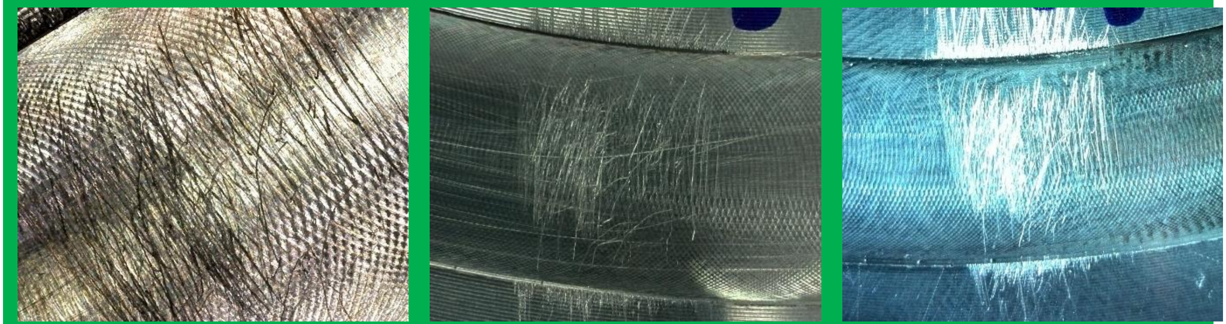
The scratches on the polished surface are the most visible. The reason for this is that the scratch is perpendicular with the polished grooves. The polished surface is really smooth and unified consequently the smaller scratches are easily seen.

Other images (one example from each type of scratch on a surface with roughness 0.8):

Details: Aluminum, roughness 0.8

Microscope Phone I. Phone II.

Green area (no leak)



Grain paper – Milled surface - Perpendicular with the vacuum surface

Green area (no leak)

Scratch by hand – Turned surface - Half external – Full power

Green area (no leak)

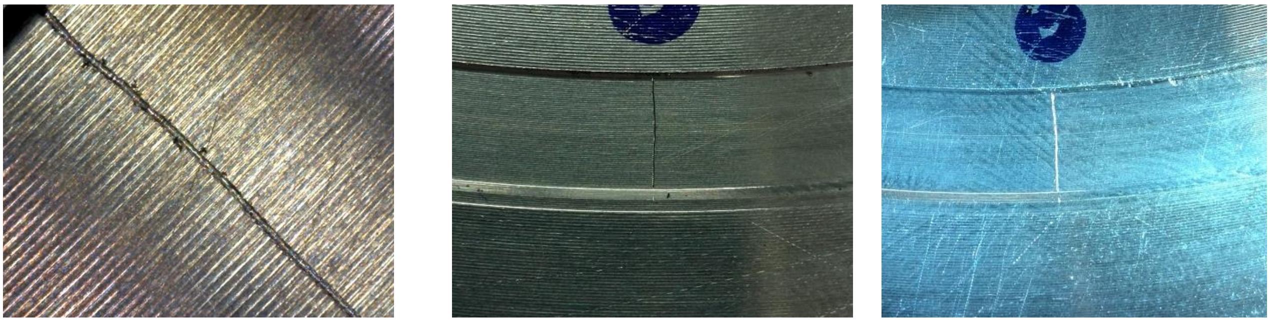
Centric scratch – Milled surface – Parallel with the vacuum surface – Weight 2749,7

The scratch with grain paper could be very varied. The most visible scratch, is a scratch by grain paper. These scratches are clearly visible and thus easy to find. Light contact between a grain paper and a vacuum surface does not create any leaks because the scratches are not very deep and wide.

The scratch with full power by hand is really visible because the depth and the width of the scratch is really deep and wide. The centric scratch is well visible on the not polished surface. Even so on the polished surface this type of scratch is almost invisible. In none of the cases this causes leaks because the scratch is following the direction of the O-ring.

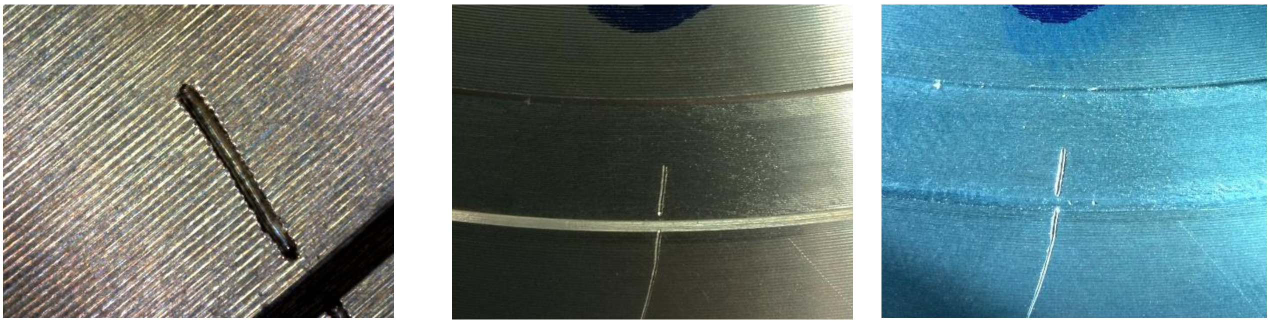
It is not always easy to see clear differences in different depths and widths of scratches. Sometimes it is clearly visible that the scratch is wider or deeper. In general, when scratches increase in depth and width, they glint more when using a flashlight. To show this visually, a table has been made to demonstrate that between a very thin scratch, a normal scratch and a very deep scratch it is distinguishable by eye with a flashlight.

Details: Aluminum, turned, full 90 degrees scratch, roughness 0,8



Weight 323,1 g

Weight 909,9 g



Weight 2749,7 g

As said before, most of the time scratches will be hard to determine in which area they belong. A thin scratch that belongs in the green area and a very deep scratch in the red area are distinguishable. Scratches that belong in the orange area are hard to determine whether they leak or not. In most of the cases, the scratch has to be measured to ensure if the vacuum surface is leaking.

5. Improve

After the measurement results are analyzed, improvements can be given. In this chapter improvements are recommended to judge whether a vacuum surface is good or not instead of rejecting the product based on experience/feeling. The improvements are based on the results, conclusions and findings. The improvements are devised by means of the PBOI-model. This means that for the Proces, Beheersing, Organisatie and Informatie improvements have been generated. Translated to English it means: Process, Control, Organization and Information. Ultimately, the improvements will be worked out in a selection matrix to decide which improvements are the best.

The improvements

Process:

- The vision of VDL-ETG is to produce products first time right (FTR). They are improving continuously in order to fulfill this. If products with vacuum surfaces have a very low chance of getting damaged/scratched, it is best to not polish the vacuum surfaces since vacuum surfaces without damages/scratches do not leak. Machining the vacuum surfaces correctly and not polishing will result in a lower fluctuation of the quality (both functional and visual) of the vacuum surfaces. By not polishing the vacuum surface, much time and energy of the employees will be saved and also reduces the amount of handling of a product, which lowers the chance on scratches to occur. Also polishing is done differently every time (not 100% exact same results).
- A roughness of 0.8 is the best resistant to leaks. Subsequently, it is recommended to produce a vacuum surface with a roughness of 0.8. Actually, it is not recommended to produce vacuum surfaces with a roughness less than 0.8. Therefore, a roughness of 0.4 was a lot of times, during the tests, the worst roughness resistant to leaks.
- Produce products with an aluminum vacuum surface because it starts to leak with deeper and wider scratches than in a stainless steel vacuum surface
- If scratches are identified by the quality inspector(s),
  1. Check the scratch on the vacuum surface and identify which is corresponding to the scratch on the scratch plate sample.
  2. Look up in the sheet ‘’Wich depths and widths cause leaks” (Appendix 2.8).
  3. It is sure that the scratch is in the green area: it is unnecessary to polish the scratch away. Therefore the scratch does not cause a leak.
  4. If the scratch belongs in the orange area or it is not possible to identify in which area it belongs:
     a. The quality inspector should measure the depth and width of the scratch with the paste and microscope.
     b. Look up in the ‘’depth and width results” appendix 2.7.
     c. Conclude with certainty if the scratch belongs in the green area, orange area or red area.
     d. A decision can be made whether to polish the vacuum surface or re-machine it.
  5. If the scratch belongs in the red area, polish or re-machine the vacuum surface.

- In general, it is not necessary to polish a centric scratch or a half external scratch. Out of the tests they did not even leak when a project member made the scratch with full force by hand.

Control

- Discuss with ASML and FEI about the results of this project because the permitted dimensions of the damages and scratches of ASML do not correspond to the results of the project. For example: ASML allows a scratch if they do not exceed a depth of 0.14 mm and a width of 0.1 mm although according to the results, the scratches already starts leaking below these dimension.

Organization

- For many employees it is unclear which roughness is best. It is also not clear what kind of damages or scratches cause leaks to a vacuum surface while they are working continuously with vacuum surfaces. This causes a lot of uncertainties and discussions between different departments. Furthermore if employees are not aware of how much time it costs to polish a vacuum surface and how big the effect can be, employees will feel less responsible to be careful with vacuum surfaces. For these reasons, the employees have to be educated by the company on these matters.

Information

- Provide the quality inspectors with the following sheets:
  - Depths and widths of the scratches (green, orange, red area), Appendix 2.7
  - ‘’Wich depths and widths cause leaks”, Appendix 2.8.
  - Visual version of the depths and widths of the scratches (green, orange, red area), Appendix 3.3.
  - “Which is the best roughness to leaks?”, Appendix 3.2.2.
  - “Which is the best kind of machining to leaks?”, Appendix 3.2.3.
- Provide the quality inspectors with the scratch sample plate.

6. Conclusion

It has been investigated what the effect of scratches is on a vacuum surface regarding leaks. The research has yielded the following results:

- Products with aluminum vacuum surfaces are better resistant to leaks than products with stainless steel vacuum surfaces. In fact, the products with aluminum vacuum surfaces had less times the first leak in comparison with the stainless steel vacuum surfaces. However, there are some cases with certain scratches, certain machined vacuum surface and certain roughness where stainless steel vacuum surfaces are better.
- Vacuum surfaces with a roughness of 0.8 is in general clearly the best roughness against leaks. On the other hand, a roughness of 0.4 is clearly the worst roughness against leaks. Actually, according to the results, a roughness of 0.4 was not even once the best roughness against leaks in different tests.
- The polished surface is the best resistant to leaks in an aluminum vacuum surface. Regarding a stainless steel vacuum surface, it is a milled surface. Although a polished surface is not much more vulnerable.

In addition keep the following in mind:

- Every kind of vacuum surface does not leak if it is not damaged.
- Full 90 degrees scratches has the most chance to cause a leak on a vacuum surface.
- During the tests, half external scratches of 90 degrees did not leak on every kind of vacuum surface. The project team even made a half external scratch by hand with full force on aluminum and stainless steel vacuum surfaces and even then it did not leak.
- Centric scratches also did not cause leaks on every kind of vacuum surface during the tests.
- Half internal scratches of 90 degrees did only cause leaks on aluminum as well as stainless steel vacuum surfaces with a roughness of 0.4.
- Scratches on vacuum surfaces made by grain paper do not cause a leak.

The depths and widths of scratches can be measured exactly by means of a mixture of pastes and a microscope. The exact depths and widths of scratches that causes and do not causes leaks, can be found in Appendix 3.7.

ASML does not accept products with vacuum surfaces that are leaking. They permit scratches up to a maximum of the following dimension:

- Depth: 0.14 mm max.
- Width: 0.1 mm max.

However, according to the results, scratches are already leaking beneath the permitted dimension. Differences in scratches on vacuum surfaces are difficult to see. However, a very thin scratch and a very deep scratch are distinguishable. The best method to distinguish different scratches is to use a microscope with 90 times magnify and by eye with flashlight. Investigation verified that if the depth and width of scratches increases, the scratches glint more when aiming the flashlight on the scratches.

For the correlation between the visual evaluation and the functionality of vacuum surfaces, a scratch sample plate can be used. Thus, a vacuum surface can be judged visually whether a surface is good. The scratch sample plate contains the same scratches as the scratches that are made on the vacuum surfaces during the tests. With the scratch sample plate and a flashlight, it is possible to determine in which area of the sample plate, the scratch on the vacuum surface belongs. It can be determined if the scratch either belongs to the green, orange or red area. Nonetheless, most of the time scratches will be hard to determine in which area they belong. A thin scratch that belongs in the green area and a very deep scratch in the red area are easy to distinguish. Scratches that belong in the orange area are hard to determine whether they leak or not. In most of the cases, the scratch has to be measured with a mixture of pastes and a microscope to ensure whether the vacuum surface is leaking. This will only take 15 minutes. Once the depth and widths are measured, it can be determined whether the scratch leaks or belongs in the orange area. If the scratch is in the orange area, the leak tester has to be used. This saves a lot of time, energy and money because the vacuum surface will not be immediately rejected when a scratch is found on the vacuum surface.

7. References

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1. Appendix A: Define

In this chapter can be found the description of the exact problem and expected results. In addition, here are the methods and tools used to describe the project and how to solve the problem.

1.1. Project planning

Phases	ACTIVITY (high level)	Week 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Define	Understand the needs of the customer	X	X	X	X	X															
	Understand high-level view of the process			X	X	X															
	Understand the problems				X	X	X														
	Make plan of approach					X															
Measure	Work preparation						X	X	X												
	Test parts with different roughnesses (functional)									X	X	X	X								
	Observe the scratches by eye and measure the scratches (visual)										X	X	X	X							
Analyze	which material is best regarding leaks?														X	X					
	which roughness is best regarding leaks?														X	X					
	which machined surface is best regarding leaks														X	X					
	which depth and width that causes leaks?														X	X	X				
Improve	Find the best material																X				
	Find the best roughness																X				
	Find the best machined surface																X				
	Find the depth and width permitted																	X			
Control	Out of Scope! (written procedures executed by VDL-ETG)																				
Report	Write concept report																		X		
	Write final report																		X	X	X

Table 13 – Project planning

1.2. Mind map

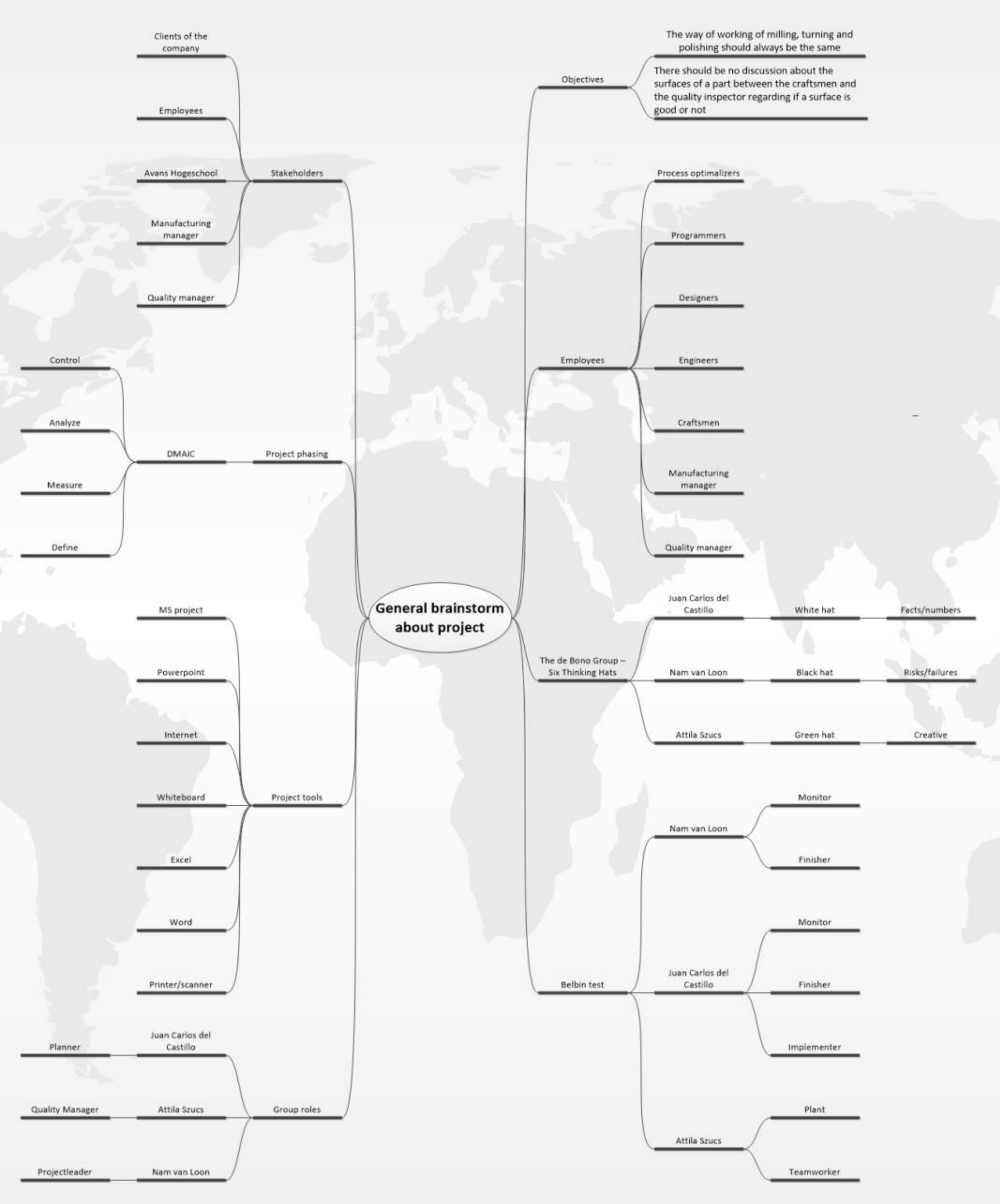


Illustration 16 – Mind map

1.3. Business model

Project name **Project scratch**	**Key activities** Understand the needs of the customer Understand high-level view of the process Work preparation Test parts with different roughnesses (functional) Explaining the relationship of scratches between visual and functional aspect Improvements of the process-flow Give information about how to control the tests	**Project sponsor:**	VDL ETG	**KPIs:** **Quality:** Percentage of good parts out of the total parts produced on the machine. **Cycle time:** Cycle time is the total time from the beginning to the end of your process, as defined by you and your customer. Cycle time includes process time, during which a unit is acted upon to bring it closer to an output, and delay time, during which a unit of work is spent waiting to take the next action.
		Project owner:	Ivo Baijens	
		Process owner:	Ivo Baijens	
Problem There isn´t a standardized way of working and finishing by the craftsmen There is no a standardized measurement and inspection for the scratches. The inline inspections are not sufficient enough to detect scratches before and after a washing procedure		**KPIs** Status of existing Quality = Good Count / Cycle Time Ratio (CTR) –	**Benefits** Reduce lead time Reduce checking time Reduce process steps Reduce rework Reduce discussions Reduce polishing time	
		Stakeholders Client Employees Project owner (Marco Klootwijk)		
Goal The way of working of milling, turning and polishing should always be the same There should be no discussion about the surfaces of a part between the craftsmen and the quality inspector regarding if a surface is good or not	**Critical S. F.** Craftsmen Project owner (Marco Klootvijk) Head of Engineering (Ivo Baijsen) Employees Human Resources Tools Testparts Machines	**Resources** Machines Tools Computers Employees Engineers Designers Buildings Energy Money	**Costs** Salaries Travelling The produced testparts Time needed from Time needed from Time for using the Energy used for the	
			In scope Parts Making Department (PMD)	
			Out Scope Systems (assemble department) Research Development (R&D)	

