Gasket Quality Control at Alfa Laval

Implementation of new measuring techniques

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Foreword

In this master thesis, all the work presented henceforth was conducted and reported in cooperation with Alfa Laval Lund AB and MLT Maskin & Laser Teknik AB Gothenburg. The department that holds the stake in the thesis is Alfa Laval's EPD team, BU GPHE - R&D & PHE - LA Quality Management department.

We want to express our gratitude towards Alfa Laval, MLT Maskin & Laser Teknik AB, and everyone who has been involved in this master thesis. A special thanks to Ashok Raj in the IT department at Alfa Laval for recommending us for the position. We want to express our sincere appreciation and gratitude towards our supervisors Helen Gustafsson and Martin Andersson from the EPD team, BU GPHE - R&D at Alfa Laval Lund AB, for providing all the resources and guiding us towards success during our journey. The experience of working with them will be memorable and a journey that we will cherish. The learning experience gained by working under them has been immeasurable.

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We are very grateful for the support from our parents and family, who have been the backbone throughout our journey. The support and the encouragement from them to pursue our dreams have brought us this far. We would like to thank our friends and classmates for making this journey very memorable. The advice and suggestions throughout the master's degree have had an impact.

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Abstract

The heat exchanger is a system where heat gets transferred between oil and other forms of lubricants from one system to another without mixing through conduction. The hot liquid is cooled by passing through the heat exchangers plates, which act as a wall between them. When hot liquid is passed between the plates, the following plates are passed with cold liquid, which carries the heat away from the system where cold liquid becomes hot and vice versa. Plates are connected close to each other, where the gasket acts as a seal separating the different liquids from mixing. The heat exchanger plates are sealed with frame from both the side tightened with bolts as per requirement. So, the gasket plays a critical role in differentiating between the two fluids. The design and manufacturing of the gasket thus become a crucial part that must be produced so that there is no variation from the actual 2D drawing and 3D model.

The main aim of the thesis is to investigate different techniques in determining the cross-section parameters of the gasket in a non-destructive manner. The current metrological methods at Alfa Laval have no emphasis on cross-section measurement. In few cases, there has been investigation performed by destructive methods. We have used Laser line Triangulation (LLT), Handheld 3D scanning for determining the cross-section parameters. We will be comparing the LLT method and Handheld 3D scanners. The data obtained by this process have been validated by using a Light optical microscope (LOM).

A deep investigation of these technologies performs a comparative study of different technologies. The Multi-Criteria Decision Making (MCDM) process is used to choose the best method for data extraction, ease of use, training, cost. We have used Analytical Hierarchy Process (AHP) to model the decision-making process.

Keywords: Quality-control, Gasketed plate heat exchangers (GPHE), Cross-section measurement, Laser line triangulation (LLT), Blue laser, Handheld 3D scanning, MCDM, AHP.

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1 Introduction

In this chapter, a short introduction of Alfa Laval, Lund AB will be followed by a brief description of the master thesis. The introduction begins with a background of the thesis topic, which helps the reader understand why Alfa Laval is interested in improving how gaskets are measured. A general introduction of Alfa Laval AB's company, purpose and research question, and challenges faced during the thesis. This chapter will then conclude with an outline of the thesis to help readers understand the basic structure of the thesis.

1.1 Background

The quality control in gaskets used for heat exchangers is one of the main concerns of the topic. The issue in terms of the measurement of the gasket dimensions is said to be challenging. Quality control is the process of maintaining a standard in the product by measuring the test sample according to the specification and ensuring the product is within the geometrical tolerances. It is considered very important for the gaskets going into the gasket plate assembly as it can completely cut down the leakage from the heat exchangers.

The growth of energy consumption and the increase of carbon footprints in the environment have led to an efficient way of transferring heat between one medium to another [1]. Heat Exchanger network is one of the cost-effective ways to recover the heat generated. *The **Heat Exchanger*** is an apparatus that helps in facilitating the heat transfer between two or more fluids flowing at different temperatures and are in thermal contact [2][3]. The mode of heat transfer can be conduction, convection, or radiation based on the type of heat exchangers. If the fluid does not evaporate or condense, it will experience a temperature change, i.e., one fluid raises in temperature, and the other fluid decreases temperature [4]. During the heat exchange process, there is sometimes a change in the liquid phase [3]. The fluids, in most cases, are separated by an exchanging surface with high heat conducting properties, which helps make sure that the liquids do not mix or leak from the surface [5]. They have been used extensively in various heat, ventilation, and air conditioning (HVAC) industries like the power plant, air preheater, economizer, heater, air conditioner, radiator, refrigeration system, automobile, chemical processing plants, etc. [2][3][4].

We shall be categorizing the heat exchangers based on the construction as the thesis aims at heat exchangers involved in the specific type of construction.

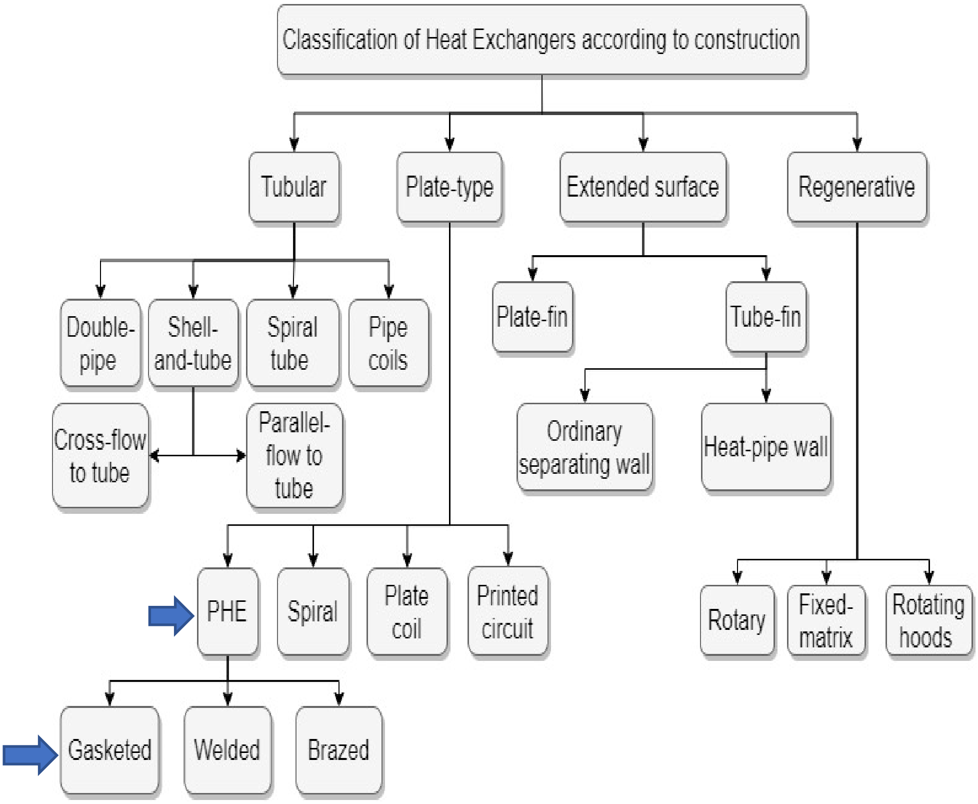


Figure 1.1 Classification of Heat Exchangers based on Construction [5]