Table 14 – Business model

1.4. CTQ tree

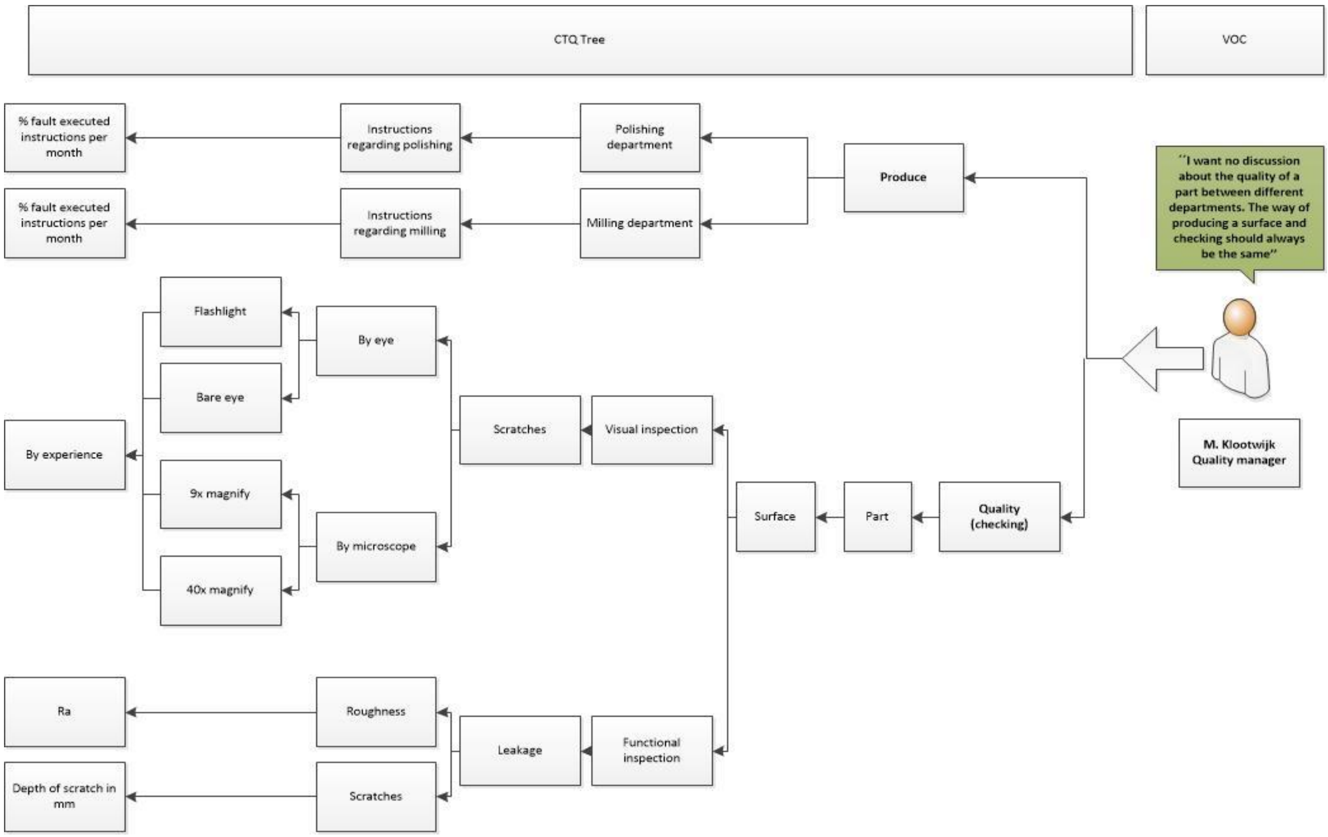


Illustration 17 – CTQ tree

1.6. SIPOC

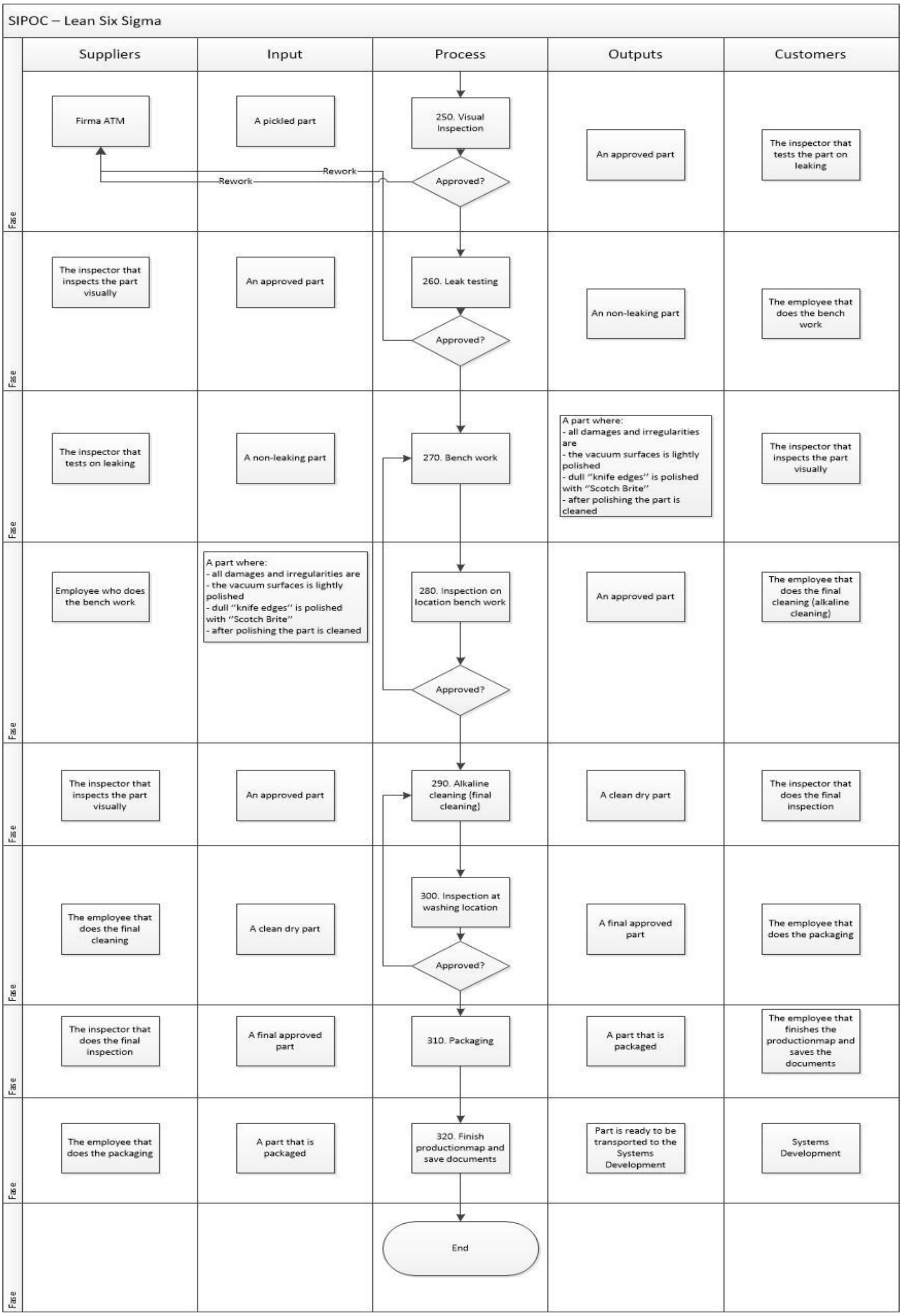


Table 15 - SIPOC

1.7. Flow chart

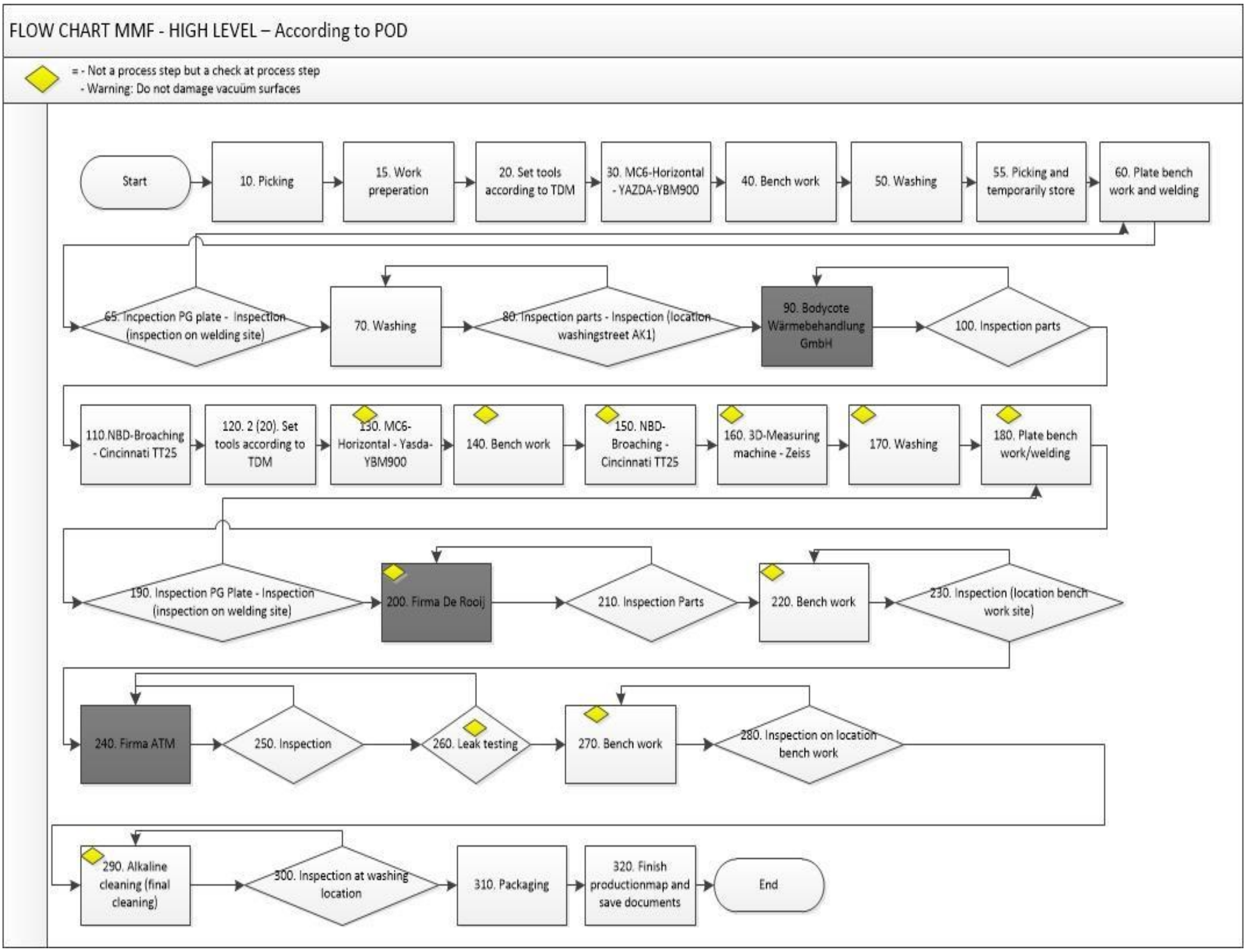


Illustration 18 – Flow chart

1.8. Roughness (Ra)

Surface roughness, often shortened to roughness, is a component of surface texture. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. Roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. However, in practice it is often necessary to know both the amplitude and frequency to ensure that a surface is fit for a purpose.

Roughness can be measured by manual comparison against a "surface roughness comparator", a sample of known surface roughness, but more generally a Surface profile measurement is made with a profilometer that can be contact (typically a diamond styles) or optical (e.g. a white light interferometer).

There are many different roughness parameters in use, but Ra is by far the most common though this is often for historical reasons not for particular merit as the early roughness meters could *only* measure Ra. Other common parameters include Rz, Rq, and Rsk. Some parameters are used only in certain industries or within certain countries.

- Ra: Average roughness. The value of the Ra is the average distance between the highest and the lowest point from the center line in the longitudinal of the main range.
- Rz: Roughness height. The average of the observed profiles of five highest and five lowest distance on the base length.
- Rmax: Maximal roughness. Distance between the peak and the valley points what has to be standardized with the center line.

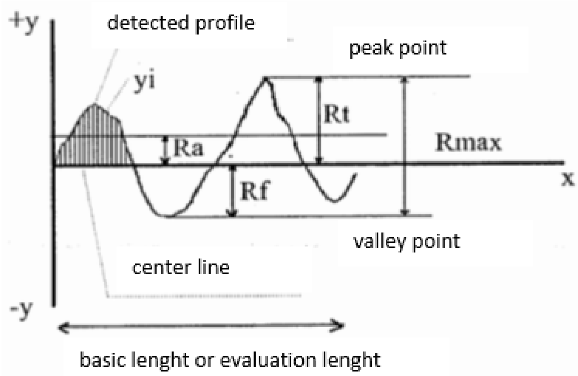


Illustration 19 - Explanation of the roughness

In case of a completely different surface structure can be also the same Ra value.

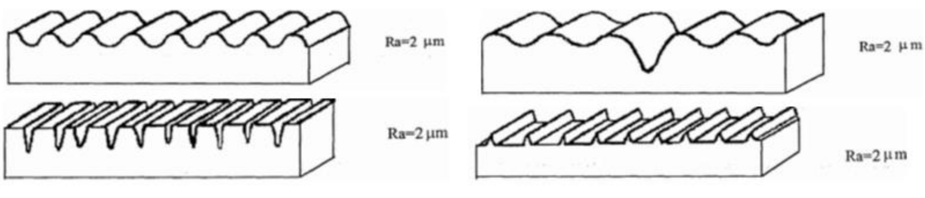


Illustration 20 – The same roughness on different surfaces

Difference between roughness on the surface by the several machining and method.

Dark line: common

Grey line: less frequent

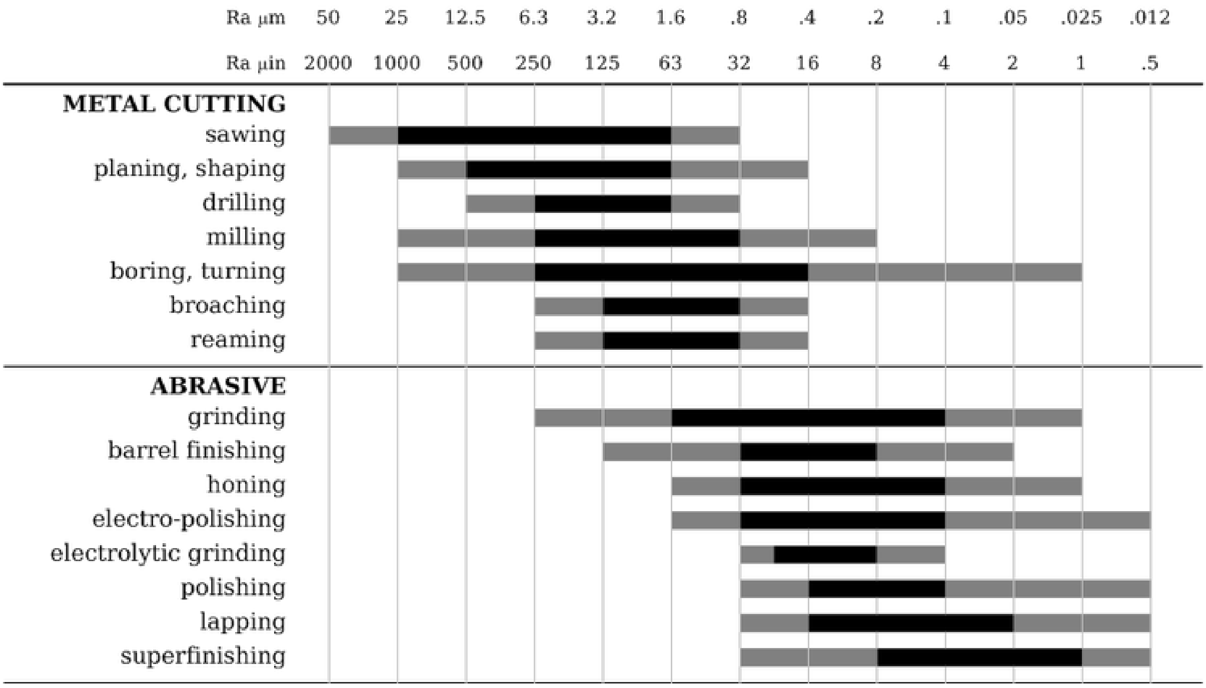


Table 16 – Difference between roughness on the surface by the several machining and method

1.9. Vacuum surface

A vacuum system typically consists of one or more pumps which are connected to a chamber. The former produces the vacuum, the latter contains whatever apparatus requires the use of the vacuum. In between the two may be various combinations of tubing, fittings and valves. These are required for the system to operate but each introduces other complications such as leaks, additional surface area for outgassing and added resistance to the flow of gas from the chamber to the pumps

- **What is vacuum?**

A vacuum is defined as a diluted gas, or the corresponding state at which its pressure or density is lower than that of the ambient surrounding atmosphere. A vacuum is defined as less than 1 Atmosphere of pressure.

- 1 atm = 105 Pa = 103 mbar = 760 Torr

Below 10-3 Torr, there are more gas molecules on the surface of the vessel then in the volume of the vessel.

- High Vacuum < 10-3 Torr
- Very High Vacuum < 10-6 Torr
- Ultra High Vacuum < 10-8 Torr

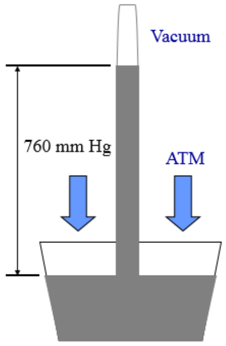


Illustration 21 - Vacuum

- **Why do we need a vacuum?**

- Keep surfaces free of contaminants.
- Process films with low density of impurities.
- Maintain plasma discharge for sputtering sources.
- Large mean free path for electrons and molecules (l =1m@7x10-5mbar)

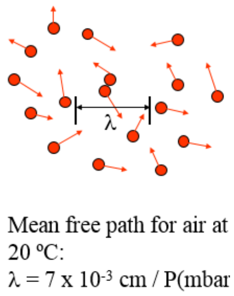


Illustration 22 – Particles on a vacuum

- **Vacuum Systems**

  - A vacuum system consists of chamber, pumps and gauges.
  - Chambers are typically made of aluminum or stainless steel and sealed with elastomer or metal gaskets.

Evacuating air from a closed volume develops a pressure differential between the volume and the surrounding atmosphere. If this closed volume is bound by the surface of a vacuum cup and a work piece, atmospheric pressure will press the two objects together. The amount of holding force depends on the surface area shared by the two objects and the vacuum level. In an industrial vacuum system, a vacuum pump or generator removes air from a system to create a pressure differential.

Because it is virtually impossible to remove all the air molecules from a container, a perfect vacuum cannot be achieved. Of course, as more air is removed, the pressure differential increases, and the potential vacuum force becomes greater.

The vacuum level is determined by the pressure differential between the evacuated volume and the surrounding atmosphere.

Atmospheric pressure is assigned the value of zero on the dials of most pressure gauges. Vacuum measurements must, therefore, be less than zero. Negative gage pressure generally is defined as the difference between a given system vacuum and atmospheric pressure.

- **Leaks and leak detection**

A leak, also referred to as leakage, enables a substance to flow toward a pressure gradient. Expressed in simpler terms, leaks are small holes through which gases or liquids flow from the side of higher pressure to the side of lower pressure. This can involve simple, harmless leaks, such as a dripping water faucet, or hazardous toxic substances that escape through leaks.
Any number of technical products will not function, or will not function for an adequate period of time, if they have leaks. Examples include: The refrigerant circulation system in refrigerators, air conditioning systems in cars, automobile tires, automotive fuel tanks or home fuel oil tanks, as well as distillation systems in the chemical or pharmaceutical industries. In many cases, the leak-tightness of machines and systems in the production process is an indispensable prerequisite for the quality of the manufactured products.
Returning to the original definition of a leak, we thus find that it is impossible to completely prevent substances from flowing through a wall. The term ”tight“, therefore refers to the requirements of the respective machine, plant or vessel, and must be quantified accordingly.

- **Leak detection with helium**

Mass spectrometers that are set to helium’s atomic weight of 4 are used to detect the presence of helium. Mass spectrometers operate only in the molecular flow range, i.e. under vacuum at pressures p of less than 10^{-4} mbar. Sector field devices are used for reasons of cost and because of their robust design.

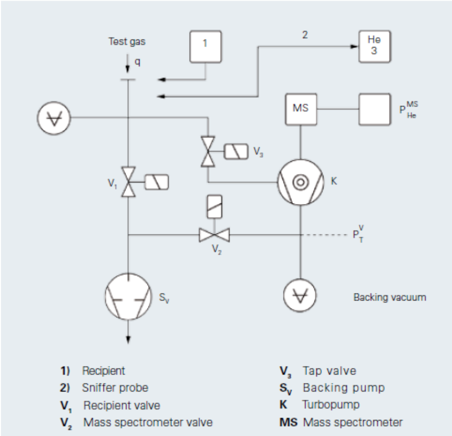


Illustration 23 – Schematic diagram of a helium counter flow leak detector

A work piece 1 is evacuated via the test gas connection with valve V1 open. Valves V2 and V1are connected in such a manner that the required backing vacuum pressure of the turbo pump always takes priority over evacuation of the work piece. Once the work piece is evacuated, it can be connected to the backing vacuum, or to a tap on the turbomolecular pump via valve V3.Depending upon the pressure range in question, helium is now sprayed onto the work piece from the outside and together with the ambient air penetrates into the work piece through leaks. The helium present in the residual gas flows counter to the pumping direction through valves V1 and V2 and through the turbopump to mass spectrometer MS, where it is detected. The differing compression ratios of the turbopump for helium and air, which differ by multiple powers of ten, are utilized in this regard. While the high compression ratio of the turbopump keeps air away from the mass spectrometer, the helium arrives there at a relatively high partial pressure. The turbopump thus acts as a selective amplifier for helium. This is why a mass spectrometer enables helium to be detected in the work piece even at pressures of less than 1 mbar. Several powers of ten of the helium partial pressure, and thus a leakage rate range of between 10 and 10 - 8 mbar l / s, can be covered by means of various taps on the turbopump (V3), as well as by operating it at different speeds that exponentially influence the compression ratio. A pressure of 10 - 3 mbar must be attained in the work piece for the highest sensitivity stage of the leak detector (inlet via V3).

- **Local leak detection**

Local leak detection is used to identify leakage in a work piece. Under the pump-down method, the work piece (vessel) is connected to the leak detector, and helium is briefly sprayed onto a suspicious area by means of a spray gun. If the pressure in the work piece is in the molecular flow range, i.e. less than 10 - 3 mbar, there will be an immediate display as a result of the high velocity of the helium atoms. At higher pressures, particularly in the laminar flow range that starts at 1 mbar, the display speed will be much slower and will be governed by the pumping speed of the leak detector‘s backing pump. Under the sniffer method (Figure 5.3), the work piece (3) is filled with a helium over pressure. A sniffer probe (2) is connected to the test gas connection. The helium that escapes through leaks in the work piece can be detected by sniffing with the probe. Individual leaks can be identified using local leak detection. However the sum of all leakage cannot be determined. That is why this process offers only limited suitability for providing a GO / NO GO indication for quality assurance purposes.

Sniffer Leak Detection	Vacuum Leak Detection
Sniffing the helium-filled workpiece	Sprayed with helium
Overpressure-proof workpiece	Vacuum-proof workpiece
Detection limit 5 · 10^{-8} mbar l/s	Detection limit 5 · 10^{-12} mbar l/s

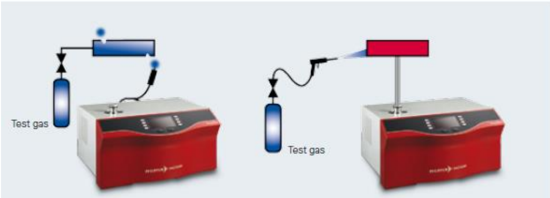


Illustration 24 – Local leak detection by means of the sniffer and vacuum surface

- **Integral leak detection**

Integral leak detection is used to determine the total of all leaks (total leakage) in the work piece. Here, too, the pump-down method and the sniffer method can be used. Under the pump-down method, a work piece is enclosed, filled with helium and the surrounding vessel evacuated. Or the work piece is evacuated (vacuum system) and the surrounding space is filled with helium. In this connection, the enclosure can be a plastic film, or it can be a rigid vessel for commercial test systems. Under the sniffer method, the work piece (e.g. an automotive fuel tank) is filled with helium and a given volume of gas is evacuated from the surrounding vessel through the leak detector's sniffer probe (Figure 5.4). The best result that can be obtained using the sniffer method is general confirmation that the work piece is tight. However this method is not suitable for quantitative integral leakage rate measurement. A pressure differential $\Delta p = p1 - p2 = 100$ mbar is sufficient when testing with an overpressure in the work piece.

Sniffer Leak Detection	Vacuum Leak Detection
Overpressure-proof workpiece	Vacuum-proof workpiece
Use of a sniffer probe	Workpiece filled with helium
Detection limit 5 · 10^{-8} mbar l/s	Detection limit 5 · 10^{-12} mbar l/s

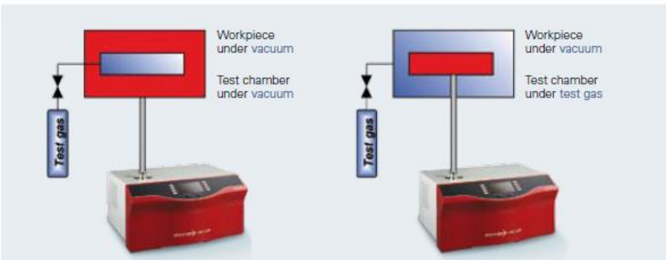


Illustration 25 – Integral leak detection by means of the sniffer and vacuum methods

- **Leak detection with helium**

The following must always be observed when using helium as the test gas: Helium is lighter than air. So when helium is used in the atmosphere, the leak detection process should always begin at the highest point of the work piece. Excessive amounts of the test gas should not be sprayed, as this can increase the concentration of helium in the ambient air, which would constantly simulate leaks that do not exist because helium accumulates in the backing pump, in the exhaust space and in the oil, and can return to the backing vacuum area from these points, the gas ballast in the backing pump must be energized if there are high leakage rates. This usually occurs automatically when the higher measuring ranges are selected in the leak detector.

- **Description of the test:**

The leak tightness of a product can be tested by imposing a vacuum on the product and using a tracer gas to on the outside find the leak. If a leakage is present the tracer gas will be sucked into the product.

- **Accept/reject criterion:**

  - The product is accepted if the Helium leak rate <1x10^-9 [mbar.l/s]
  - The product is rejected if the Helium leak rate >=1x10^-9 [mbar.l/s]

- **Required hardware:**

A means for imposing a vacuum on the product.
A portable leak detector using a helium mass spectrometer with a minimum inboard sensitivity of 5x10^-10 [mbar.l/s]

- **Required media:**

Tracer gas: Helium, at least grade 4.5
Depending on cleanliness of the application area:
For purging after completion test:
Nitrogen or Argon purified to UHP grade 7 (99.99999%) with the following maximum impurities:

- <50 [ppb] moisture
- <50 [ppb] oxygen
- <2 [ppb] total hydrocarbons

Nitrogen or Argon shall be filtered close to the point of use to 0.01 microns absolute

- **Detection limit:**

5x10^-10 [mbar.l/s]

- **Measurement duration:**

Estimation: At least 30 sec. per connection (connect the part to the helium tester)
Maximum measurement time is 5 minutes if O-rings are used (He permeation will influence measurement)

1.10. The O-ring

An O-ring, also known as a packing, or a toric joint, is a mechanical gasket in the shape of a torus; it is a loop of elastomer with a round cross-section, designed to be seated in a groove and compressed during assembly between two or more parts, creating a seal at the interface.

The O-ring may be used in static applications or in dynamic applications where there is relative motion between the parts and the O-ring. Dynamic examples include rotating pump shafts and hydraulic cylinder pistons.

O-rings are one of the most common seals used in machine design because they are inexpensive, easy to make, reliable, and have simple mounting requirements. They can seal tens of megapascals (thousands of psi) of pressure.

- **Vacuum applications**

In vacuum applications, the permeability of the material makes point contacts quite useless. Instead, higher mounting forces are used and the ring fills the whole groove. Also, round back-up rings are used to save the ring from excessive deformation. Because the ring feels the ambient pressure and the partial pressure of gases only at the seal, their gradients will be steep near the seal and shallow in the bulk (opposite to the gradient of the contact stress. High-vacuum systems below 10^{-9} Torr use copper or nickel O-rings. Also, vacuum systems that have to be immersed in liquid nitrogen use indium O-rings, because rubber becomes hard and brittle at low temperatures.

2. Appendix B: Measure

The goal of this work is to evaluate the effect of scratches and damages on a vacuum surface to the functionality. In this chapter, the design of the experiment for this evaluation is described.

2.1. Planning

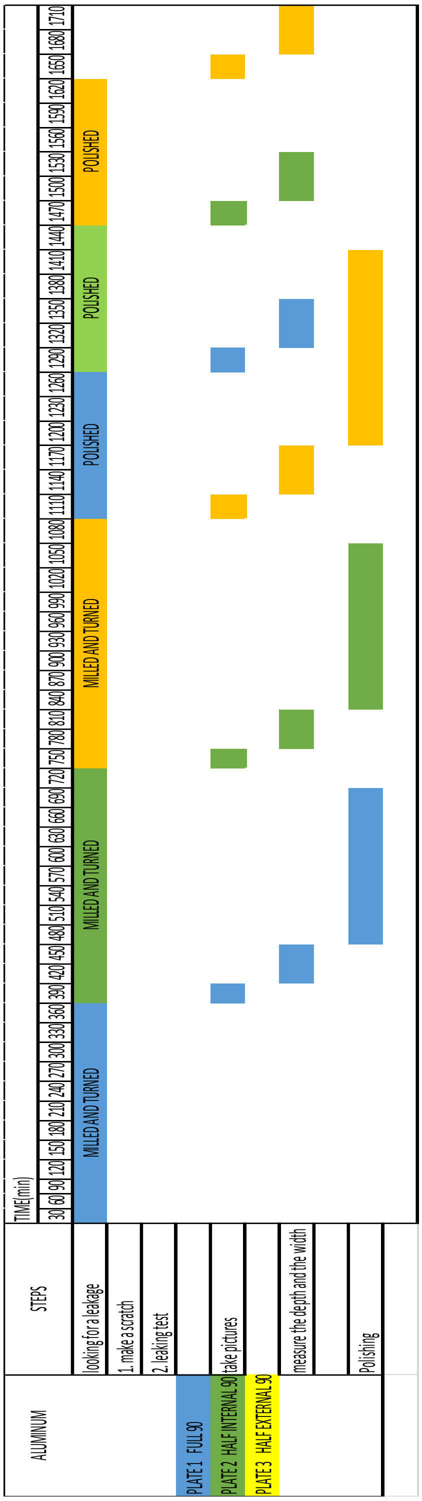


Table 17 – Project planning

2.2. Design test product 1

The plate:

We design a plate with a groove that is a vacuum surface. We have to produce three with three different roughness (0.4, 0.8, and 1.4).

We use always the same kind of O-ring because we only want to work on the different roughness and how the scratches effect on them.

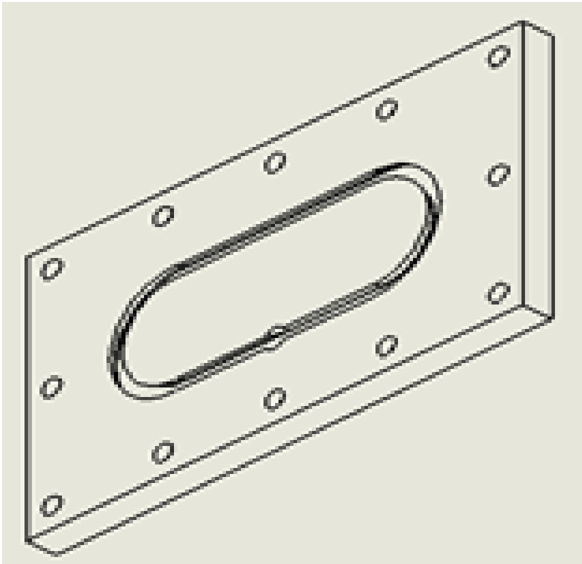


Illustration 26 – Design 1: The plate

1. The top view:

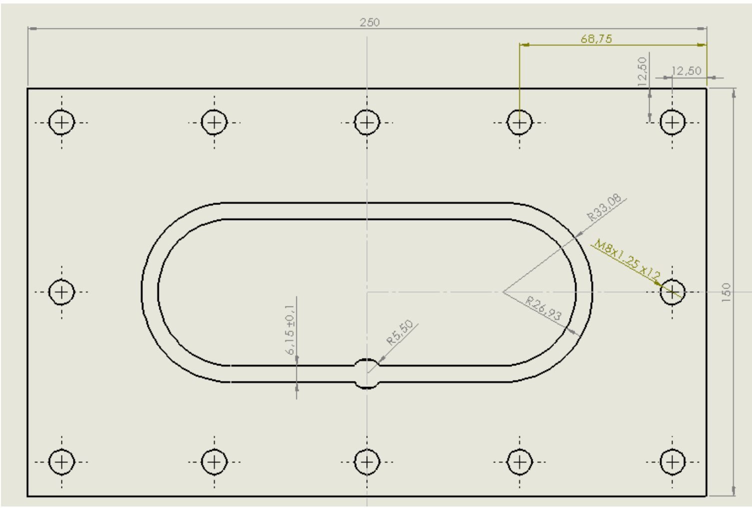


Illustration 27 – Design 1: The plate – Top view

2. Front view:

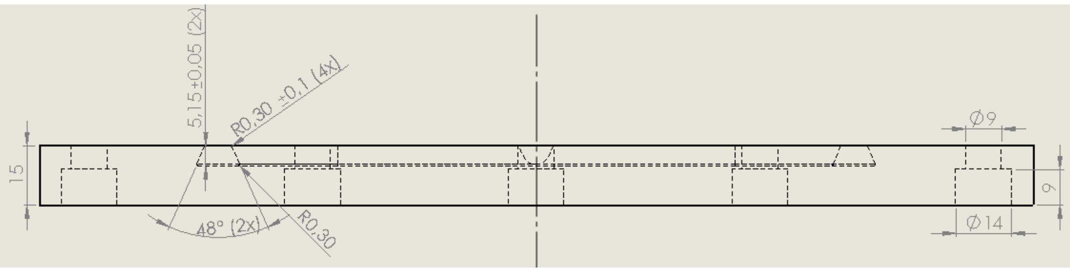


Illustration 28 – Design 1: The plate – Front view

The chamber:

We design a chamber with a groove that is a vacuum surface. We have to produce three with three different roughness (0.4, 0.8, and 1.4). The chamber has the pump entrance for the tester and it is standardized.

1. Top view:

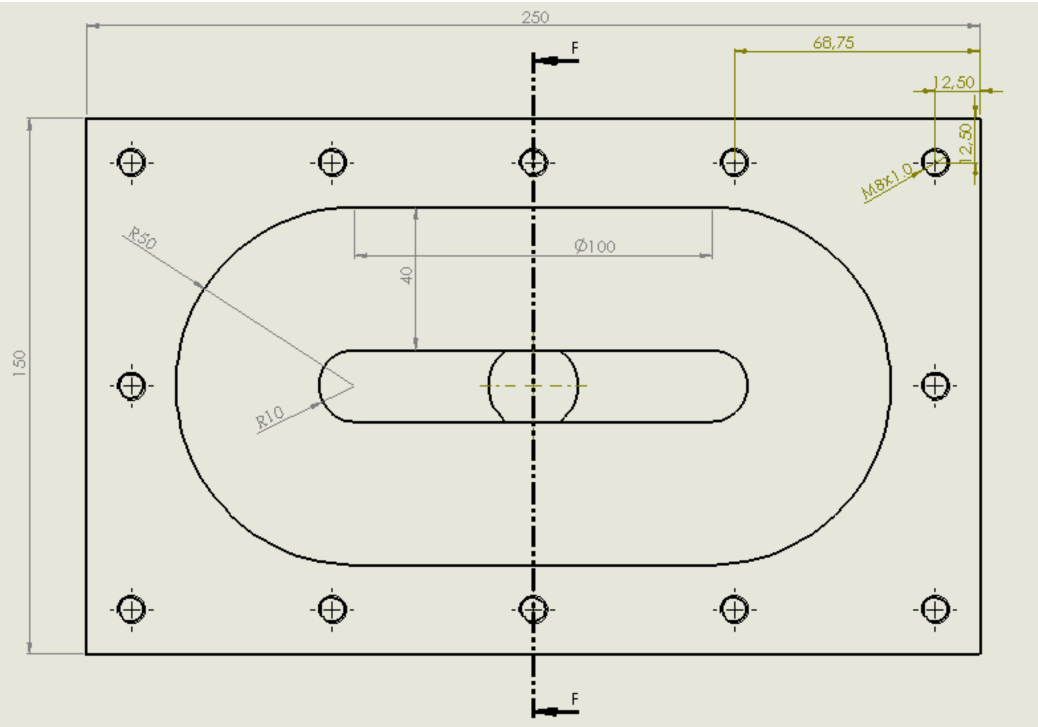


Illustration 29 – Design 1: The chamber – Top view

2. Right view:

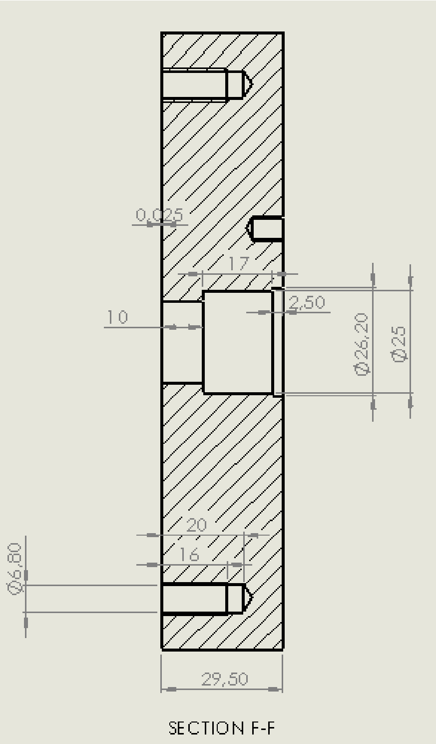


Illustration 30 – Design 1: The chamber – Right view

3. Plant view

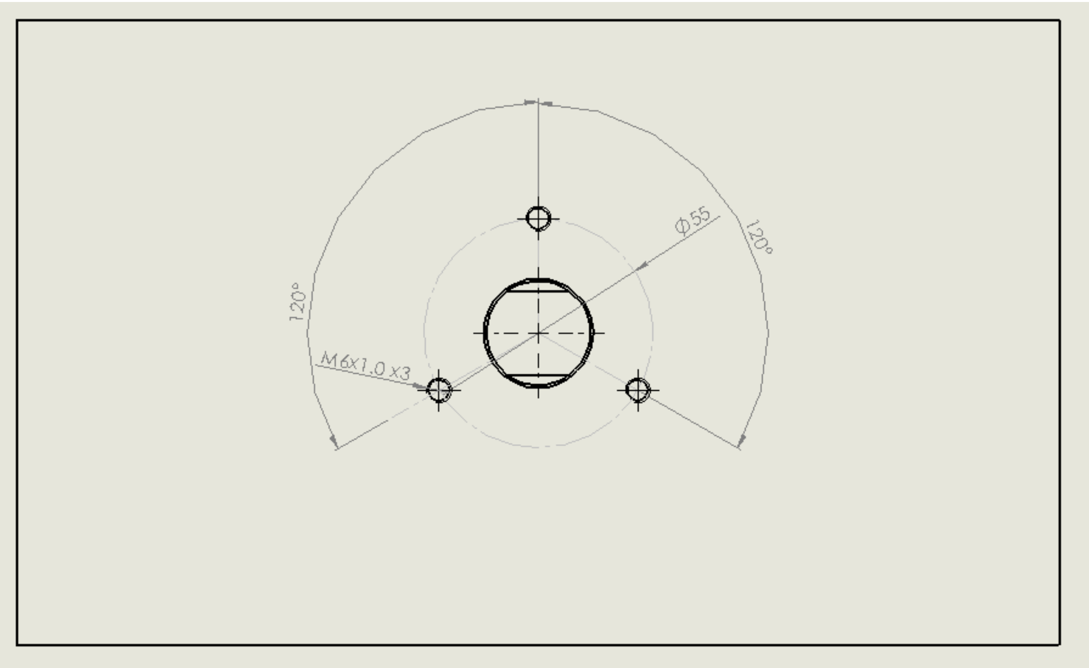


Illustration 31 – Design 1: The chamber – Plant view

2.3. Design test product 2

It is decided to design a plate. On one side, there are three different grooves with three different roughness machined by turning and on the other side there are the same but machined by milling. We can know what the differences are when you do the vacuum surfaces with two different tools.