Gasket plate heat exchangers(GPHE) are the product that will be investigated for the thesis work. The basic working principle of the GHPE is the thin corrugated plates are arranged as a compact network of plates next to each other [6], as shown in below Figure 1.2. The gaskets are held on the plate's edges to help set a boundary for the fluid flow and avoid leakage from the plate network. The network of plates has a frame plate connected to one of the corners with a circular hole on the corners for the inlet and exit valve for the fluid flow. The movable cover, support column, guiding bar, and tightening bolts help in compressing the complete setup and forming a seal within the rigid frame at the corners of the plate pack creates a parallel flow channel where fluid one travels through odd-numbered plates and fluid two travels via the even number plates [6].

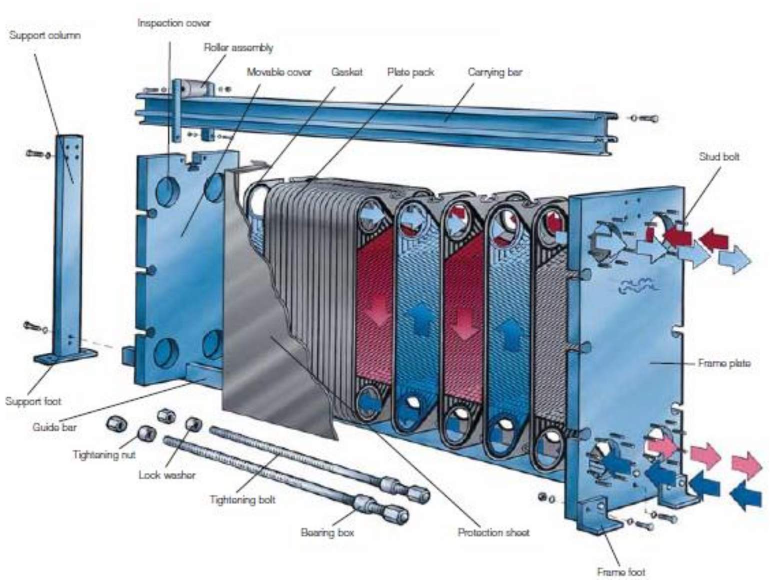


Figure 1.2 Gasket Plate heat exchangers construction by Alfa Laval [6].

Pressure drop is one of the essential factors for sizing and rating the heat exchangers [7]. The ease of adding more plates and easier removal of the plates for inspection make this system of heat exchangers one of the simpler systems in terms of maintenance.

The gaskets are mounted on the plates by:

- Glued gaskets
- Clip-on gaskets
- Snap-on gaskets

Accuracy and faster quality control methods are necessary to favor all the components to overcome the challenges associated with time and cost. The iron triangle relation between time, price, and quality justify their mutual connection [8]. The iron triangle is the method to assist project managers in assessing and balancing the competing demands of expense, time, and quality in their projects.

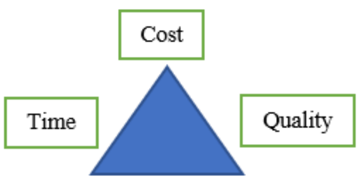


Figure 1.3 Iron triangle diagram

The concept of the iron triangle is they are interdependent on the three constraints. For instance, if any increase in quality would result in a rise in cost and time. The three sides are in constant contact and restructure accordingly. Hence, the name iron triangle. The manufactured gasket must be close to the design as possible and be compared with the 3D model or 2D cross-section drawing. Accuracy in measuring would reduce the amount of rework or scraping of the components produced, again referred to as an iron triangle diagram. Following the high-quality standard and methods in terms of instruments is therefore considered very important.

Research and implementation of cutting-edge technology can help the company with better quality assurance practices. One of them is the nuclear power plant, where high-quality assurance is significant in achieving the pre-eminent result.

To resolve the problem, we will be following deep research in modern measuring instruments and scanning devices and shortlist a few of the methods suitable for solving the problem. Based on the various techniques and other factors mentioned in the other sections, we shall rank the different processes. Based on the ranking, we shall be validating the results and select the best technique to solve the problem.

The outcome of the investigation to solve the current problem:

- Produce highly accurate and reliable results as the research will involve the validation and check for repeatability of the products.
- The process will be ranked in terms of user-friendliness and, therefore, making the process more convenient.
- Check the dimensions of the cross-section of the gaskets without performing destructive tests.
- The complete process can consume less time when compared to the traditional method.

1.2 Formulating Research question

The main challenge of the thesis would be to present methods for control of dimensions of the cross-sections. Current methods used by the company are slow and sometimes miss the goal. With this master thesis, we investigate to find faster and more accurate quality control of gasket dimensions. We focus on the research topic:

What is the most feasible method for measuring the gasket cross-section parameters used in the heat exchanger?

1.3 Introduction to Alfa Laval

Alfa Laval AB, headquartered in Lund, is one of the world leaders in manufacturing heat transfer solutions, separators, and filters. A heavy machinery industry that has significant applications in the Marine, energy, and food industry. The company is spread globally, including countries like Denmark, Italy, India, China, the United States, Japan, etc. According to stats of 2016, the global workforce is over 17,000 employees and global revenue of $4,715.96 million.

The thesis is performed under the department of R&D for Gasket Plate Heat Exchanger in Existing product development (GPHE EPD). The department is involved in creating innovative technology and concepts to fulfill future industry growth needs. The EPD department is continuously interested in the improvements, tests, and verifications process. The department is directly responsible for any changes in the technical information in terms of Design, Material, function, etc. The current thesis helps in improving the methods for measuring in the department of gasket quality control. The association between the EPD and the Quality department will remain the critical stakeholders for the results obtained from the thesis.

1.4 Delimitation

When it comes to quality, some of the aspects that are not focused on during the course of this thesis are

- Manufacturing process and techniques.
- Design and materials of the gaskets.
- Dimension measurement like length, distortion, flatness, leakage factors, mechanical properties of gaskets, etc.
- Change in the gasket design.

1.5 Outline of the Thesis

In this thesis work, we initially start with the introduction where we give information regarding the heat exchanges and gasketed plate heat exchangers (GPHE) and introduce Alfa Laval and talk about the delimitation of the thesis. Then we give information regarding the critical elements of the thesis in the theoretical background. We then move on to the research methodology, where we discuss how we shall perform the thesis. We then investigate the current quality control method in the next section and determine the pros and cons of the current quality control method. Then we follow it up with the new technique, which we investigate to measure the cross-section. We provide some key observations and establish a SWOT analysis of the techniques. In the next part, we validate the obtained data and then use AHP to rank the best method and select the method to set it up in Alfa Laval. We discuss the result and conclude the thesis with the future scope and ways to implement the process.