It is necessary three different O-rings with different diameters but the characteristics of them have to be the same.

The chamber is standardized, we need three chambers because the diameter and the roughness of the vacuum surface have to be different.

1. **The female part (counterpart)**

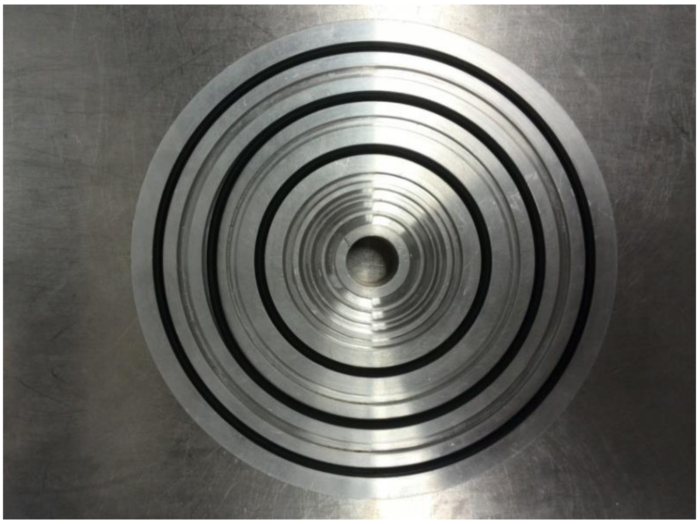


Illustration 32 – Design 2: The female part

2. **The male part**

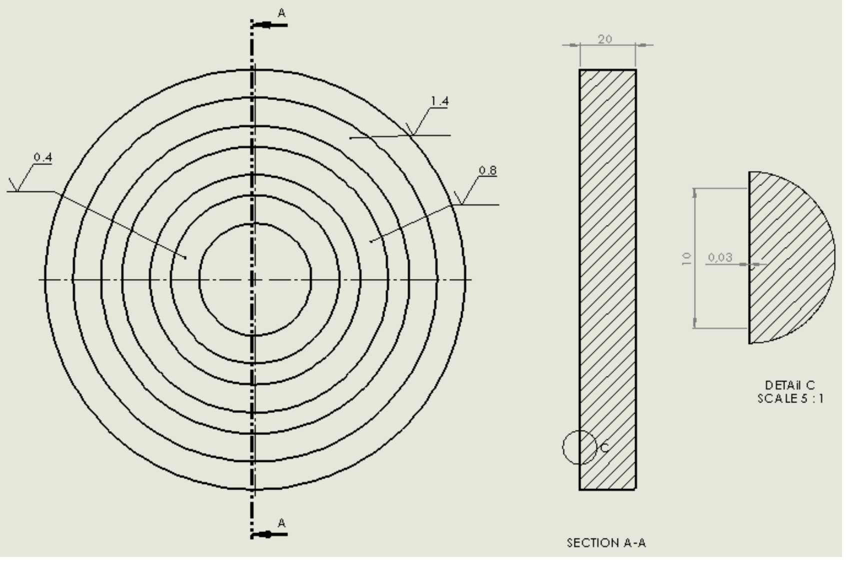


Illustration 33 – Design 2: The male part

2.4. Method of polishing

In this section it is shown the steps that must be followed to have a surface perfectly polished. Each material is polished with different grain papers in relation to the level of roughness. The roughness is assumed to be the same before and after being polished.

Aluminum:

- Ra 0.4: grain paper 100 and finishing with Scotch Brite
- Ra 0.8: grain paper 120 and finishing with grain paper 150
- Ra 1,4: grain paper 180 and finishing with grainpaper240

To have a good surface is recommended to use Scotch Brite and clean the surface with paper and isopropyl.

Stainless Steel:

- Ra 0.4: grain paper 150 and finishing with 180
- Ra 0.8: grain paper 240 and finishing with 320
- Ra 1,4: Scotch Brite

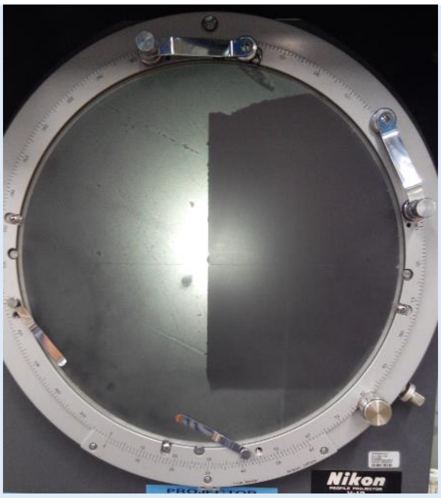
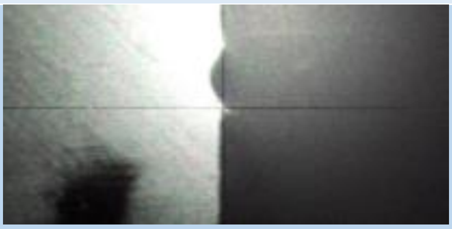
To have a good surface is recommended to use scotch Brite and clean the surface with paper and isopropyl.

Scotch-Brite is a line of abrasive cleaning pads produced by 3M. The original product line consists of spun polypropylene fiber with about nine grit variations. Scotch-Brite also contains "Alox", which is a trade name for aluminum oxide.

2.5. Measure the depth of the scratch

The method is a mixture of paste. It is based on a catalyst and a base. The measurement of the depth and width with the microscope is subjective and it is recommended to measure it at least twice.
The steps explain how to use them

1		**Pastes**
2		Mix the paste with a blade
3		Put the mixture on the scratch and wait 15 min until the paste is dried
4		Cut the paste with a blade into thin slides

5		Put the slide on the microscope
5.1		Initial point
5.2		Final point Depth: 0,027 mm Width: 0,068 mm

2.6. Test results

In this section, the test results describes every scratch that was made during the measure phase and the tests showing if a scratch leak or not.

Signs:

- n in the green cell means that the scratch does not cause leak on the vacuum surface.
- y in in the red cell means that the scratch causes leak on the vacuum surface.
- CO_2 value: The quantity of the air what the vacuum tester sucks in to the machine at the particular investigated scratch.
- Helium value: The quantity of the helium what the vacuum tester sucks in to the machine at the particular investigated scratch.

Aluminum FULL 90 degrees scratch

Not polished surface:

Aluminium
Experiment 1 (FULL 90')

Without scratch

Ra 0,4		Ra 0,8		Ra 1,4	
Turned	Milled	Turned	Milled	Turned	Milled
n	n	n	n	n	n

With scratch

Weight (gram)	Turned (Ra 0,4)	CO_2 value	Heli value	Milled (Ra 0,4)	CO_2 value	Heli value
230,7	n			n		
323,1	n			n		
463,5	y	3,4x10^-8	1,8x10^-6	y	3,4x10^-8	1,8x10^-6
601,4	y	4x10^-8	4x10^-4	y	4x10^-8	4x10^-4
694,2						
832,9						
909,9						

Weight (gram)	Turned (Ra 0,8)	CO_2 value	Heli value	Milled (Ra 0,8)	CO_2 value	Heli value
230,7	n			n		
323,1	n			n		
463,5	n			n		
601,4	n			Y	1,0x10^-9	5.6x10-6
694,2	n			y	1,0x10^-9	2,0x10^-7
832,9	y	1,2x10^-8	1,0x10^-5			
909,9	y	2,9x10^-9				

Weight (gram)	Turned (Ra 1,4)	CO_2 value	Heli value	Milled (Ra 1,4)	CO_2 value	Heli value
230,7	n			n		
323,1	n			n		
463,5	n			n		
601,4	y	2.3x10^-9	1.3x10^-5	n		
694,2	y	5,0x10^-9	6,9x10^-6	y	2,7x10^-9	1,0x10^-6
832,9				y	1.3x10^-8	4.9x10^-5
909,9						

Table 18 – Test results: Aluminum – Full 90 degrees scratch – Not polished surface

Polished surface:

Without scratch

Ra 0.4	Ra 0.8	Ra 1.4
Polished	Polished	Polished
n	n	n

With scratch

Weight (gram)	Polished (Ra 0.4)	CO_2 value	Heli value	Polished (Ra 0.8)	CO_2 value	Heli value	Polished (Ra 1.4)	CO_2 value	Heli value
323,1	n			n			n		
463,5	n			n			n		
601,4	n			n			n		
786,6	n			n			n		
962,2	y	4,0x10^-9	2,5x10^-6	n			n		
1102	y	8,0x10^-8	1,5x10^-5	n			n		
1240,7				n			n		
1378,6				n			n		
1511,8				y	1,0x10^-9	4,5x10^-6	n		
1654,7				y	3,9x10-9	1,6x10-6	n		
1834,9							y	5,5x10^-9	1.5x10^4
2017,2							y	4,2x10^-9	1.5x10^4

Table 19 - Test results: Aluminum – Full 90 degrees scratch – Polished surface

Aluminum HALF EXTERNAL 90 degrees scratch

Not polished surface:

Aluminium
Experiment 2 (HALF EXTERNAL 90')

	Without scratch					
	Ra 0,4		Ra 0,8		Ra 1,4	
	Turned	Milled	Turned	Milled	Turned	Milled
	n	n	n	n	n	n

	With scratch					
	Ra 0,4		Ra 0,8		Ra 1,4	
Weight (gram)	Turned	Milled	Turned	Milled	Turned	Milled
230,7	n	n	n	n	n	n
463,5	n	n	n	n	n	n
694,2	n	n	n	n	n	n
909,9	n	n	n	n	n	n
1378,6	n	n	n	n	n	n
1834,9	n	n	n	n	n	n
2286,5	n	n	n	n	n	n
2746	n	n	n	n	n	n

Table 20 - Test results: Aluminum – Half external 90 degrees scratch – Not polished surface

Polished surface:

	Without scratch		
	Ra 0.4	Ra 0.8	Ra 1.4
	polished	polished	polished
	n	n	n

	With scratch		
	Ra 0.4	Ra 0.8	Ra 1.4
Weight (gram)	polished	polished	polished
1834,9	n	n	n
2286,5	n	n	n
2746	n	n	n

Table 21 - Test results: Aluminum – Half external 90 degrees scratch – Polished surface

Aluminum HALF INTERNAL 90 degrees scratch

Not polished surface:

Aluminium
Experiment 3 (half int 90')

Without scratch					
Ra 0,4		Ra 0,8		Ra 1,4	
Turned	Milled	Turned	Milled	Turned	Milled
n	n	n	n	n	n

	With scratch											
	Ra 0,4						Ra 0,8		Ra 1,4			
Weight (gram)	Turned	CO_2 value	Heli value	Milled	CO_2 value	Heli value	Turned	Milled	Turned	CO_2 value	Heli value	Milled
230,7	n			n			n	n	n			n
463,5	n			n			n	n	n			n
694,2	y	9,2x10^-9	1,6x10^-6	n			n	n	n			n
832,9	y	8x10^-8	2x10^-6	y		2,0x10^-6	n	n	n			n
962,2				y	2,0x10^-8	4,0x10^-6	n	n	n			n
1142,4				y		6,0x10^-6	n	n	n			n
1378,6							n	n	n			n
1602,4							n	n	n			n
1834,9							n	n	n			n
2286,5							n	n	n			n
2746							n	n	y	2x10^-8	2x10^-4	n

Table 22 – Test results: Aluminum – Half internal 90 degrees scratch – Not polished surface

Polished surface:

Without scratch		
Ra 0.4	Ra 0.8	Ra 1.4
Polished	Polished	Polished
n	n	n

	With scratch								
	Ra 0.4			Ra 0.8			Ra 1.4		
Weight (gram	Polished	CO_2 value	Heli value	Polished	CO_2 value	Heli value	Polished	CO_2 value	Heli value
694,2	n			n			n		
832,9	n			n			n		
962,2	n			n			n		
1142,4	n			n			n		
1378,6	n			n			n		
1602,4	y	1,0x10^-8	1,0x10^-5	n			n		
1834,9	n			n			n		
2065,6	y	1,0x10^-8	2,0x10-6	n			n		
2286,5	y	3,8x10-8	1,4x10-4	n			n		
2746				y	1x10-9	1,6x10-6	y	1x10-9	1,1x10-6

Table 23 - Test results: Aluminum – Half internal 90 degrees scratch – Polished surface

Aluminum Centric scratch

Not polished surface:

Aluminium
Experiment 4 (Centric scratch)

	With scratch					
	Ra 0,4		Ra 0,8		Ra 1,4	
Weight (gram)	Turned	Milled	Turned	Milled	Turned	Milled
2746	n	n	n	n	n	n

Table 24 - Test results: Aluminum – Centric scratch – Not polished surface

Polished surface:

	With scratch		
	Ra 0,4	Ra 0,8	Ra 1,4
Weight (gram)	Milled	Milled	Milled
2746	n	n	n

Table 25 - Test results: Aluminum – Centric scratch – Polished surface

Aluminum Scratch with grain paper

Not polished surface:

Aluminium Experiment 5 (scratch with grain paper)								
	With scratch							
	Ra 0,4			Ra 0,8		Ra 1,4		
Grainpaper	Milled	Heli value	Turned	Milled	Turned	Milled	Turned
-	y	1,2x10^-6	n	n	n	n	n

Table 26 – Aluminum – Scratch with grain paper – Not polished surface

Polished surface:

	Ra 0.4	Ra 0.8	Ra 1.4	
Grainpaper	Polished	Polished	Polished	
-	n	n	y	1,5x10^-6

Table 27 - Aluminum – Scratch with grain paper – Polished surface

Aluminum Full power external scratch by hand

Aluminium Experiment 6 (full power external scratch by hand)								
With scratch								
Ra 0.4			Ra 0.8			Ra 1.4		
Milled	Turned	Polished	Milled	Turned	Polished	Milled	Turned	Polished
n	n	n	n	n	n	n	n	n

Table 28 - Aluminum – Full power external scratch by hand

Aluminum Full power internal scratch by hand

Aluminium Experiment 6 (full power internal scratch by hand)						
With scratch						
Milled	Heli value	Turned	Polished	Milled	Turned	Polished
Ra 0,8				Ra 1,4		
y	5x10^-6	n	n	n	n	n

Table 29 - Aluminum – Full power external scratch by hand

Stainless steel FULL 90 degrees scratch

Not polished surface:

Stainless steel Experiment 1 (FULL 90')						
Without scratch						
Ra 0,4		Ra 0,8		Ra 1,4		
Turned	Milled	Turned	Milled	Turned	Milled	
n	n	n	n	n	n	

	With scratch																	
	Turned	CO_2 value	Heli value	Milled	CO_2 value	Heli value	Turned	CO_2 value	Heli value	Milled	CO_2 value	Heli value	Turned	CO_2 value	Heli value	Milled	CO_2 value	Heli value
Weight (gram)	Ra 0,4						Ra 0,8						Ra 1,4					
323,1	n			n			n			n			n			n		
407,8	n			n			n			n			n			n		
463,5	n			n			n			n			n			n		
554,4	n			n			n			n			n			n		
694,2	n			n			n			n			n			n		
832,9	n			n			n			n			n			n		
948,5	n			n			n			n			n			n		
1102	y	4,0x10^-8	2,6x10^-6	y	8,0x10^-8	8,5x10^-6	n			n			n			n		
1240,7	n			n			n			n			n			n		
1378,6	n			y	5x10^-8	6,3x10^-6	n			y		1,1x10^-5	n			y	2,6x10^-9	3,0x10^-6
1511,8	y	5x10-8	6.4x10-5	n			n			n			n			n		
1654,7	y		1.4x10-4	n			n			n			n			y	5x10^-9	6x10^-5
1794,5				y	8x10^-8	4x10^-6	y	5x10^-9	2.6x10^-5	n			n					
1925,8							y	1x10^-9	1.5x10^-5	y	4x10^-8	1x10^-5	y	3x10^-9	2,7x10^-6			
2065,6										y	8x10^-8	3.6x10^-6	y	5x10^-9	3.6x10^-6			

Table 30 – Stainless steel: Full 90 degrees scratch – Not polished

Polished surface:

Without scratch		
Ra 0.4	Ra 0.8	Ra 1.4
Polished	Polished	Polished
n	n	n

	With scratch								
	Polished	CO_2 value	Heli value	Polished	CO_2 value	Heli value	Polished	CO_2 value	Heli value
Weight (gram)	Ra 0.4			Ra 0.8			Ra 0,8		
694,2	n			n			n		
909,9	n			n			n		
1142,4	n			n			n		
1279,3	y	2.9x10^-9	1.2x10^-6	n			n		
1423	y	1x10^-8	2.2x10^-6	n			n		
1563,8				n			n		
1701,7				n			n		
1834,9				y	2x10^-9	3x10^-5	y	3,9x10^-9	1x10^-5
2065,6				y	4x10^-9	1,0x10^-5	y	8x10^-9	1,1x10^-5

Table 31 - Stainless steel: Full 90 degrees scratch – Polished

Stainless steel HALF EXTERNAL 90 degrees scratch

Not polished surface:

Stainless steel
Experiment 2 (HALF EXTERNAL 90')

Without scratch					
Ra 0,4		Ra 0,8		Ra 1,4	
Turned	Milled	Turned	Milled	Turned	Milled
n	n	n	n	n	n

	With scratch					
	Ra 0,4		Ra 0,8		Ra 1,4	
Weight (gram)	Turned	Milled	Turned	Milled	Turned	Milled
948,5	n	n	n	n	n	n
1240,7	n	n	n	n	n	n
1511,8	n	n	n	n	n	n
1794,5	n	n	n	n	n	n
2065,6	n	n	n	n	n	n
2323,4	n	n	n	n	n	n
2606,4	n	n	n	n	n	n
2887,6	n	n	n	n	n	n

Table 32 - Stainless steel: Half external 90 degrees scratch – Not polished

Polished surface

Without scratch		
Ra 0.4	Ra 0.8	Ra 1.4
Polished	Polished	Polished
n	n n	n n

	With scratch		
	Ra 0.4	Ra 0.8	Ra 1.4
Weight (gram)	Polished	Polished	Polished
909,9	n	n	n
1142,4	n	n	n
1378,6	n	n	n
1602,4	n	n	n
1834,9	n	n	n
2065,6	n	n	n
2284,8	n	n	n
2980,4	n	n	n

Table 33 - Stainless steel: Half external 90 degrees scratch – Polished

Stainless steel HALF INTERNAL 90 degrees scratch

Not polished surface:

Stainless steel
Experiment 3 (half int 90')

Without scratch					
Ra 0,4		Ra 0,8		Ra 1,4	
Turned	Milled	Turned	Milled	Turned	Milled
n	n	n	n	n	n

	With scratch									
	Ra 0,4						Ra 0,8		Ra 1,4	
Weight (gram)	Turned	CO_2 value	Heli value	Milled	CO_2 value	Heli value	Turned	Milled	Turned	Milled
948,5	n			n			n	n	n	n
1102	n			n			n	n	n	n
1240,7	n			n			n	n	n	n
1378,6	n			n			n	n	n	n
1511,8	n			n			n	n	n	n
1654,7	y	3.4x10^-8	1.6x10^-6	y	4x10-8	1.6x10-5	n	n	n	n
1794,5	n			n			n	n	n	n
1925,8	n			y	3,2x10-8	2,5x10-5	n	n	n	n
2065,6	n			n			n	n	n	n
2196,9	y		2,9x10-6				n	n	n	n
2323,4							n	n	n	n
2467,1							n	n	n	n
2606,4							n	n	n	n
2887,6							n	n	n	n
3351,1							n	n	n	n

Table 34 - Stainless steel: Half internal 90 degrees scratch – Not polished

Polished surface:

Without scratch		
Ra 0,4	Ra 0,8	Ra 1,4
Polished	Polished	Polished
n	n	n

	With scratch				
	Ra 0,4			Ra 0.8	Ra 1.4
Weight (grams)	Polished	CO_2 value	Heli value	Polished	Polished
1378,6	n				
1511,8	n				
1654,7	n				
1794,5	y	1.8x10^-9	1,0x10^-5		
1925,8	n			n	n
2065,6	y	2.7x10^-9	8.4x10^-5	n	n
2284,8				n	n
2515,5				n	n
2980,4				n	n

Table 35 - Stainless steel: Half internal 90 degrees scratch – Polished

Stainless steel Centric scratch

Stainless steel
Experiment 4 (Centric scratch)

	With scratch								
	Ra 0,4			Ra 0,8			Ra 1,4		
Weight (gram)	Turned	Milled	Polished	Turned	Milled	Polished	Turned	Milled	Polished
2749,7	n	n	n	n	n	n	n	n	n

Table 36 - Stainless steel: Centric scratch

Stainless steel Scratch with grain paper

Stainless steel Experiment 5 (scratch with grain paper)								
With scratch								
Ra 0,4			Ra 0,4			Ra 0,4		
Turned	Milled	Polished	Turned	Milled	Polished	Turned	Milled	Polished
n	n	n	n	n	n	n	n	n

Table 37 – Stainless steel – scratch with grain paper

Stainless steel Full power external scratch by hand

Stainless steel Experiment 5 (full power internal scratch by hand)								
With scratch								
Ra 0,4			Ra 0,4			Ra 0,4		
Turned	Milled	Polished	Turned	Milled	Polished	Turned	Milled	Polished
n	n	n	n	n	n	n	n	n

Table 38 – Stainless steel – Full power internal scratch by hand

Stainless steel Full power external scratch by hand

Stainless steel Experiment 6 (full power external scratch by hand)								
With scratch								
Ra 0.4			Ra 0.8			Ra 1.4		
Turned	Milled	Polished	Turned	Milled	Polished	Turned	Milled	Polished
n	n	n	n	n	n	n	n	n

Table 39 - Stainless steel – Full power external scratch by hand

2.7. Depths and widths results

In this section, the following tables describes the depths and the widths of the scratches. The tables shows the results that are not in the report. It is formed by the last deepest scratch that does not cause a leak and also the first two scratches (after the last deepest scratch that does not cause a leak) that are causing a leak were measured.