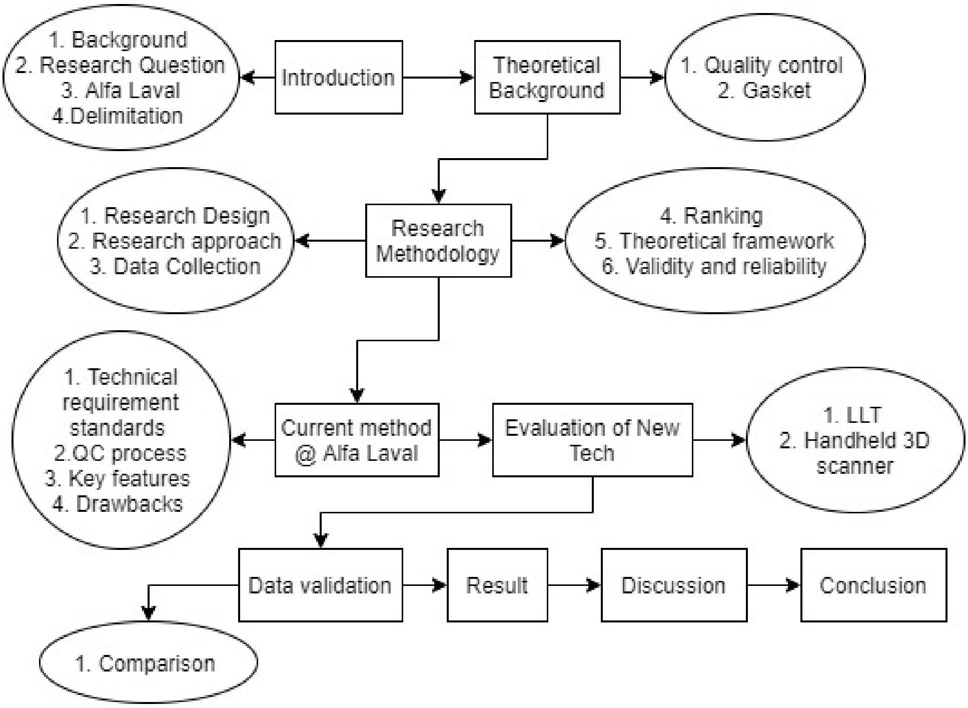


Figure 1.4 Outline of thesis

2 Theoretical Overview

In this section, we shall discuss in detail the background. Also, we will provide the readers a piece of in-depth information regarding the terminologies that have been used quite often in the further sections. This information can also help the readers understand the importance of the research topic.

2.1 Quality Control

"Cost is more important than quality, but the quality is the best way to reduce cost." - Genichi Taguchi

Quality philosophy has traditionally been centered on creating and implementing a business culture that emphasizes customer attention, continuous improvement, and data-driven decision-making [9]. A high-quality product provides a sustained competitive advantage, and to achieve this goal. Companies must excel in the skilled application of tools and techniques [10]. "Quality is conformance to requirements or specification" – Crosby (page 8, 1979) [11]. The three most critical aspects of quality can be summarized into [11]:

- **Quality of design**
  The product must be designed to meet the least minimal needs of the customer.
- **Quality of conformance**
  How well the product conforms to the specification of the design.
- **Quality of performance**
  How well the product performs when it is used and provides customer satisfaction.

There are, however, other ways to define quality, and according to [12], quality can be defined as:

- Quality is fitness to use.
- Quality is inversely proportional to variability

Finally, it is the customer that decides if the product has reached the expectations. The customer's loyalty is directly affected by the quality of the service provided, which will provide customer satisfaction [13]. Focusing on the customers' needs, competitor's activities, and resources can lead to better customer value [14]. So customer satisfaction is godly satisfaction.

To achieve the best quality of products and customer satisfaction, the vision for the policies and goals needs to be aligned with results. This can be done through managerial processes.

Three managerial processes that are extensively used in quality are [15]:

- Quality planning
- Quality control
- Quality improvement

Quality control (QC) is the set of procedures set by the manufacturers to ensure the products produced will comply with the standards set by customers. Quality control is a managerial process to provide stability and attain goals set by an organization [15]. In order to maintain stability, the QC process evaluates the actual performance, compares it with the goals, and takes necessary actions[15]. Variability is one of the main reasons QC is used to improve the quality of products [12]. These variations can be known with feedback on products. There is always a small amount of deviation in each of the products produced. Customers will always see the variations in the products rather than the mean of the product. Sources of variation should be studied and eliminated. Quality is inversely proportional to variability[12]. Waste is often a result of variability. Less variability will reduce money spent on rework in critical parts and save effort, time, and energy [12]. So, to maintain stability, quality process control consists of three basic steps [15]

- Evaluate the current process with goals
- Compare the current process with goals
- Take actions to make it right

These goals may be set for the long or short term. The benefits of quality control will not be realized in a short period. Since the data available in the short term will be limited, practitioners cannot predict the trend using this available information. These plans will yield a reasonable rate of returns in the long term perspective for the goals set by the organization [11].

To improve quality and process improvements, a set of procedures should be followed and should be practiced. These procedures should identify and solve the root cause of the problem and ensure a permanent solution with a long-term goal because of the problem. DMAIC is one such procedure. All the steps in DMAIC are often associated with six-sigma procedures. The acronym for DMAIC stands for five steps in sequence - Design, Measure, Analyze, Improve, Control. This effectively focuses on creative thinking and brings an efficient method to overcome the problem [12].

2.1.1 Problem-solving tools

To meet customer expectations and make the process more stable, the variability of the product around nominal dimensions should be minimized. Statistical quality control is a collection of problem-solving tools used to improve quality, quality planning, and reduce variability [15]. They are easy to use, have substantial implications, and can be tried on any process [12]. There are seven primary tools. They are called magnificent seven.

- **Control charts**

Control charts trace the reasons for the variations. They have their contribution in predicting the trends. With this trend, practitioners can monitor the process and determine when action is required before the limitations are reached and quality is compromised. The control chart is the graphical display of the characteristics that have been measured. In this chart, the center line represents the average value of characteristics. The upper control limit and lower control limit are the tolerance given to the dimension [11]. These processes provide clear information on the dimensions of the products, which may not comply with the standards set by the customer. After some investigations, the sources for these variations are systematically eliminated. Hence, each product's tolerance limits give the nominal value a higher and lower limit [12].

- **Histogram**

The histogram is similar to a bar chart that groups numerical data into bins, cells, or intervals [12]. Histogram groups the data from a range of data given and plots them with no gaps between the bars. Bins should be of equal width to visualize the data clearly [11]. The capability of a process can be estimated using a histogram, which provides a quick visual representation of the process performance [12].