Weight (g) / Depth and width (mm)		ALUMINIUM – Half internal scratch of 90º								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH no Leak	weight	463,5	2284,8	2284,8	150	2284,8	2284,8	300	2284,8	2284,8
	width	0,089	0,111	0,11	0,056	0,149	0,129	0,88	0,152	0,134
	depth	0,015	0,026	0,027	0,015	0,036	0,028	0,021	0,033	0,03
SCRATCH no Leak	weight		2749,7	2749,7		2749,7				
	width		0,14	0,147		0,155				
	depth		0,034	0,031		0,041				
SCRATCH Leak	weight	694,2			832,9		2749,7	1654,7	2749,7	2749,7
	width	0,097			0,066		0,133	0,109	0,167	0,144
	depth	0,021			0,021		0,029	0,025	0,036	0,036
SCRATCH Leak	weight	832,9			909,9			2065,6		
	width	0,103			0,071			0,121		
	depth	0,023			0,023			0,027		

Table 40 - Depths and widths results: Aluminum – Half internal 90 degrees scratch

Weight (g) / Depth and width (mm)		ALUMINIUM – Half external scratch of 90º								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH no Leak	weight	2284,8	2284,8	2284,8	2284,8	2284,8	2284,8	2284,8	2284,8	2284,8
	width	0,128	0,139	0,141	0,126	0,121	0,132	0,122	0,133	0,126
	depth	0,027	0,028	0,025	0,028	0,043	0,031	0,021	0,036	0,029
SCRATCH no Leak	weight	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7
	width	0,146	0,144	0,144	0,127	0,144	0,14	0,139	0,155	0,149
	depth	0,035	0,041	0,047	0,04	0,055	0,04	0,035	0,059	0,041

Table 41 - Depths and widths results: Aluminum – Half external 90 degrees scratch

Weight (g) / Depth and width (mm)		ALUMINIUM – Centric scracth								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH no Leak	weight	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7
	width	0,12	0,143	0,147	0,145	0,158	0,141	0,142	0,147	0,139
	depth	0,028	0,036	0,036	0,029	0,035	0,036	0,026	0,028	0,022

Table 42 - Depths and widths results: Aluminum – Centric scratch

Weight (g) / Depth and width (mm)		STAINLESS STEEL – Half internal scratch of 90º								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH NO LEAK	weight	1511,8	2887,6	2887,6	1511,8	2887,6	2887,6	1654,7	2515,5	2515,5
	width	0,07	0,07	0,084	0,072	0,091	0,107	0,066	0,077	0,068
	depth	0,021	0,024	0,024	0,015	0,024	0,03	0,014	0,024	0,018
SCRATCH NO LEAK	weight		3351,1	3351,1		3351,1	3351,1		3351,1	3351,1
	width		0,103	0,97		0,078	0,102		0,087	0,085
	depth		0,33	0,027		0,025	0,028		0,026	0,02
SCRATCH LEAK	weight	360			1794,5			1794,5		
	width	0,079			0,072			0,078		
	depth	0,025			0,018			0,017		
SCRATCH Low´	weight	420			2065,6			2065,6		
	width	0,084			0,128			0,081		
	depth	0,025			0,029			0,019		

Weight (g) / Depth and width (mm)		STAINLESS STEEL								
		Half external scratch of 90º								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH NO LEAK	weight	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2284,8	2284,8	2284,8
	Width	**0,07**	**0,066**	**0,072**	**0,08**	**0,045**	**0,045**	**0,077**	**0,078**	**0,069**
	depth	**0,024**	**0,019**	**0,025**	**0,023**	**0,027**	**0,022**	**0,016**	**0,02**	**0,02**
SCRATCH NO LEAK	weight	3351,1	3351,1	3351,1	3351,1	3351,1	3351,1	3351,1	3351,1	3351,1
	Width	**0,083**	**0,079**	**0,074**	**0,1**	**0,082**	**0,077**	**0,093**	**0,088**	**0,084**
	depth	**0,024**	**0,021**	**0,026**	**0,031**	**0,03**	**0,024**	**0,019**	**0,024**	**0,023**

Table 43 - Depths and widths results: Stainless steel – Half internal 90 degrees scratch

Table 44 - Depths and widths results: Stainless steel – Half external 90 degrees scratch

Weight (g) / Depth and width (mm)		STAINLESS STEEL								
		Centric scratch								
		Milled			turning			Polished		
		Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4	Ra 0.4	Ra 0.8	Ra 1.4
SCRATCH no Leak	weight	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7	2749,7
	width	**0,078**	**0,081**	**0,076**	**0,082**	**0,091**	**0,075**	**0,092**	**0,089**	**0,083**
	depth	**0,024**	**0,036**	**0,031**	**0,03**	**0,022**	**0,026**	**0,026**	**0,019**	**0,021**

Table 45 - Depths and widths results: Stainless steel – Centric scratch

2.8. Which depths and widths causes leaks?

In this section, the charts represents the green, orange and red areas based on the results of the depth and width results. The charts shows the results that are not in the report.

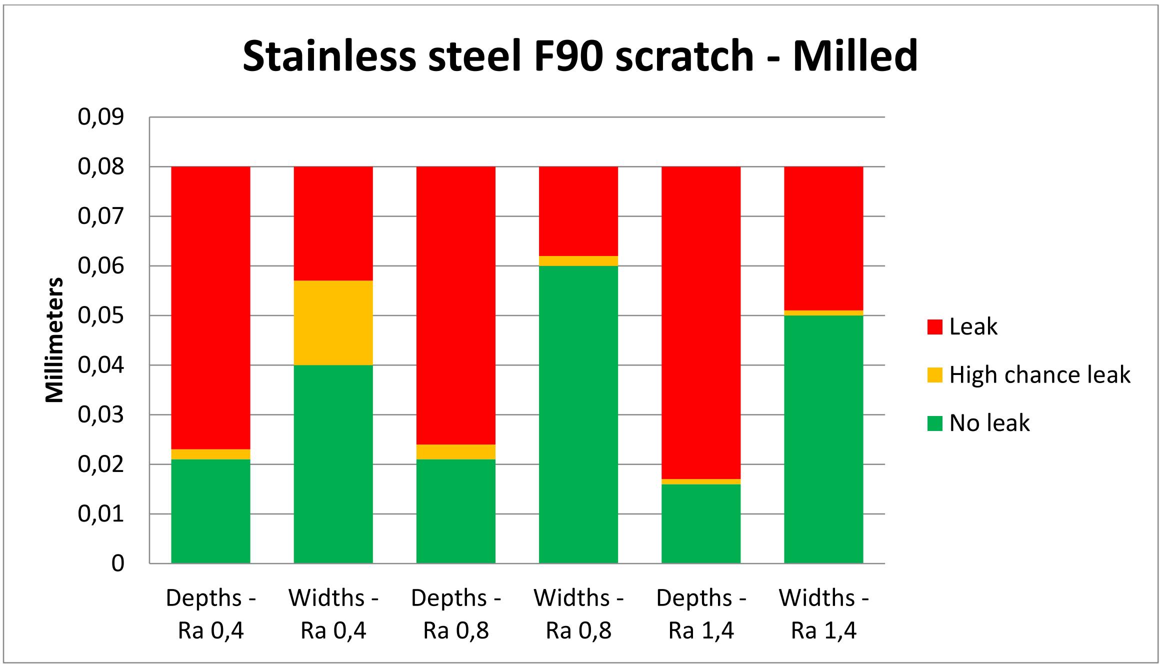


Illustration 34 – Depths and widths bands: Stainless steel – Full 90 degrees scratch - Milled

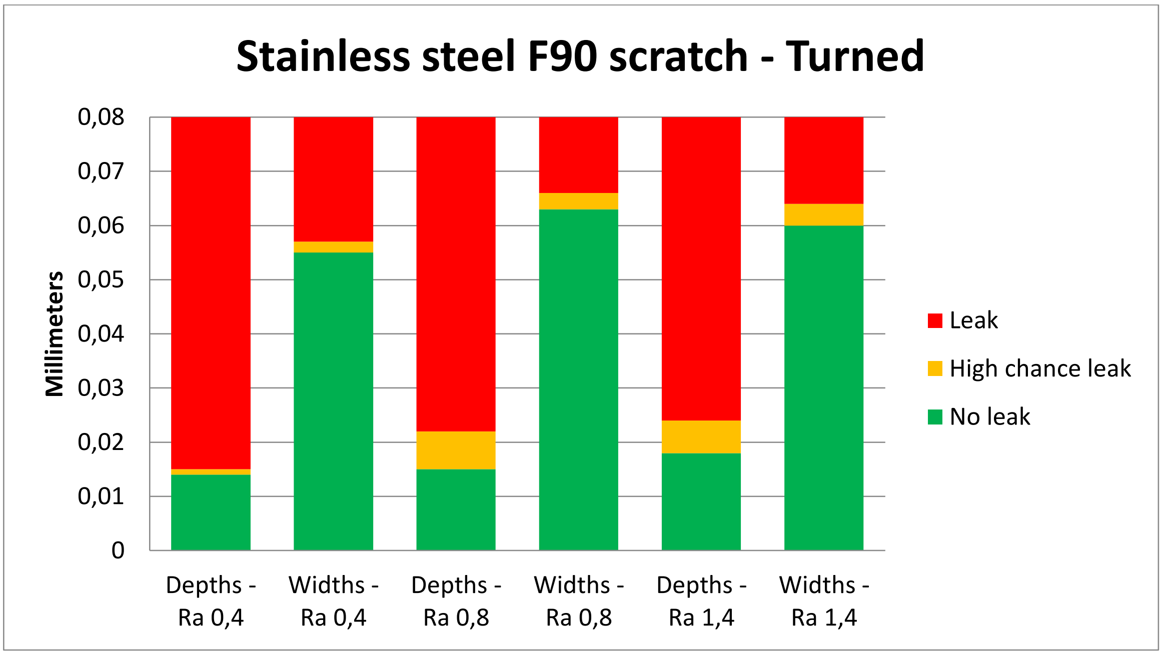


Illustration 35 - Depths and widths bands: Stainless steel – Full 90 degrees scratch – Turned

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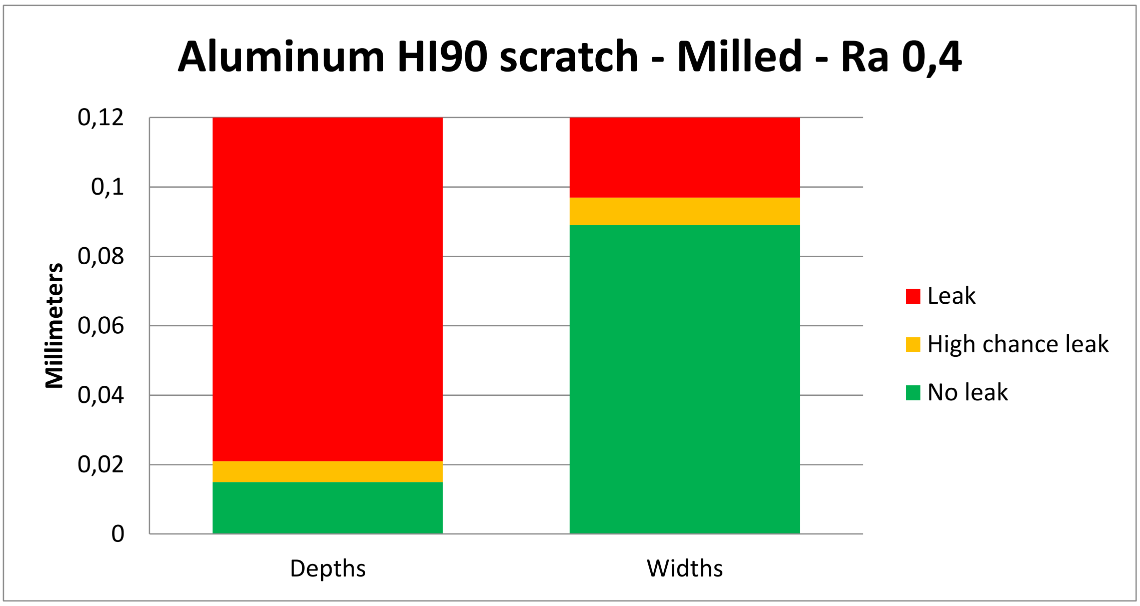


Illustration 36 - Depths and widths bands: Aluminium – Half internal 90 degrees scratch – Milled – Ra 0.4

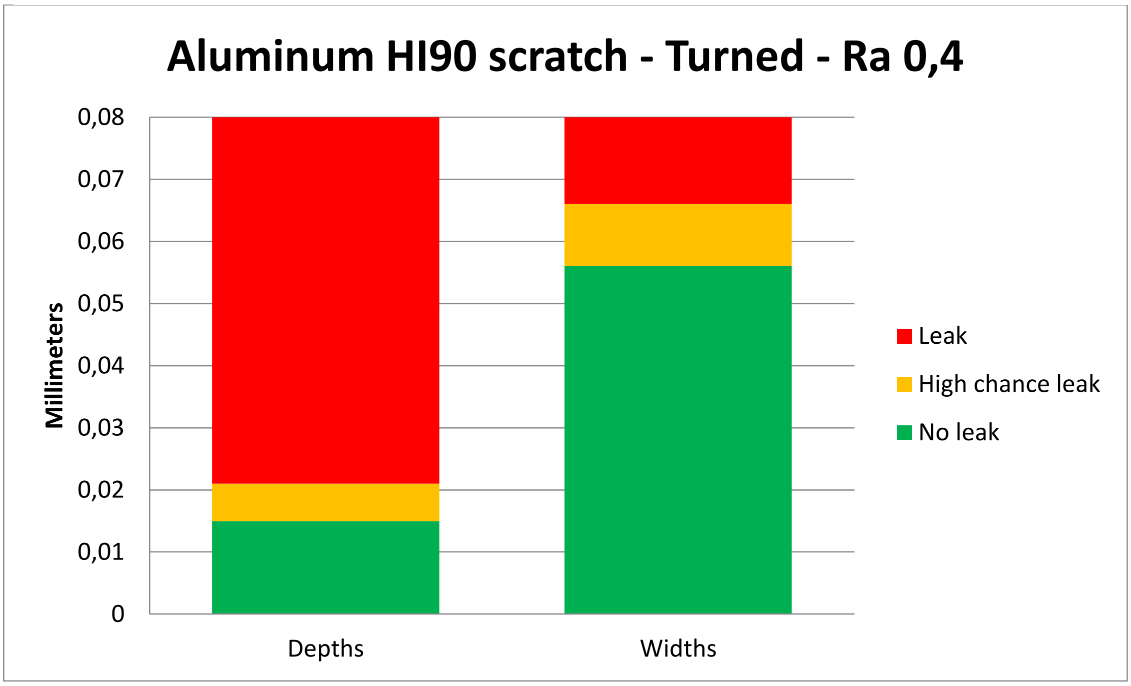


Illustration 37 - Depths and widths bands: Aluminum – Half internal 90 degrees scratch – Turned – Ra 0.4

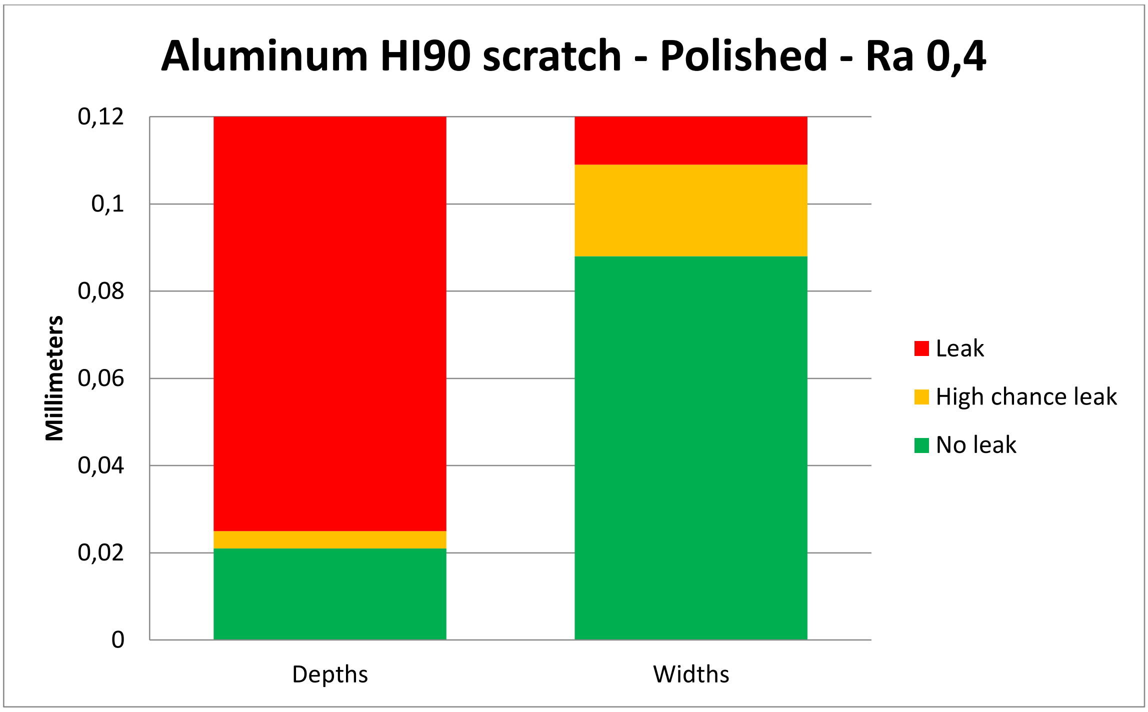


Illustration 38 - Depths and widths bands: Aluminum – Half internal 90 degrees scratch – Polished – Ra 0.4