- **Check sheets**

A check sheet is mainly used to collect data about the historical or current operating data about the process under investigation. Check sheets are often used in the early stages of the improvement process and detect non-conformance and the source of the defect [15]. Check sheets are designed for specific purposes. Each sheet should have clear information on the type of data collected, defect lists, provision to tabulate the no. of defects, part information, the analyst name, date, etc. This helps in finding all the possible defects which have occurred in the brief period. Check sheets are the most common measure step in the DMAIC [12].

- **Pareto chart**

A Pareto chart is a frequency distribution that arranges the data according to the category in which it is designed. They are measure and analyze steps in DMAIC. In this chart, the highest possible defects will be represented first. Then the following defects will be followed. Hence this gives a decreasing curve for the defects. Users can quickly identify the frequently occurring defects [12].

- **Cause and effect diagram**

Also known as the fishbone diagram or Ishikawa diagram. A cause and effect diagram is best suited to identify the potential root cause of the problem. This falls to analyze and improve part of DMAIC [12]. When examining a defect, most likely problems will be listed out. Subcategories for these main problems will be listed below them.

- **Defect concentration diagram**

It is a picture showing all the views of the product. Various types of defects will be marked on the picture, and analysis will occur to see if the location of the defect on the product has all the information for the potential cause of the defect. A defect concentration diagram helps analyze part of DMAIC [12].

- **Scatter diagram**

A Scatter diagram helps identify the correlation between the two variables. Data of the two variables are collected and are plotted against each other on a different axis. The formation of the points on the chart will speak about the relation between them [12].

2.1.2 Sampling

In quality control, it is not feasible to get all the products in the population due to restrictions in time, cost, and methods used for checking. Instead of measuring all samples in lots, few samples from a population are inspected to obtain process or product data [11]. Based on the data obtained, a decision is made whether to accept or reject the lot. Accepted lot is sent to the production, and rejected ones are sent back to the supplier.

Sampling is one of the vital aspects of quality assurance. It will result in inspection and decision-making regarding the product [12]. This aspect of quality assurance is primarily done for receiving or incoming products from the supplier. Sampling will also determine where the source of product and measurement variability are present [15].

There are three approaches to lot sentencing:

- Accept with no inspection
- 100% inspection
- Acceptance sampling

Acceptance sampling plans do not provide any quality control. They give the decision on whether the lot is accepted or rejected. It provides output if the sample or process conforms to the requirements of the design. Acceptance sampling can be reduced if the supplier quality can be relied upon, thus reducing costs [15]. It can be a midway between no inspection and 100% inspection. Acceptance sampling is practical when testing is destructive, cost and time for 100% inspection is high when 100% inspection is not technologically feasible etc. There are different ways to classify acceptance-sampling plans [12].

- **Single-sampling plan**
  One sample from n units is taken at random for a lot, and a decision is made based on the data obtained by the sample.
- **Double sampling plan**
  A sample is taken, and the decision is made to accept, reject or take a second sample. If a second sample is taken, then the decision will be based on both the samples taken into consideration.
- **Multiple-sampling plan**
  This is an extension of the double-sampling plan, in which more than two samples are taken into consideration for deciding regarding the disposition of the lot.

A few essential considerations need to be followed to implement the acceptance sampling plan [12] effectively.

- A lot should be homogenous.
- Larger lots are preferred over smaller lots.
- A lot should have a suitable material handling system, so it makes it relatively easy for inspection.

2.1.3 Accuracy and precision

Accuracy is the measure of how close the value is to the standard value of the measurement. Closer the values to the standard, then the system is more accurate. Precision is how often the value repeats itself. They might differ from each other due to random errors. The system should always be accurate and precise. With these two terms, we can define repeatability and reproducibility. Reproducibility produces the same results when different operators use the same gauge for measurement. Repeatability is how often the gauge repeats itself [12].

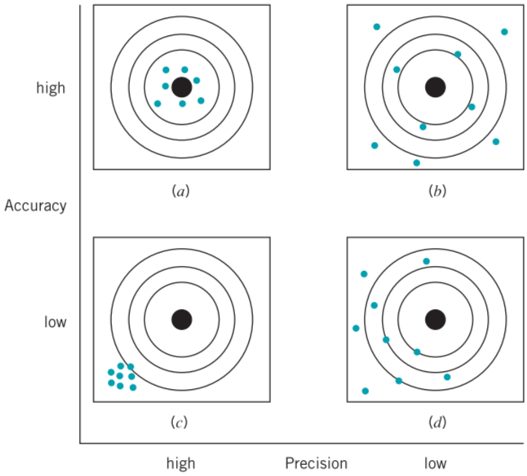


Figure 2.1 Concept of accuracy and precision [12]

The gauge (a) is accurate and precise, the gauge (b) is accurate but not precise, the gauge (c) is not accurate but precise, the gauge (d) is either accurate or precise.

2.2 Gaskets

Gaskets are a sealing material that can be compressed between two stationary flanges to create a static seal and act as a boundary to avoid mixing and leakage from the system to withstand temperature and pressure [16][17]. Figure 2.2 shows how that is held between two flanges by either compression or encapsulation to maintain the sealing effect between two surfaces.

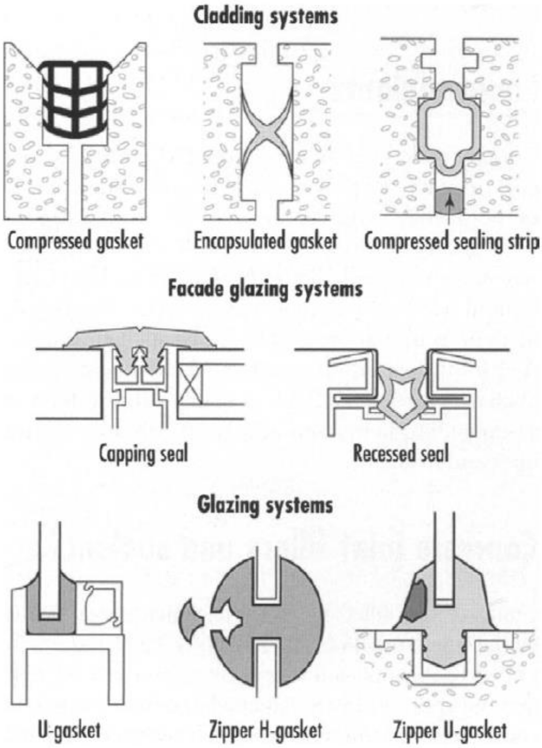


Figure 2.2 Types of the sealing of the gaskets based on the flange shape [18]

The type of gaskets are chosen based on the criteria like temperature, pressure in the system, corrosive nature of the materials, compressibility and creep resistance, and ability to erode with the mating surface of the flange [17]. The gaskets can be classified (shown in Figure 2.3) based on the type of materials the gaskets are made. The materials are primarily dependent on the priority within the process. The gasket materials can be altered based on the application and the nature of the fluids and the system. This gasket must tolerate destructive properties that are exerted by the medium in the system[17]. A metallic gasket is generally used for high-temperature applications, and non-metallic gaskets are used in a highly corrosive environment [17]. The most commonly used gaskets are polymer gaskets in various industries due to their incredible corrosion resistance and good sealing performance [17].

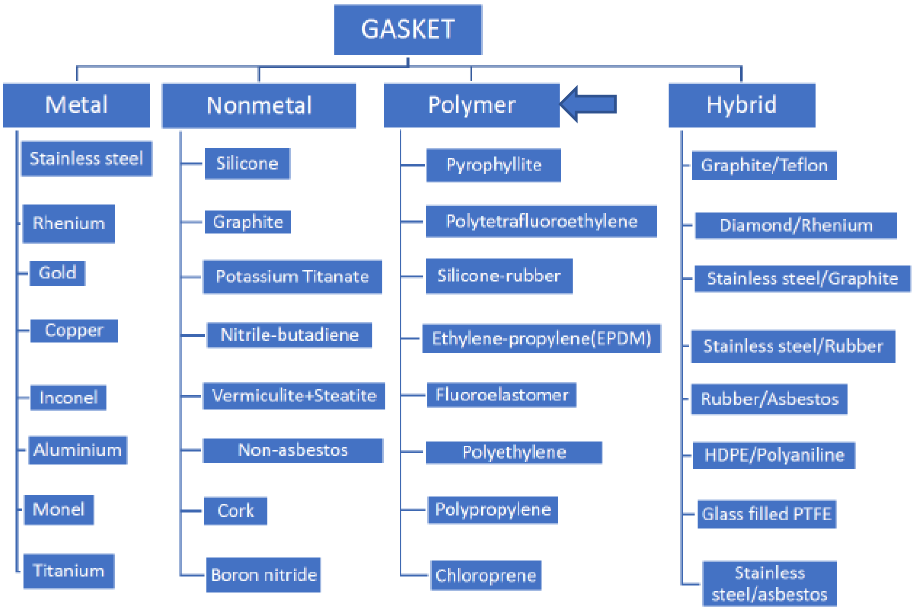


Figure 2.3 Classification of gasket materials [17]

The Hybrid gaskets are used by altering the material based on the property that must be enhanced [17]. The metallic and non-metallic materials can be combined to produce a combination of excellent sealing performance and strength of metallic materials [17].

In our thesis, we will dig deeper into the polymer gaskets used in Alfa Laval. Based on the customers' requirements of heat exchangers, the gasket material can vary for different applications. In the upcoming sections, we will be dealing with the features of gaskets, specifically in terms of heat exchangers and the manufacturing of the current gaskets, which can provide information regarding the techniques that can help relate to the issues that can occur within the gaskets during the quality control.

2.2.1 Polymer Gaskets

In the above section, we saw various materials that are used for gasket manufacturing. In this sub-section, we will give a detailed explanation of the materials used in Alfa Laval. We will also discuss why selecting the suitable material is vital for various applications.

The base material used in terms of the gasket in GPHE's are polymers, and the polymers are further classified into other organic compounds shown in Figure 2.3 in previous section 2.2.

Polymers are molecules comprising molecules with long sequences of one or more atoms or groups of atoms linked by a covalent bond [19]. Small molecules that link with each other to form polymers are called monomers [20]. The chemical process in which monomers react and polymers are achieved is called polymerization [19][20]. Polymeric materials tend to have unique properties based on the type of molecules being bonded and how they are bonded with each other [21]. Some polymers bend and stretch like rubbers and polyesters, and some are hard and tough like glass, etc., [21].

In gasket applications, the polymer that can bend and stretch like Elastomers or rubbers are used. Elastomers are primarily used in terms of sealing as they have features such as:

- Naturally resilient materials allow them to squeeze into joints and flanges under loading conditions [22].
- Possesses physical properties such as tensile strength, elongation, etc. [22].
- Elastomers can resist temperature, chemical reactions, aging, and seals fluids like oil and other chemical fluids with a longer life and reduced maintenance [22].
- In some instances, Elastomers are food-grade, and some materials have approvals from FDA and EFSA, etc. [22].

The commonly used Elastomer's type materials for gaskets in the industries are:

- Ethylene-Propylene Rubbers (EPDM)
- Nitrile Rubber (NBR)
- Fluorocarbon Rubber (FKM)

3 Research methodology

Research is defined by Higher Education Funding Council for England (HEFCE) *as an "original investigation undertaken in order to gain knowledge and understanding"*([33], p.16, 2009). "*Methodology is the collection of methods or rules by which a particular piece of research is undertaken*" ([34], p.386-387, 2005). This section illustrates the research methodology used in this thesis work to answer the questions of our study. This section starts by giving a detailed overview of the research method followed by research design, method of analysis, and finally concluding by validity and reliability of the data.

3.1 Research Design

According to Bryman and Bell, the research design is a framework for collecting and analyzing data [35]. Research design is a framework that directs the execution of a research method and the following data analysis. This plan includes how the research is structured and describes the plan for measuring, collecting, and analyzing the data. There are five different research designs[35]: experimental design, cross-sectional design, case study design, longitudinal design, and comparative design. We have used comparative design to choose between the technologies because our research question is to select the most appropriate technology for gasket quality control. Quantitative research tends to emphasize more on data collection and analysis rather than conducting literature studies. Once the data is obtained, comparisons can shed light on the influence of each technology characteristic, which will eventually lead to the research question of the work. Once the data is obtained, comparisons can be made to shed light on the influence of each technology characteristic, which will eventually lead to the research question of the work. This will also provide a more holistic and in-depth exploration of the parameters.

3.2 Research Approach

In this work, quantitative research is used to collect the data, and further comparative research is used to analyze the data from the existing method and the laser triangulation techniques. Quantitative research relies on the collection and analysis of numerical data to come up with conclusions based on it [36]. It instructs the user to apply mathematical, computing, and statistical approaches to construct a cause and effect link between the variables [37]. This type of research is also known as empirical research because it can be measured accurately and precisely. Objective approach and deductive reasoning are being used in this method.

The quantitative research method is best suited for this thesis work since the data needed for further analysis is obtained by experimentation via laser techniques. Even the data for an existing method is measured using gauges and measurement scales. This method allows the generalization of results to larger sampling sizes[37]. Data analysis is done by using raw data obtained by experimentation and finally represented using statistical curves. The general steps involved in conducting any quantitative research are listed below[36].