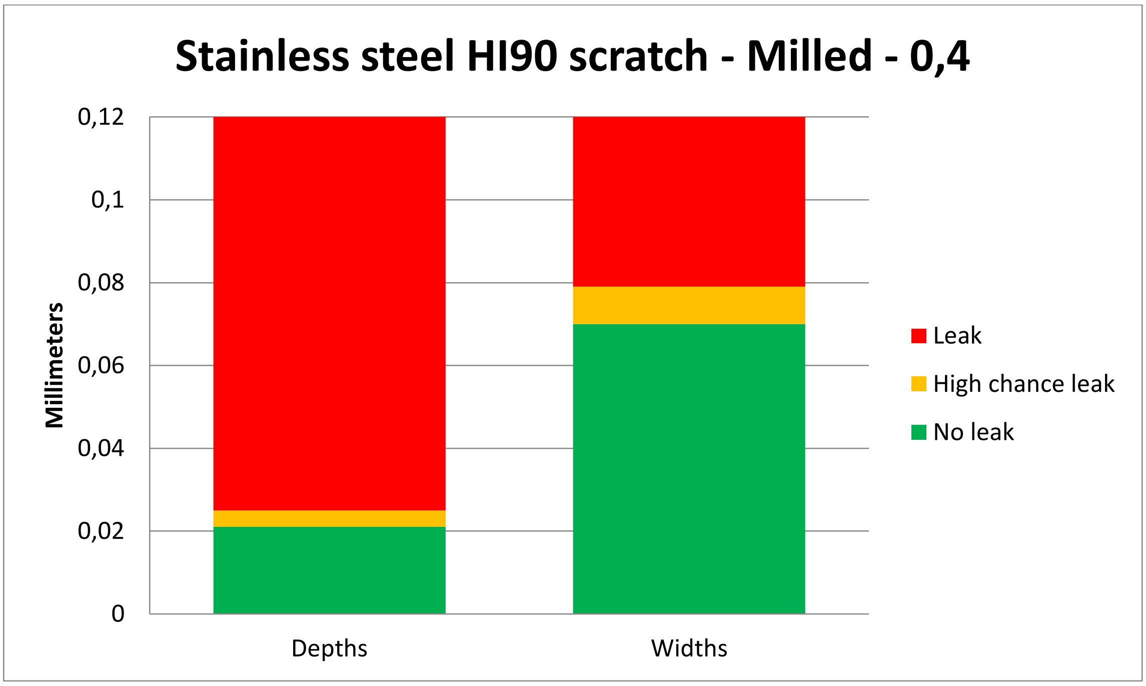


Illustration 39 - Depths and widths bands: Stainless steel – Half internal 90 degrees scratch – Milled – Ra 0.4

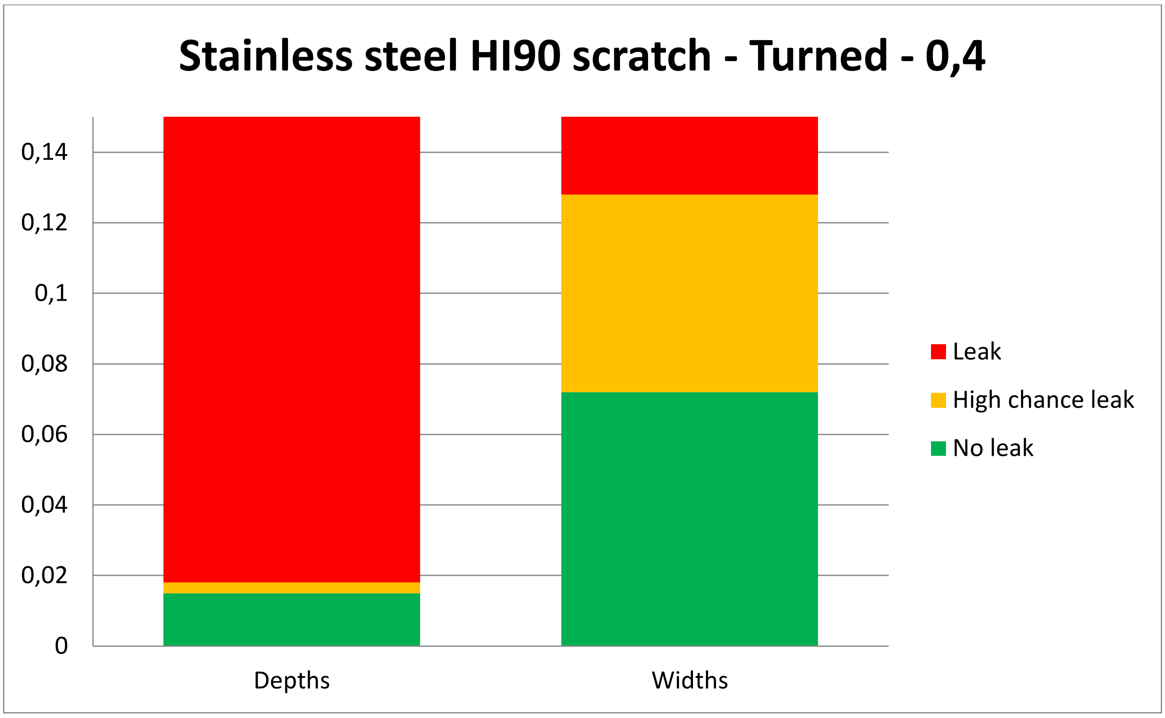


Illustration 40 - Depths and widths bands: Stainless steel – Half internal 90 degrees scratch – Turned – Ra 0.4

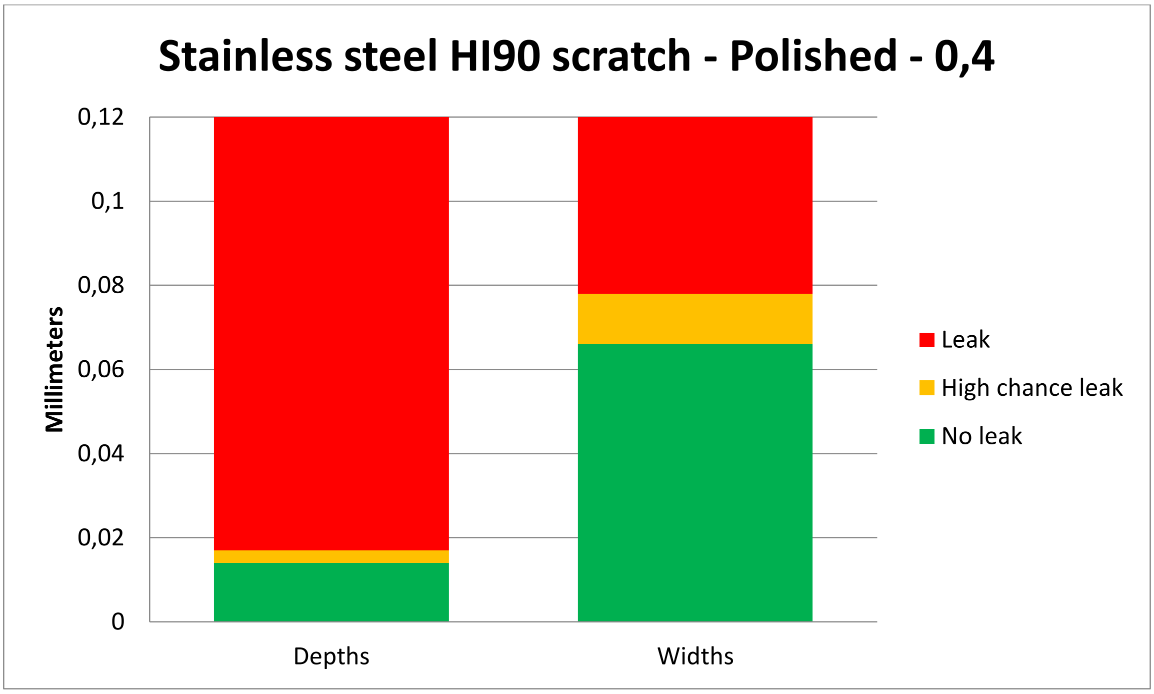


Illustration 41 - Depths and widths bands: Stainless steel – Half internal 90 degrees scratch – Polished – Ra 0.4

3. Appendix D: Analyze

3.1. Weight of blocks against depth of scratch

In the following charts are shown the relation between the weight of the blocks and the depth of the scratches. It is possible to see that most of the lines have a linear correlation. It means that an increase of the weight on the scratch tool entails an increase on its depth.

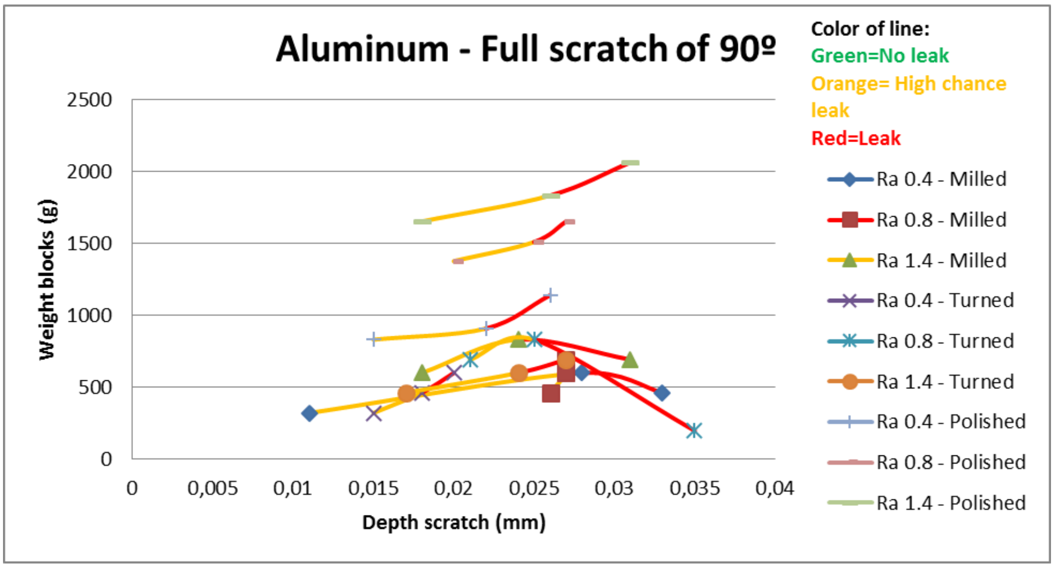


Illustration 42 – Weight of blocks against depth of scratch -Aluminum

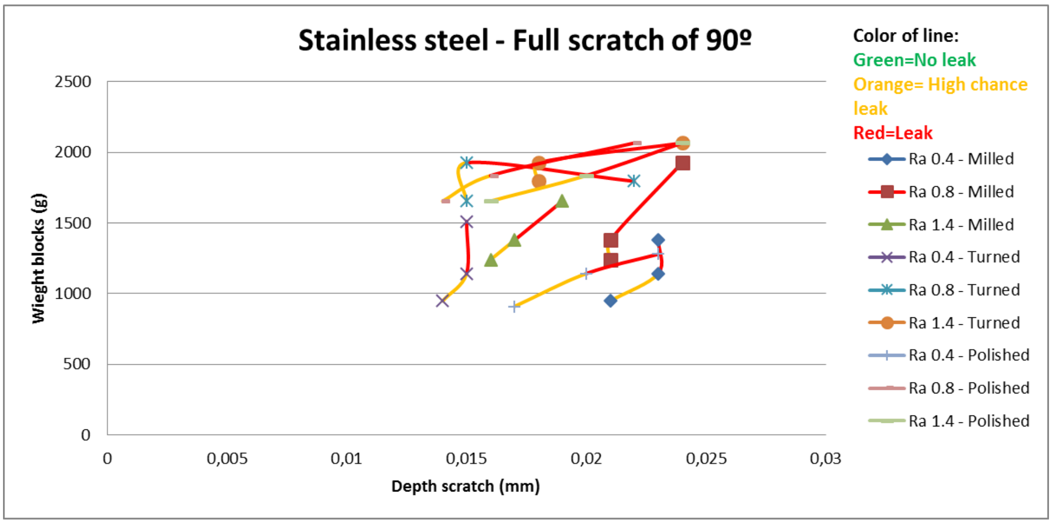


Illustration 43 - Weight of blocks against depth of scratch -Aluminum

3.2. Functional Analysis

3.2.1. Which material is best resistant leaks?

The following tables describes which material leaks first in each level of roughness and each kind of machining.

No scratch	Machining	Material that leaks first
Ra 0,4	Turned	/
	Milled	/
	Polished	/
Ra 0,8	Turned	/
	Milled	/
	Polished	/
Ra 1,4	Turned	/
	Milled	/
	Polished	/

Table 46 - Material that leak first – No scratch

Both aluminum and stainless don't leak without a scratch at all roughness and all kinds of machining.

Full 90 degrees scratch	Machining	Material that leaks first
Ra 0,4	Turned	Stainless Steel
	Milled	Stainless Steel
	Polished	Stainless steel
Ra 0,8	Turned	Stainless steel
	Milled	Stainless steel
	Polished	Stainless steel
Ra 1,4	Turned	Stainless steel
	Milled	Stainless steel
	Polished	Stainless steel

Table 47 - Material that leak first – Full 90 degrees scratch

Aluminum is the most vulnerable material in case of a full 90 degrees scratch on the vacuum surface.

Half external 90 degrees scratch	Machining	Material that leaks first
Ra 0,4	Turned	/
	Milled	/
	Polished	/
Ra 0,8	Turned	/
	Milled	/
	Polished	/
Ra 1,4	Turned	/
	Milled	/
	Polished	/

Table 48 - Material that leak first – Half external 90 scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

Half internal 90 degrees scratch	Machining	Material that leaks first
Ra 0,4	Turned	Depth: SS Width: Al
	Milled	Depth: Al Width: SS
	Polished	Aluminum
Ra 0,8	Turned	/
	Milled	/
	Polished	Aluminum
Ra 1,4	Turned	Aluminum
	Milled	/
	Polished	Aluminum

Table 49 - Material that leak first – Half internal 90 scratch

Aluminum is the most vulnerable material in case of a half internal 90 degrees scratch on the vacuum surface. However it must be mentioned that with a roughness of 1.4 with a turned surface the aluminum only starts to leak with a scratch which can be considered deep. In those cases the scratches 0.109 mm.

Centric scratch	Machining	Material that leaks first
Ra 0,4	Turned	/
	Milled	/
	Polished	/
Ra 0,8	Turned	/
	Milled	/
	Polished	/
Ra 1,4	Turned	/
	Milled	/
	Polished	/

Table 50 - Material that leak first – Centric scratch

Both aluminum and stainless don't leak with a centric scratch at all roughness and all kinds of machining.

Full power external scratch by hand	Machining	Material that leaks first
Ra 0,4	Turned	/
	Milled	/
	Polished	/
Ra 0,8	Turned	/
	Milled	/
	Polished	/
Ra 1,4	Turned	/
	Milled	/
	Polished	/

Table 51 – Material that leak first – Full power external scratch by hand

Both aluminum and stainless don't leak with a full power external scratch by hand at all roughness and a turned surface.

3.2.2. Which roughness is best resistant to leaks?

The following charts represents which roughness is best resistant to leaks. It is represented the other different cases that are not included in the report.

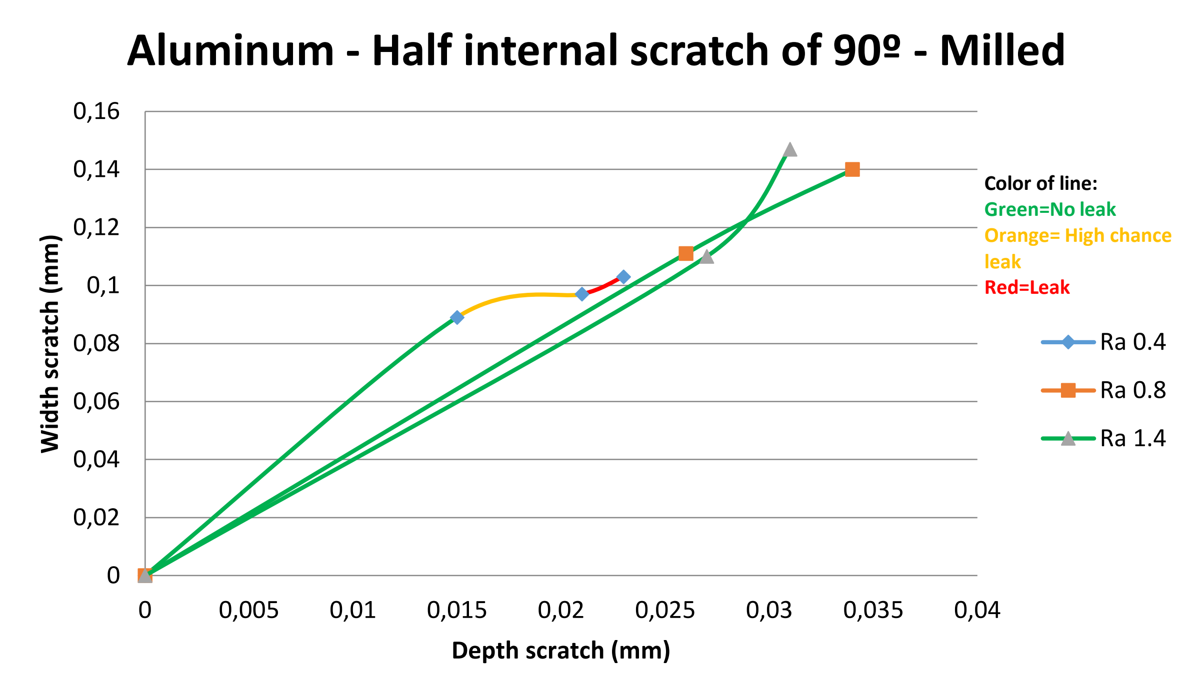


Illustration 44 – Best resistant roughness: Aluminum – Half internal 90 degrees scratch - Milled

Illustration 45 -Best resistant roughness: Aluminum – Half internal 90 degrees scratch - Turned

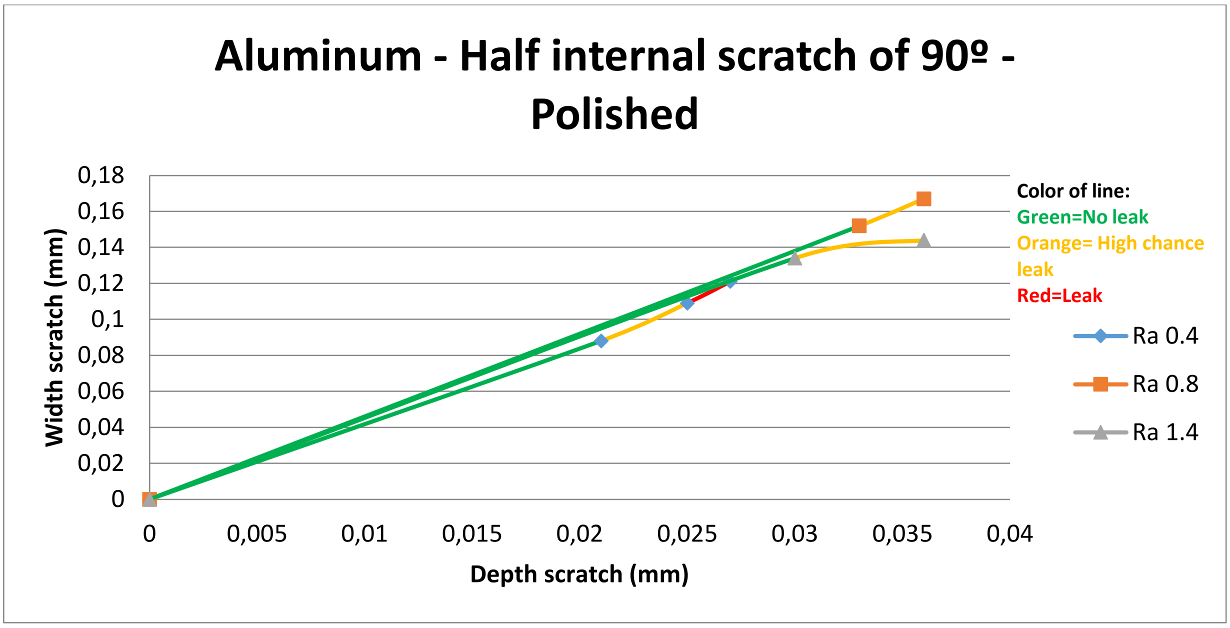


Illustration 46 - Best resistant roughness: Aluminum – Half internal 90 degrees scratch - Polished

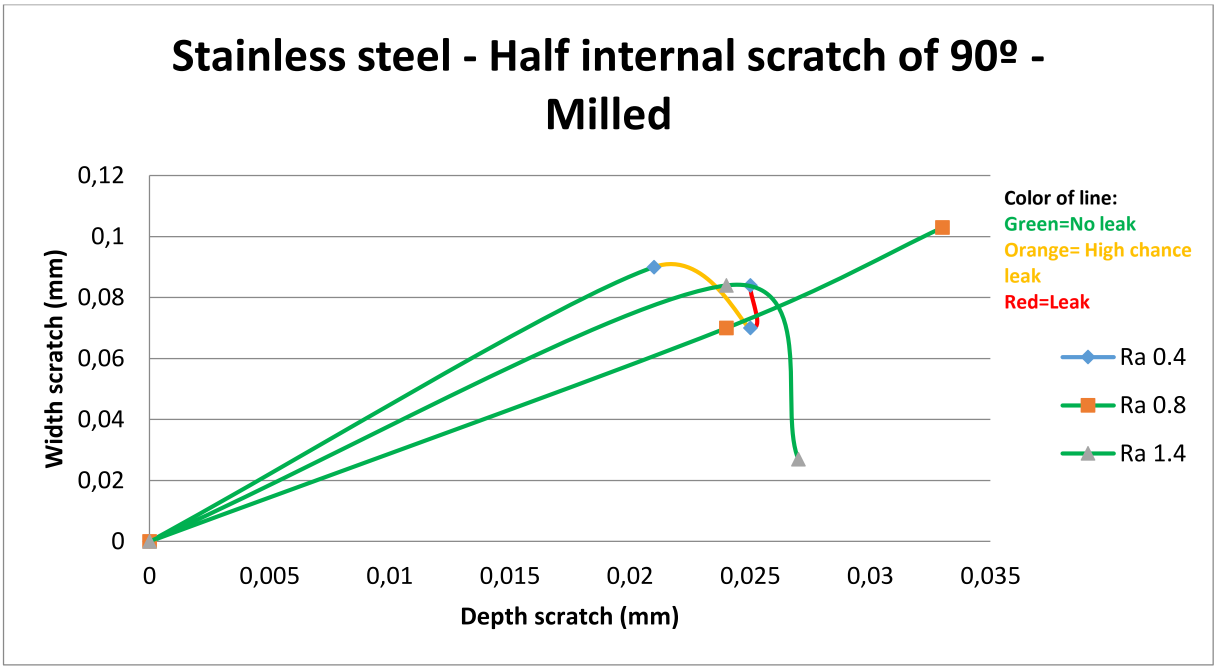


Illustration 47 - Best resistant roughness: Stainless steel – Half internal 90 degrees scratch – Milled

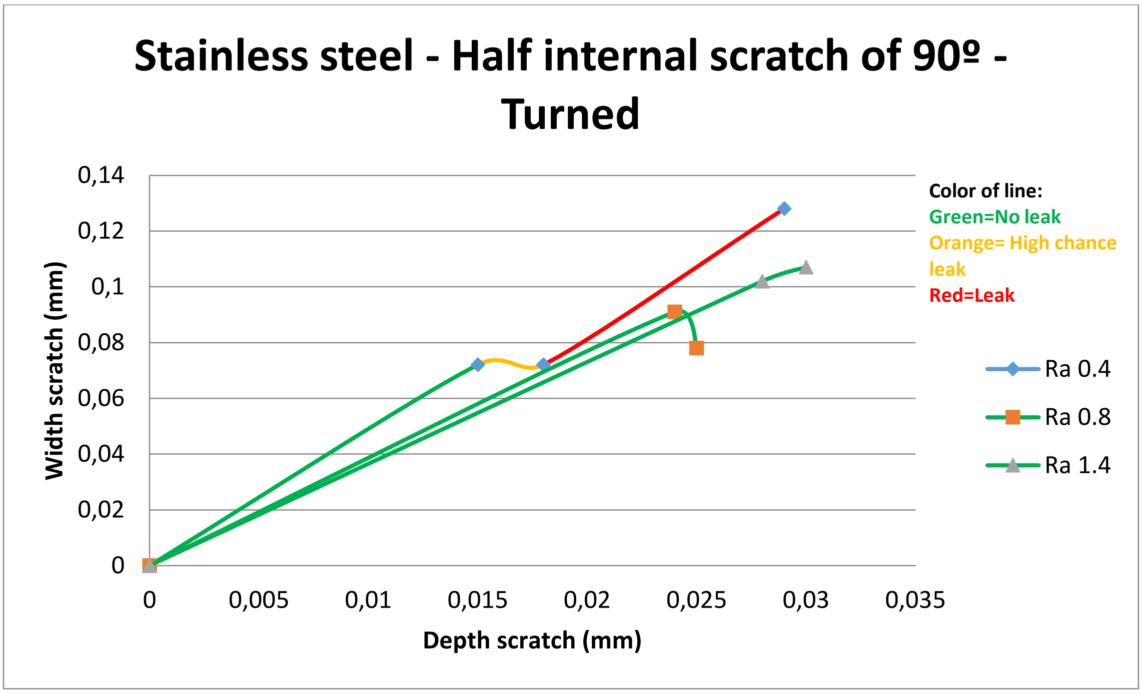


Illustration 48 - Best resistant roughness: Stainless steel – Half internal 90 degrees scratch - Turned

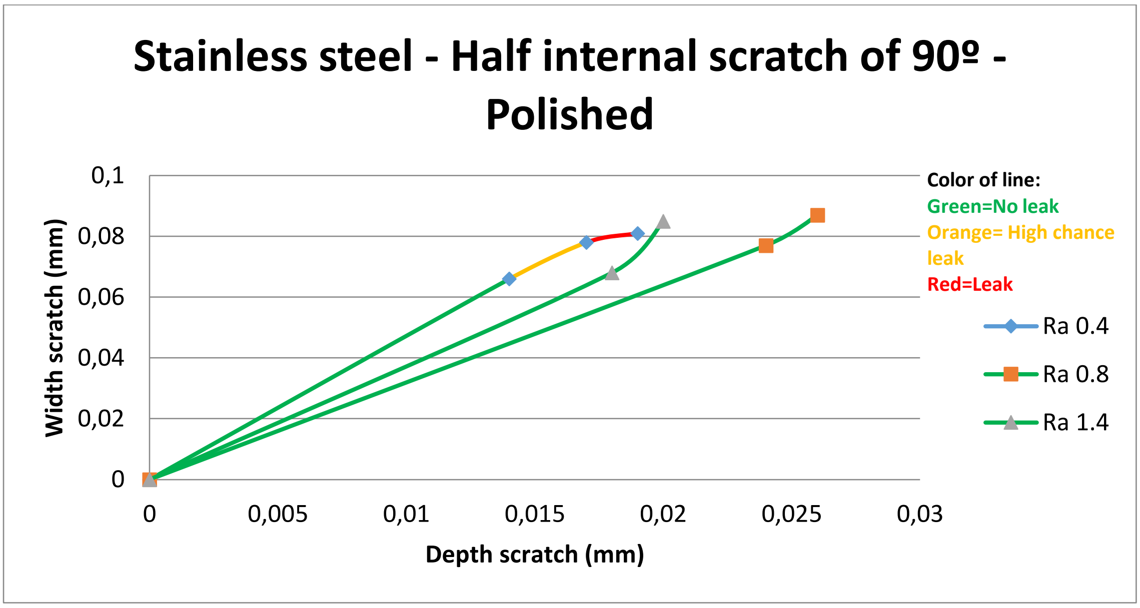


Illustration 49 - Best resistant roughness: Stainless steel – Half internal 90 degrees scratch – Polished

The following tables describes which level of roughness leaks first and the best roughness in each kind of machining vacuum surface.

No scratch	Machining	Roughness that leak first	Best roughness
Aluminum	Turned	/	/
	Milled	/	/
	Polished	/	/
Stainless steel	Turned	/	/
	Milled	/	/
	Polished	/	/

Table 52 – Best and worst roughness – No scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

Full 90 degrees scratch	Machining	Roughness that leak first	Best roughness
Aluminum	Turned	1,4	0,8
	Milled	0,4	1,4
	Polished	0,4	1,4
Stainless steel	Turned	0,4	0,8
	Milled	1,4	0,8
	Polished	1,4	0,4

Table 53 - Best and worst roughness – No scratch

Roughness 0.8 is the best roughness in case of a full 90 degrees scratch, while roughness 0.4 is the most vulnerable on the vacuum surface.

Half internal 90 degrees scratch	Machining	Roughness that leak first	Best roughness
Aluminum	Turned	0,4	0,8 and1,4
	Milled	0,4	0,8 and 1,4
	Polished	0,4	0,8
Stainless steel	Turned	0,4	0,8 and 1,4
	Milled	0,4	0,8 and 1,4
	Polished	0,4	0,8

Table 54 - Best and worst roughness – Half internal 90 degrees scratch

Roughness 0.8 is the best roughness in case of a half internal 90 degrees scratch, while roughness 0.4 is the most vulnerable on the vacuum surface.

Half external 90 degrees scratch	Machining	Roughness that leak first	Best roughness
Aluminum	Turned	/	/
	Milled	/	/
	Polished	/	/
Stainless steel	Turned	/	/
	Milled	/	/
	Polished	/	/

Table 55 - Best and worst roughness – Half external 90 degrees scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

Centric scratch	Machining	Roughness that leak first	Best roughness
Aluminum	Turned	/	/
	Milled	/	/
	Polished	/	/
Stainless steel	Turned	/	/
	Milled	/	/
	Polished	/	/

Table 56 - Best and worst roughness – Centric scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining

Full power external scratch by hand	Machining	Roughness that leak first	Best roughness
Aluminum	Turned	/	/
	Milled	/	/
	Polished	/	/
Stainless steel	Turned	/	/
	Milled	/	/
	Polished	/	/

Table 57 - Best and worst roughness – Full power external scratch by hand

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

3.2.3. Which kind of machining is best resistant to leaks?

The following charts represents which kind of machining is best resistant to leaks. It is represented the other different cases that are not included in the report.

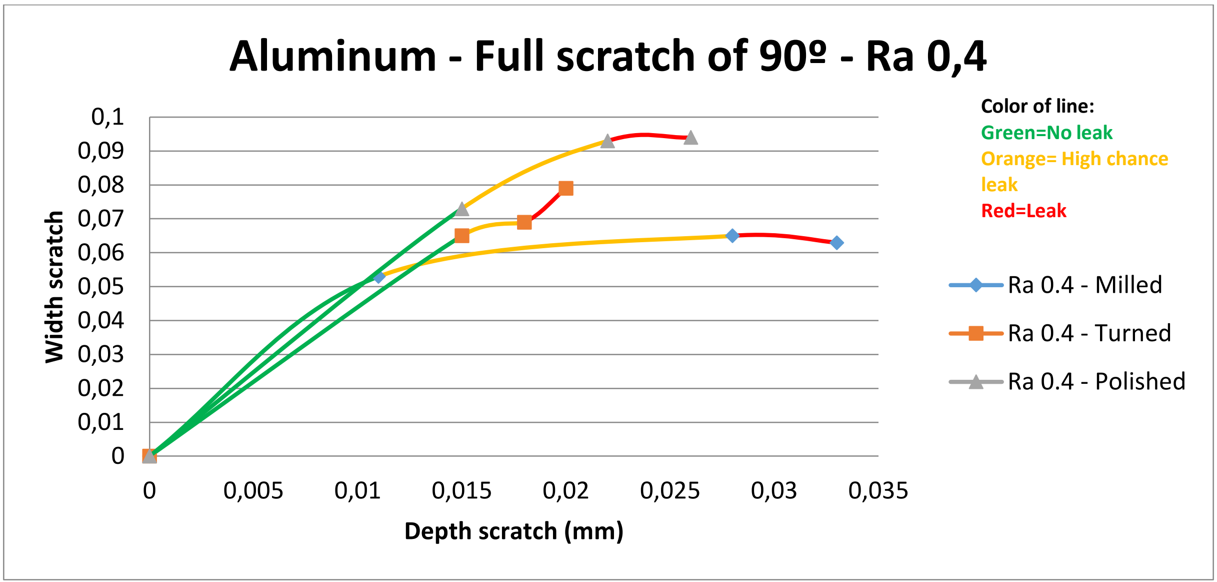


Illustration 50 - Best resistant machined surface: Aluminum – Full 90 degrees scratch – Ra 0.4

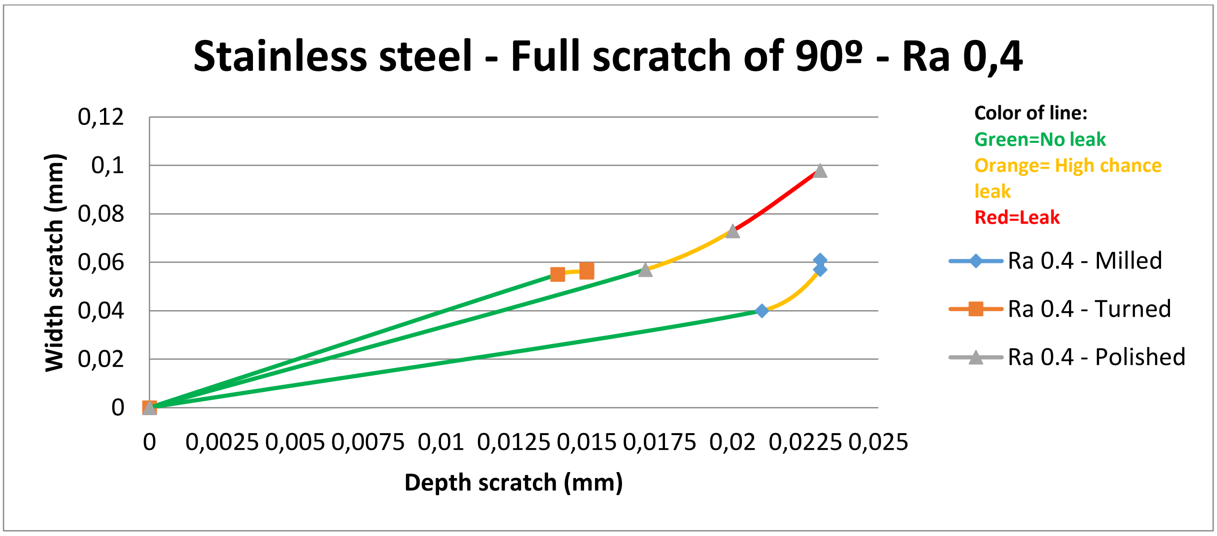


Illustration 51 – Best resistant machined surface: Stainless steel – Full 90 degrees scratch – Ra 0.4

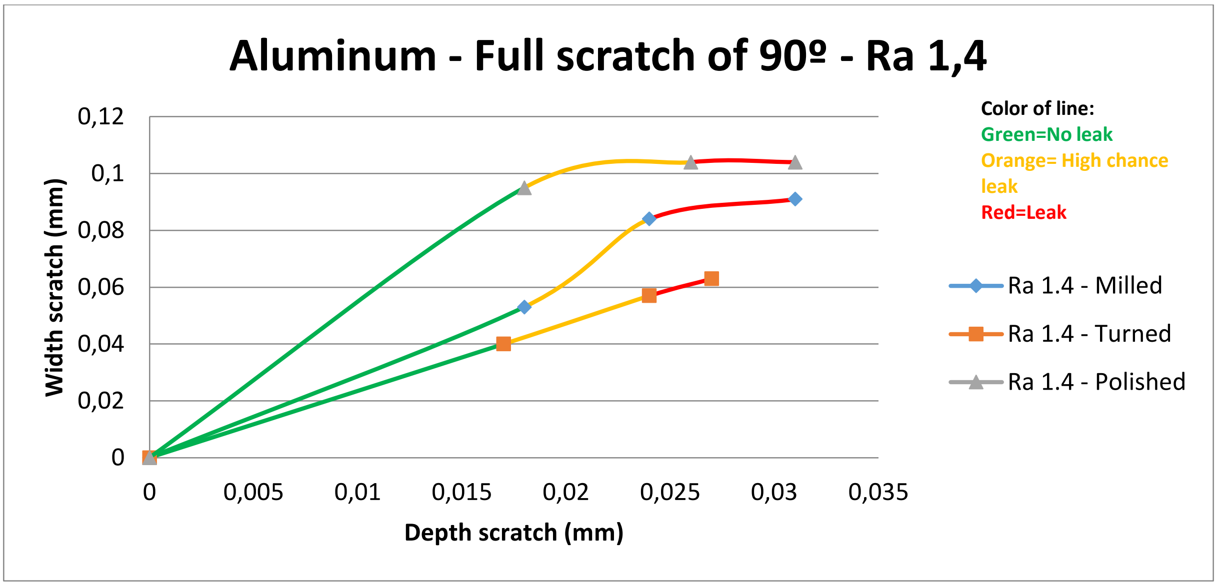


Illustration 52 - Best resistant machined surface: Aluminum – Full 90 degrees scratch – Ra 1.4

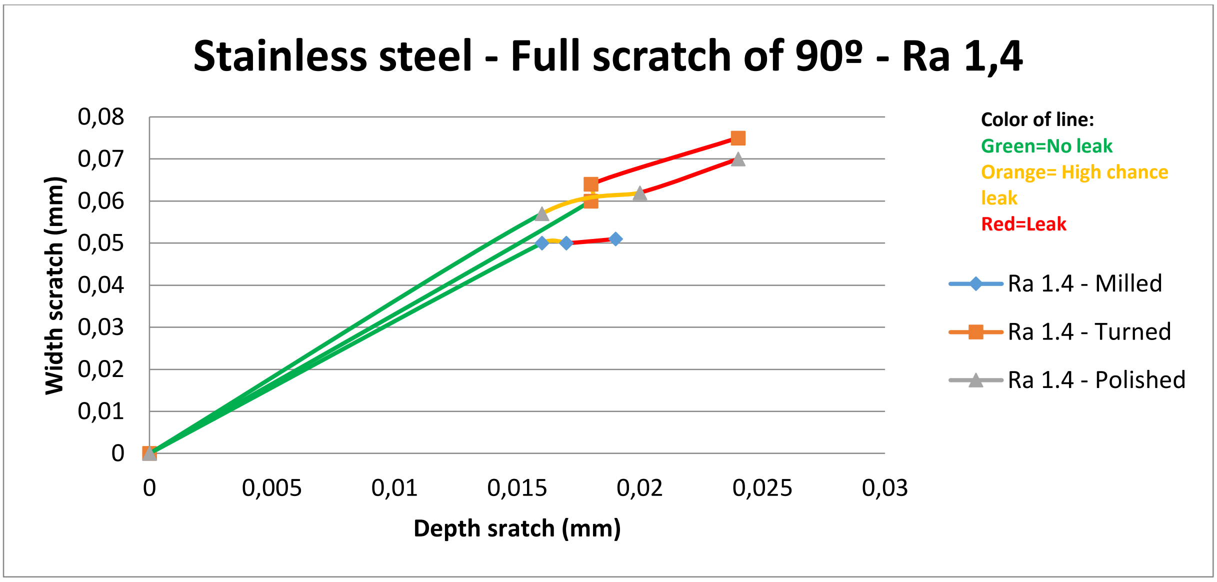


Illustration 53 - Best resistant machined surface: Stainless steel – Full 90 degrees scratch – Ra 0.4

The following tables describes which kind of machining leaks first in each level of roughness.