- Identification of research problem
- Research questions and hypotheses should be clearly defined
- Review and development of literature
- Development of research plan
- Collection of data
- Analysis of data
- Development of conclusions and recommendations

A comparative study is one of the non-experimental research design approaches to conduct quantitative research[36]. The unit of comparison and sampling of the contexts should be analyzed closely. If the validity and reliability of data for each other processes can be shown, correlations can be compared between measured and other variables within each process[38]. This study would be best suited for our thesis since the aim will be to select the best suitable technology to improve the quality control of the gasket. This is achievable only by comparing the technologies with each and listing out the pros and cons of the technology.

Steps in conducting a comparative research study are shown below[36]:

- Identification of the topic/problem to be studied
- Identification and selection of participants
- Specification of design and procedures for data collection
- Collection of data
- Analysis of data
- Answering research question

The analysis will be conducted from the detailed study of the technology and the experimental data obtained. Critical parameters for cross-section measurement that cannot be measured using the current procedure will be measured, and results will be compared with the laser technologies. The data for the critical parameters listed in earlier sections will be obtained by experimentation, and the flow of solution is provided with the help of a theoretical framework. Finally, we conclude by suggesting better technology to make the quality control process more effective and efficient.

3.3 Data Collection

Data collection is a practical activity that must be completed within the restrictions of time, space, and resources[39]. It is also a means to collect relevant information which will be used in answering our research questions. Data can be classified into primary and secondary data. Primary data is obtained by the researcher for their research question to be answered. Data is obtained by experiments, observations, questionnaires, and interviews[39].

Journals and literature studies obtain secondary data and articles to understand better the research problem and technologies being used[39]. To obtain primary data, quantitative research is employed. For the current manual process in the QC department, data is collected manually using measurement scales and tabulated for further comparison.

The data is collected by using the laser line triangulation method. The software scanCONTROL, developed by the makers of the gadget MICRO-EPSILON, is used to acquire data for this method. The output and outcomes will be presented in a graphical format that can be easily interpreted and statistically plotted.

Using hand scanner laser technology, the gasket is scanned using a hand scanner that works on laser triangulation. Using this, the gasket is scanned in the required section, and a 3D model of the gasket is obtained using software called VXelements - a 3D software platform. This model is imported to model analysis software called “Polyworks,” which further performs the required data extraction from the model. The results obtained can be formulated into a report using inbuilt options in the software. Gaskets are sent to a tool factory for further analysis, where the gaskets are analyzed using a photographic scanning device.

3.4 Ranking and Selection method for the best alternative

In this section, Multi-Criteria Decision-Making methods (MCDM) technique is used to select the best alternative for the existing method among the technologies used. The authors have used Analytical Hierarchy Process (AHP) to achieve this objective.

AHP is carried out by decomposing the goal into the different hierarchical structures to determine the pairwise comparison of the criteria once the weight coefficient of different criteria is calculated, finally giving the rank based on the results.

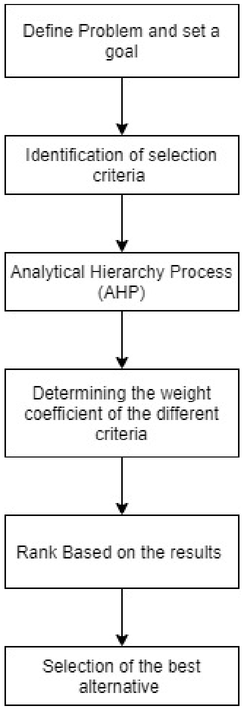


Figure 3.1 Flowchart of the AHP

AHP was developed by T. L. Saaty [40]. It is one of the MCDM techniques. This process compares the theory of measurement pairwise, which creates a correlation between the criteria. It is helpful to obtain the weights of different criteria and compare the relative importance of alternatives to the subject's criteria. The process can decompose a complex problem into a hierarchy of subproblems which can be solved individually[41].

The AHP method stated by Saaty is based on axioms. Reciprocal axiom says that matrix constructed will be paired reciprocal, i.e., if an object is ten times larger than the other one, another object is 1/10 times smaller than the object. Dependency axiom states comparison is conceded with a group of elements from one level concerning the elements in a higher level, i.e., lower-level comparison depends on the higher-level element. Expectation axiom says if any change in the hierarchy structure requires re-calculation of the priorities in the new hierarchy.

Homogeneity axiom, i.e., comparison between the elements, is possible only when they are comparable. For example, the ant's weight cannot be compared with the weight of the whale [40][42]. These axioms also form the basis of our matrix formation. The basic hierarchy structure for AHP used in this combination is shown below in Figure 3.2.

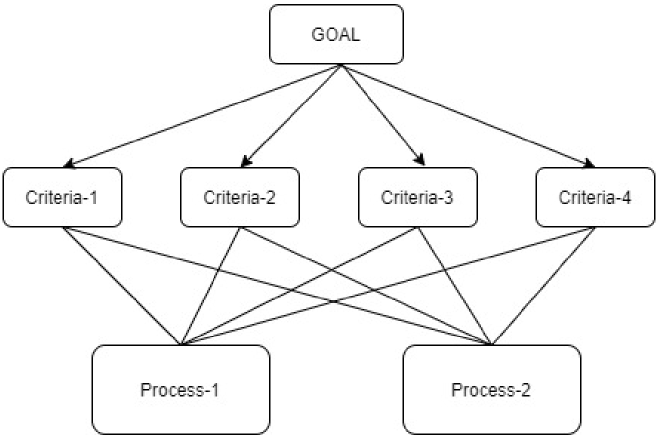


Figure 3.2 AHP hierarchical structure

The criteria in level-2 in Figure 3.2 are made according to the priorities set to achieve the goal. In AHP, weighing each criterion with another is followed according to the fundamental scale Table 1 shown below[40].

Table 1 Scale for the relative importance

The intensity of the absolute scale	Definition	Discussion
1	Equal importance	Two criteria contribute equally
3	Moderate importance	When one criterion is more important than other
5	Strong importance	When one criterion is more important than other
7	Very strong importance	When one criterion dominates the other criteria
9	Extreme importance	When one criterion has the highest possible order over the other
2,4,6,8	Intermediate values	In case of compromise between them.

The selected criteria based on the application will be compared with each other. The intensity scale will be given according to Table 1. These criteria will be written in a matrix form by listing the same criteria in the x and y-axis. When the same criteria are compared with each other, it is given the importance of scale 1. Accordingly, if a relatively higher criterion is compared with lower importance criteria, Table 1 gives the importance.

Steps followed in AHP for calculating the weights of the criteria are

Step.1 Determine the goal and list the criteria.

Step.2 Determine the pairwise comparison matrix.

Comparison is conducted by using the relative importance of the criteria.

$$W = \left[\frac{w_i}{w_j}\right] = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix} [42]$$

Where i, j= 1, 2, …n
w = vector of current weights of alternative

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} [42]$$

a_{ij}= preference weight of a_i obtained by comparison with a_j
A= comparison matrix

Step.3 Calculate the normalized pairwise comparison matrix and determine the criteria weight.

Pairwise comparison matrix A is normalized, and then weights are computed.