No scratch	Roughness	Kind of machining that leak first
Aluminum	0,4	/
	0,8	/
	1,4	/
Stainless steel	0,4	/
	0,8	/
	1,4	/

Table 58 – Kind of machining that leak first – No scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

Full 90 degrees scratch	Roughness	Kind of machining that leak first
Aluminum	0,4	Turned
	0,8	Milled
	1,4	Turned
Stainless steel	0,4	Turned
	0,8	Polished
	1,4	Milled

Table 59 - Kind of machining that leak first – Full 90 degrees scratch

The polished surface is the best machined surface in case of a full 90 degrees scratch while the turned surface is the worst vacuum surface. These results are with all roughness and aluminum and stainless steel.

Half external 90 degrees scratch	Roughness	Kind of machining that leak first
Aluminum	0,4	/
	0,8	/
	1,4	/
Stainless steel	0,4	/
	0,8	/
	1,4	/

Table 60 - Kind of machining that leak first – Half external 90 degrees scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

Half internal 90 degrees scratch	Roughness	Kind of machining that leak first
Aluminum	0,4	Milled
	0,8	Polished
	1,4	Polished
Stainless steel	0,4	Turned
	0,8	/
	1,4	/

Table 61 - Kind of machining that leak first – Half internal 90 degrees scratch

The turned surface and the milled surface are the best machined surface in case of a half internal 90 degrees scratch while the polished surface is the worst vacuum surface. The difference is not big between them. These results are with all roughness and aluminum and stainless steel.

Centric scratch	Roughness	Kind of machining that leak first
Aluminum	0,4	/
	0,8	/
	1,4	/
Stainless steel	0,4	/
	0,8	/
	1,4	/

Table 62 - Kind of machining that leak first – Centric scratch

Both aluminum and stainless don't leak with different scratches at all roughness and all kinds of machining.

3.3. Visual evaluation

These examples were not included in the report. These pictures shows the same example in different conditions. The weight is in grams and the depth and width are in mm

4. Details: Stainless steel, not polished, full 90 degrees scratch, milled surface, roughness 0,8
   Microscope Photo I. Photo II.

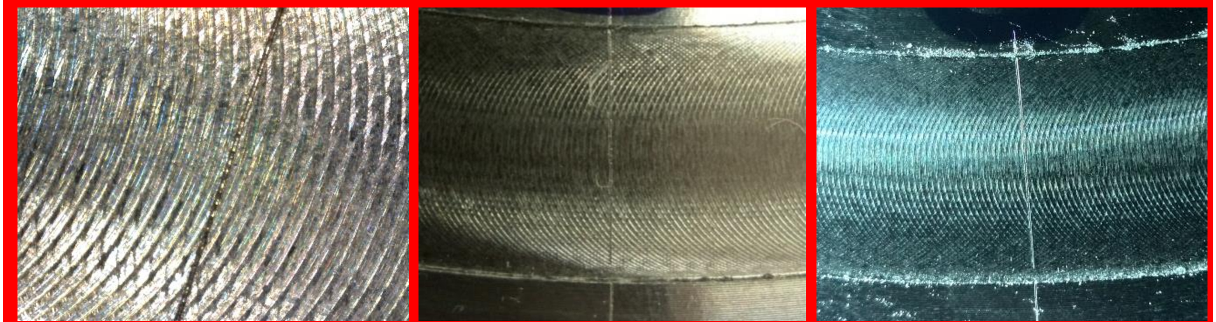
Green area (no leak)

Weight 1240,7 – Width 0,06 – Depth 0,021

Orange area (high chance leak)

Scratches between the green and red area have a high chance of leaking.

Red area (leak)



Weight 1378,6 – Width 0,062 - Depth 0,021

Weight 1925,8 – Width 0,067 - Depth 0,024

Generally to see the differences between the scratches on the stainless steel are very difficult and complicated. The appearance of the scratches are around the same independently the used weights, because widths and depths are really close to each other. The reason for this the material is the one of the hardest metal.

5. Details: Stainless steel, not polished, full 90 degrees scratch, turned surface, roughness 0,8

Microscope Photo I. Photo II.

Green area (no leak)

Weight 323,1

Orange area (high chance leak)

Scratches between the green and red area have a high chance of leaking.

Red area (leak)

Weight 1794,5 – Width 0,066 - Depth 0,022

Weight 1925,8 – Width 0,089 - Depth 0,015

6. Details: Stainless steel, polished, full 90 degrees scratch, milled surface, roughness 0,8

Microscope | Photo I. | Photo II.

Green area (no leak)

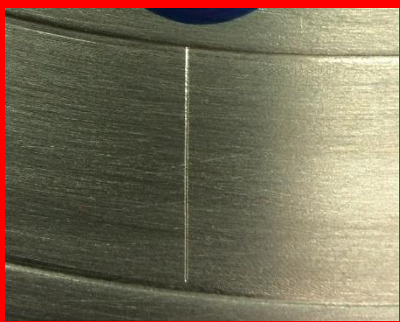
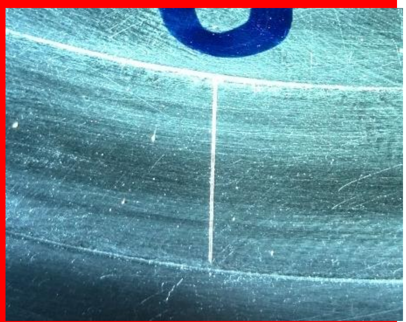


Weight 323,1

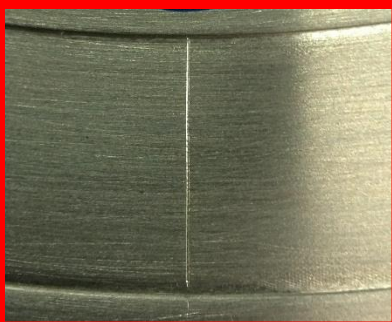
Orange area (high chance leak)

Scratches between the green and red area have a high chance of leaking.

Red area (leaking)

Weight 1834,9 – Width 0,069 - Depth 0,016

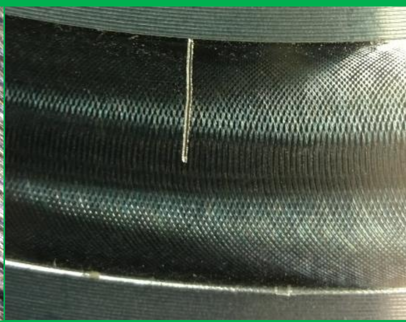
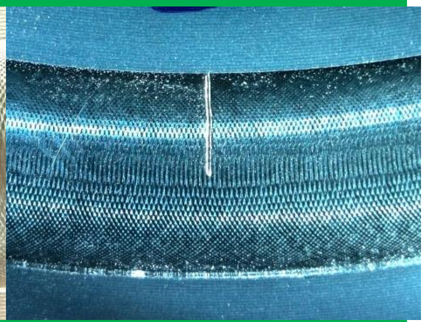




Weight 2065,6 – Width 0,072 - Depth 0,022

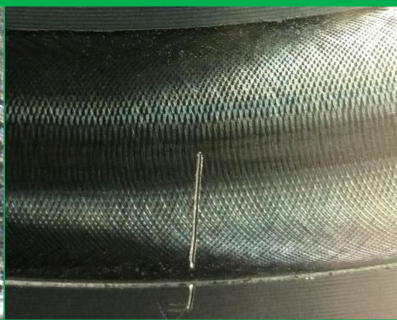
7. Details: Aluminum, roughness 0,8

Microscope | Photo I. | Photo II.

Green area (no leak)

Half internal – Milled surface - 90 degrees scratch – Weight 2749,7 – Width 0,14 – Depth 0,034


Half external – Milled surface - 90 degrees scratch – Weight 2749,7 – Width 0,144 – Depth 0,041

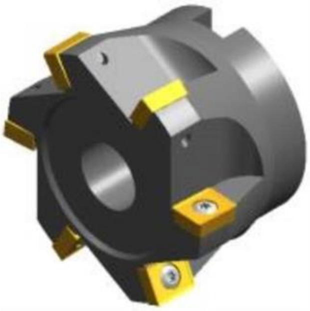
4. Appendix F: Interviews

Questions and answers:

Factoring Engineer 1:

- **What kind of tools does the company use?**
  We have tools with 2 different materials:
    - HM=Hard Metal + coating (blue and gold) (with some kind of powder melted together so it becomes hard)
    - HSS=High Speed Steel

  The HM is available with inserts:



  But at the moment they cannot adjust the height of each separate blade. Now they are working on a tool where you can adjust the heights of the blades but it is very expensive.

  The HM is also available without inserts:

  We use for example a tool that has blades to mill the product. Only the tool becomes blunt after using it a certain times. The problem is then that each blade has different heights and that is why you create a different roughness. It takes a lot of time to change the blades.

- **How do you know when the blade is dull?**
  We look by eye if it is blunt or not. Based on that we decide whether to change the blades or not.

  But we also check with the help of a measure machine called Zoller. Howitworks:

    - Put the tool in the Zoller
    - The Zoller measures the length and the diameter of the blades of the tool.

  - If the blades of the tool is not on the same height they throw the tool away

- **How do you check the products on roughness after milling and turning?**
  We do not check the products on roughness. But in the future with the new upcoming machine they will check the roughness. Now they look by experience if it has the right roughness. They feel with the hand and look by eye.

- **How long does it take to polish a surface, before and after the new machine?**
  After milling or turning the product has a roughness of 0.8 it takes 8 hours.

- **What do you think about the packaging now?**
  The wooden box at the moment is a bit too small. The product is wrapped in two plastic bags. The plastic bag can make a scratch. When the product is taken to the systems it goes to a room and there they take the first bag off and after that the product goes to the assembly place and there they take off the second plastic bag. There is a prototype for a new way of packaging. It is a kind of a wisawhite box. It is not wood, it is a kind of composite.

- **We thought about some kind of sticker to put on the vacuum surface to prevent scratches. What do you think about it?**
  I think we can work on our idea of the sticker on the vacuum surface but it must resist the pickling process.

- **How do you think the scratches can be prevented?**
  Improve the motivation of the employees. Educate them and make them feel responsible. Because at the moment, nobody feels responsible for the product.

- **How do they test the products?**
  Systems department tests different on leaking than the AK1 department. The systems department uses 2 O-rings and AK1 uses 1 O-ring.

Factoring Engineer 2:

- **You suggested a different test product than we designed. What is your suggestion?**
  I was thinking about a kind of disc. On one side of the disc there are 3 surfaces with different roughness machined by turning. On the other side of the disc there are the same 3 surfaces with different kinds of roughness but machined by milling. This disc can consist of aluminum or stainless steel, it's what you prefer. You can connect this disc to a standard counterpart. This standard counterpart is already available in the company. The counterpart will be connected to the vacuum tester. The counterpart consists of 3 grooves where the O-ring can be placed.

Factoring engineer 3:

What are the most important parameters for an O-ring?

You have 3 different variables in which an O-ring can vary:
- Shore A. This is the hardness of the O-ring. For example the hardness of an O-ring can be FKM 75SH.
- Dimensions. An O-ring can have different dimensions.
- Material. You have for example O-rings of VITON and SCUBR. For some ASML products we use SCUBR O-rings. My suggestion is not to use the SCVBR O-ring because it is too expensive and used for special product.

- **Which O-ring do you suggest we should use?**
  It depends on your test product. There are lots of different O-rings. We have for example ERIKS be and Parker as suppliers for O-rings. On the website of them you can find all the different kinds of O-rings. There you can choose an O-ring that suits best for your test product. I give you a number of the business development manager of ERIKS that you can contact with. He knows more about O-rings and how it is related to the vacuum surface. Sometimes you can see a scratch with a certain view of angle. But you can't see the same scratch with another view of angle.

- **What is the way to check the small products? We saw that with big products they only use the eye and flashlight.**
  They have some microscopes to magnify 40 times with led light (FEI). The vacuum surface. In the big products it is not necessary to magnify the product so much and only with the eye and a flashlight from different angles is enough.

- **Why don´t they use a microscope like the small products?**
  The specifications (demands) are not so high, so you can do it with the experience and without a microscope. Also it is really difficult to handle the loop with the hands (the image is not really clear).

- **What do you think is the best roughness? Because we hear from different people different roughness what they think is best. We don't know a lot about roughness, maybe you can tell us more about roughness. Is it better to have a rough vacuum surface or a smooth one?**
  I think it depends on the sealing. For the O-ring I think 0.8 roughness is best.

- **What kind of products do you seal the vacuum surface?**
  There are three ways to sealing:
  - O-rings
  - Plastic ring
  - Metal ring

- **What way does the roughness effects on the O-ring?**
  It´s dependable on the tightness. ASML expects less magnify because they are less critical.

- **On which kind of projects are/were you involved in?**
  I did a project on what is good and what is wrong on the FEI products. I didn´t reached a conclusion on what's wrong and what right.

- **What does FEI exactly want from a vacuum surface?**
  FEI says the vacuum surface needs to be magnified 40 times and it can't have scratches

- **How do the employees judge whether a surface is good?**
  The employees inspect on experience and they know what ASML wants but not specific.

- **What do you think is the best solution to prevent scratches on vacuum surfaces?**
  You must prevent human people working on the products. Because after the milling there are burrs on the product. These burrs need to be removed by craftsmen. And if craftsmen are removing it there is a chance that there will be scratches. Prevent polishing vacuum surfaces by craftsmen.

- **What is a big factor that causes scratches?**

There is so much handling in the factory. During the handling they damage the product. VDL does perfectly know what products which machining they need, but they don´t know how to handle the products.

- **Is it possible to remove all the burrs with the machine?**
  It´s not possible to take away all the burrs with the machine only.

- **What are the customers of VDL-ETG?**
  Our customers are: FEI, ASML, KLA, WALTERS, and CYMERS.

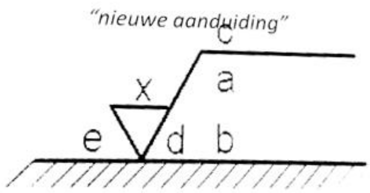
- **On what project are you now working on?**
  I am busy with a project about the process of the checking steps of the products.

Quality manager:

- **Can we know the Rz and Rm with roughness meter?**
  No, this is not possible. It only measures the Ra.

- **How to measure the depth of the tool marks? Because you have mountains and valleys. Because you cannot see it with your bare eye.**
  There is no way to measure the depth of the tool marks or scratches.
- **What is a C-surface?**
  C-surface is used to indicate a vacuum surface. This means that the machining tracks must always be in the direction of the vacuum groove or concentric of the surface.

- **Can you explain us how the surface roughness looks like on drawing?**



a=the roughness parameter (without indication the Ra-value is always meant)
b=a (if necessary) second parameter
c=kind of machining for example milling, or turning
d=the direction of the machining tracks for example radially, perpendicular to the projection plane or concentric.
e=the place for the machining allowance in mm

Inspector:

- **How do you inspect a vacuum surface?**
  - I receive a document with the products that I need to inspect.
  - I inspect the vacuum surface visual. For some products this can be by eye with the help of a flashlight or by microscope. So first I inspect if there are no damages/spots on the product. If the product is a vacuum chamber then I have to check if there on the inside are no damages/spots. If the product is a part that is assembled in a vacuum chamber then I have to check on the whole product of there are no damages/spots.
  - If I find damages/spots I contact the QA (factory engineer). He will considerate it with the technician to determine what actions will be taken to fix the damages/spots

- If there are spots on the product which are determined that those are liquid spots, then these can be removed with IPA or Demi water
- I check the product also on the presence of dirt and oil. This is especially for (blind) mortises and cut-away. The thread in the mortises should be dry and free of oil. Blind mortises must be especially at the bottom clean and dry. With cut-away I check especially the corners.
- If I find dirt and/or oil then I clean the product with the help of brushes, if necessary with IPA to dissolve the dirt. If it is persistent dirt that cannot be removed by the above method then I contact the QA (factory engineer) to adjust the process together.
- IPA: needed to remove spots from the components
- Ethanol: needed to clean O-rings (Viton)
- Demi water: needed to remove spots from the components
- Black-light (UV): UV lamp is used to make the spots and dust that are present on the components visible.

- **Can we measure a scratch?**
  Yes, you can use a kind of paste. You can put this paste on the scratch and the paste will harden after a minute or so. After it is hardened you can pull out this paste and put this under a microscope in order to measure a scratch.

<u>**Craftsmen:**</u>

- **Why do you polish the vacuum surface?**
  In order to make a good vacuum seal, vacuum surfaces need to be polished so that the machining grooves are in line with the grooves (O-ring).

- **How is the vacuum surface related to the speed of the milling machine?**
  The vacuum surface depends on the milling speed. If it's milled slowly, the surface is smoother.

- **On which products are the most problems?**
  Most problems are on the MMF products

- **From what materials do MMF products consist of?**
  Most of the parts of the MMF are stainless steel, only the underside of the product is from aluminum.

- **We want to use roughness of 0.2, 0.8 and 1.4. What roughness do you recommend to use for our tests?**
  0.2 is too smooth and will probably leak. A roughness of 0.4 is recommended.

- **Is it possible to make a surface rougher instead of smoother with sandpaper or scotch Brite?**
  With sandpaper you can make the surface even more rougher and with scotch brite you finish (make it smoother) the roughness of the vacuum surface

- **Which roughness is used most for the products?**
  Most of the products are milled and turned with a roughness of 0.8. So, the suggestion is to at least use a roughness of 0.8 in your tests.

- **The tool marks that are still on the vacuum surface after its polished, does this cause a leaking?**
  Small tool marks do not make the product leaking but the quality department is still rejecting it because they are afraid of leakings.

- **Does it happen that sometimes you damage the product a bit?**
  Sometimes if we polish the vacuum surface with grain paper we often make a small wipe with the sandpaper. The quality department is rejecting that because they are afraid of leaking.

- **Which grain paper do you use to polish aluminum products?**
  When you have to polish aluminum you start with sandpaper grain 180 because it is softer than stainless steel. After that for the required roughness you use sandpaper grain 240.

- **Which sandpaper do you use to polish stainless steel products?**
  With stainless steel products we start with sandpaper grain 100 or 120. After that for the required roughness you use sandpaper grain 180-240

- **What is the difference between a scratch and a tool mark and is this clearly visible?**
  The difference between the tool marks and the scratches are really big, the scratch is much deeper and more vulnerable for leakings than the tool traces.

- **What do you actually do if you have to polish the vacuum surface?**
  With the sandpaper you polish the vacuum surface from centric surface into straight lines surface. And after that with scotchbrite you polish the surface to make it smoother for the required roughness.

- **Is it possible in this company to measure the roughness?**
  Yes it is. There is a device to measure the roughness but when you measure the roughness, the device makes a scratch, and then you have to polish that part again.

- **What happens after you're done with polishing the vacuum surface?**
  The inspector comes to inspect the vacuum surface on scratches/defaults. If he finds a default or a scratch, it has to be polished again.

- **Does it occur a lot that the vacuum surface needs to be polished again?**
  Yes this happens a lot. The inspector wants to have a perfect surface when sometimes we think it is not necessary because we think it is not leaking.

- **How do you think scratches occur in this company?**
  At the other department they are not really aware of the cause of a scratch on a vacuum surface. So they are not careful with the product. They make for example scratches with their nail. Or letting tools drop on the surface. Also after machining there are burrs on the vacuum surface and when they turn the product, the burrs will rub over the vacuum surface. This makes scratches. In the past the way of milling occurred scratches. Now they have a different method of milling where it does not make scratches. Also people who do not work a long time here are not aware of how much time and work it costs to rework the product.

TABLE OF TABLES

TABLE OF ILLUSTRATIONS

Appendix