Normalization matrix

$$a_{ij}^* = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} [42]$$

For all j= 1, 2, …n

Weight calculation

$$W_i = \frac{\sum_{i=1}^{n} a_{ij}^*}{n} [42]$$

For all j= 1, 2, …n

Step.4 Check for consistency of the matrix.

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \text{ [42]}$$

CI = Consistency Index

λ_{max}= referencing index

n = no. of alternatives

$$CR = \frac{CI}{RI} \text{ [42]}$$

CR= consistency ratio

RI = random consistency index

Table 2 Random consistency index (RI)

n	1	2	3	4	5	6	7	8	9	10
Random consistency index (R.I.)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

We get random consistency index (RI) from above Table 2. The obtained C. I should be 0.10 or less. If it is not less than 0.10, the problem should be studied and revised.

3.5 Theoretical framework

This section will contain how the authors have used the analytical model for comparison by taking Bereday's model as inspiration. This section will also explain the methodology followed to achieve the research question.

3.5.1 Bereday's Analytical Model

As shown in Figure 3.3 below, this model consists of four steps for undertaking comparative studies. They are as follows: Description, Interpretation, Juxtaposition, and comparison. A short description of each case is described separately, followed by an interpretation of each case. The juxtaposition of cases that belong to the same type will be examined according to the research question. Further comparison takes place on the data to be compared to reach our goal of the research question. Since this model gives out the differences and similarities by comparing different technology parameters, the authors chose this model as the framework for comparison.

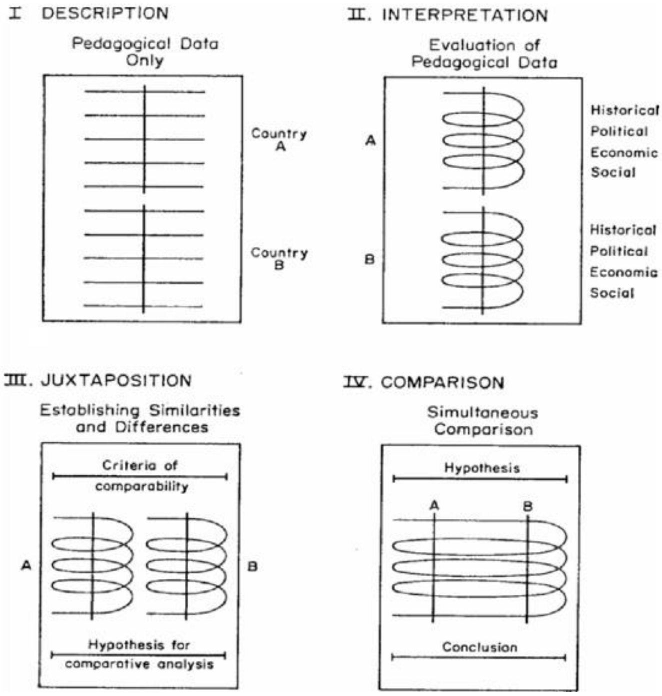


Figure 3.3 Bereday's Model for Undertaking Comparative studies[43]
Reprinted from Comparative Education Research: Approaches and Methods p.86
Edited by Mark Bray, Bob Adamson and Mark Mason, 2007

The data collection will occur quantitatively, followed by comparisons with the gaskets at different sections with the CAD model and completed by a final comparison of the same sections of different gaskets using two laser technologies. Firstly, the aim is to identify the similarities and what parameters the technologies can find out. It is then followed by collecting the data for different gaskets at different sections in them. Finally, comparing the data for reliability and validity with other technology with higher accuracy and precision.

Steps according to Bereday's model of methodology

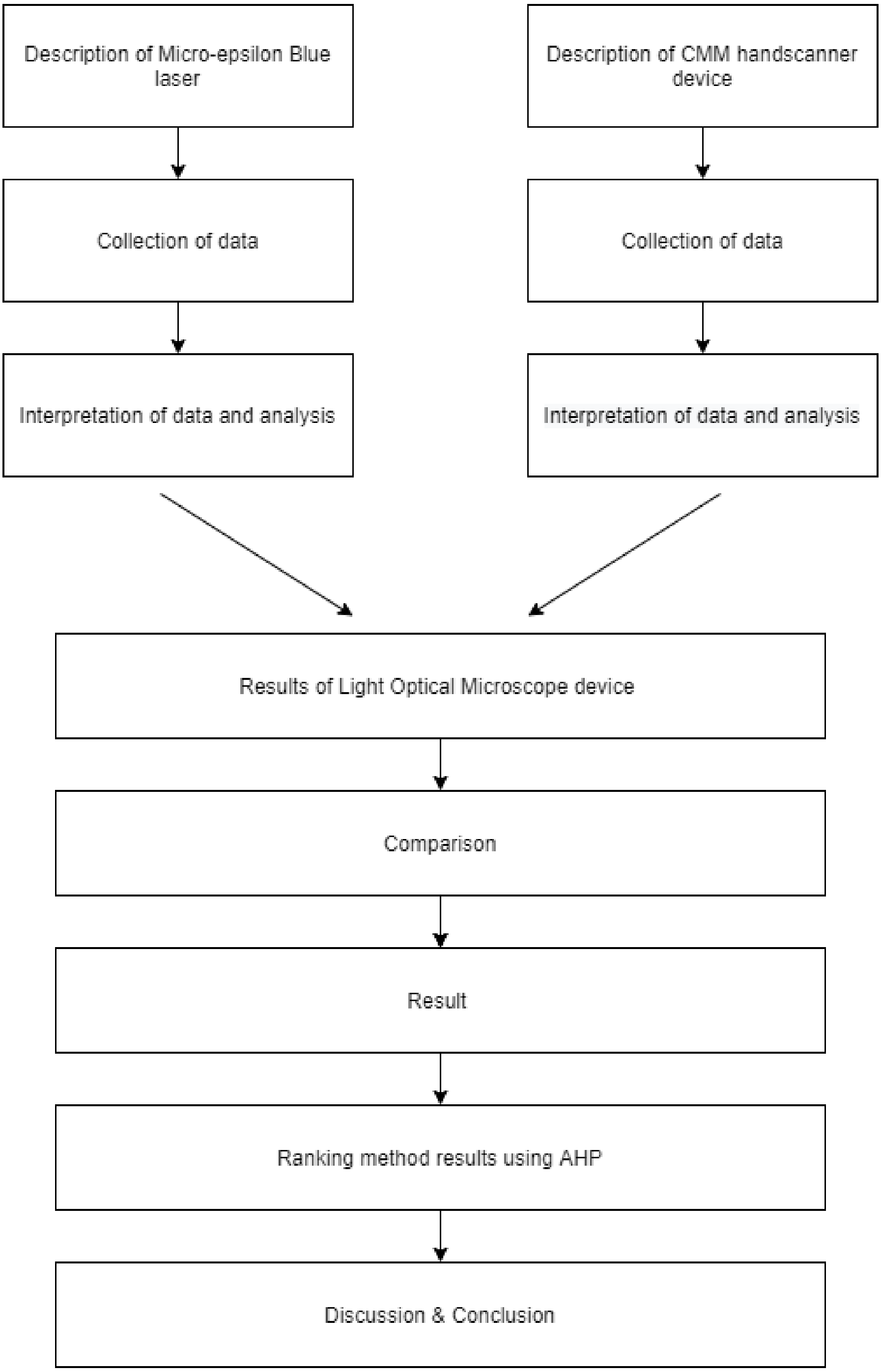


Figure 3.4 Model of methodology (Adopted from [43])

It is necessary to have sufficient parameters to make a meaningful comparison between two technologies or methods. According to Figure 3.4, a description of the technology is detailed, followed by data collection, interpretation, and analysis. Comparison and finally concluding will be the next phase of the model. To make any meaningful comparative study, examining the causes at work and the relationship between the causes is essential. The priority is to identify comparability parameters as shown in the model, which will be done in the technology description

3.6 Validity and reliability

Internal validity *"is concerned with the question of whether a conclusion that incorporates a causal relationship between two or more variables holds water"*([35], p.42). In this thesis, internal validity is high since there is an association between the critical factors, which eventually leads to error. External validity *"is concerned with the question of, whether the results of the study can be generalized beyond specific research context"* ([35], p.43). Accordingly, the findings of this work cannot be generalized, and it can be stated that external validity is low. The results obtained by this work will be validated with the results from a light optical microscope for the same samples and at the same cross-section. The accuracy and precision of the results obtained by the light optical microscope are high.

Reliability is concerned with whether the results of the study are repeatable or not [35]. In this research, the reliability of the data is medium because we employ laser technology to measure data. Any vibration or movement may produce fluctuations in the data acquired, and the average value obtained will deviate from the nominal. However, the results acquired using both approaches will not be 100% repeatable at any given time. The values will be close to each other, but variation could be in the second or third decimal place, where the measurement unit is in millimeters (mm). Values obtained are close/within the tolerance limit, which raises the work's reliability. The equipment used for obtaining data is calibrated accordingly.

4 Evaluation of gasket quality at Alfa Laval

In this chapter, we shall be discussing the technical requirements for the gaskets and how they undergo the validation process upon delivery of initial samples from the suppliers. Readers will understand the technical aspects of the gasket measurement. This will be followed by a detailed study of the current methods for evaluating cross-sections, surface defects, flash, attachment geometries, and surface roughness. The study will give information regarding the different instruments used to measure various inspection areas of the gaskets. We shall also provide the key features of existing methods and drawbacks, which can be further used as a standard for selecting new techniques. The overall macro shape evaluation, such as distortion, missing attachment features, and length, will not be subject to investigation in this project.

After approval of initial samples (approval certificate sent to the supplier), the quality in production is followed up by suppliers in samples taken from every batch to secure that all delivered gaskets are according to specification and Alfa Laval has access to the inspection data.

4.1 Technical requirement standards

This section gives a detailed explanation of the standards that are set for the quality department. These standards help in generating a fundamental structure of the verification process. The technical requirements are described in terms of critical and non-critical areas and the different inspection areas.

4.1.1 Critical and Non-Critical Areas

The gaskets have specific areas that are considered critical areas and few areas that can be regarded as non-critical. The feature of critical and non-critical areas is tabulated in the below Table 3.

Table 3: Critical and Non-critical Areas.

Critical Area	Non-critical area
The sealing area and the fluid contact areas are considered critical areas.	The section of gaskets that are not in direct contact with fluids in the heat exchanger when assembled.
These areas should not have any defects as this would affect the whole process.	There is flexibility to have minor errors in this area as this will not affect the function.
No repair or alteration is allowed in this region.	Repair is allowed in this part of the gasket, providing adequate strength and geometry are maintained.

The critical areas are the marked areas, whereas the unmarked sections are considered non-critical, as shown in Figure 4.1. During the assessment of the critical and non-critical areas, the gaskets must be observed for minor defects. If the minor imperfections are repeated, it is then classified as a significant defect. All the significant defects are rejected during the quality control (QC) process.

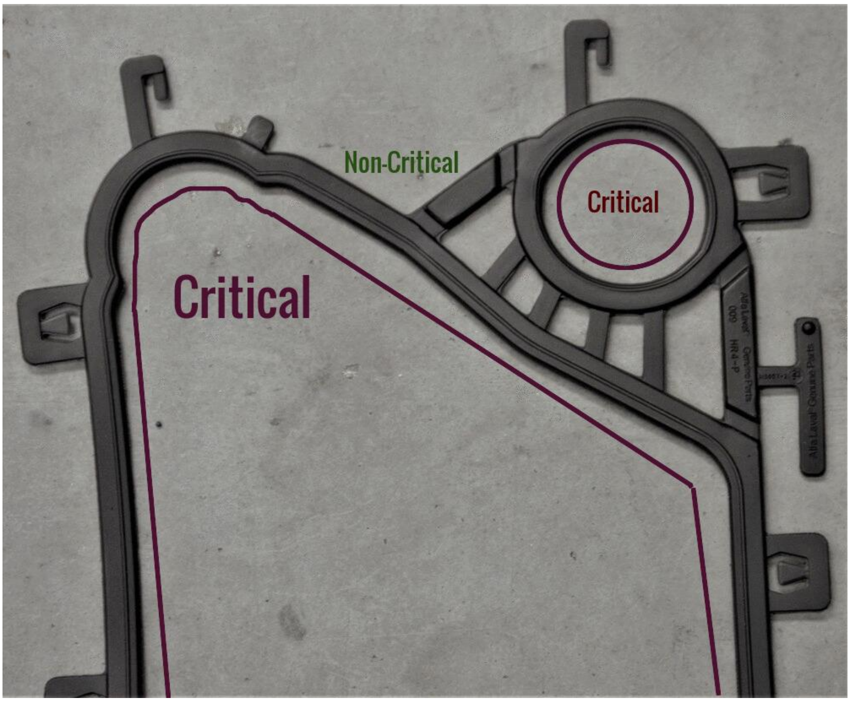


Figure 4.1 Critical and Non-critical areas of the gasket

4.1.2 Inspection areas

The areas in the gaskets are assessed for various defects during the QC process called inspection areas. The reasons why this may occur are explained in the above section 4.1. In this subsection, we present the various defects that occur during the manufacturing and the quality standards set by Alfa Laval for assessing the inspection areas. The inspection areas and defects are listed and explained below:

i. Contamination

Contamination is one of the defects that might occur during the manufacturing or post-processing of the gaskets. Any foreign materials like sand, plastics, or metallic burrs that will get partially or wholly submerged into the gasket materials will be considered a significant defect. Contamination caused by foreign materials can cause rejections.

ii. Snap-on

These are the features of the gaskets that are provided for the assembly of the heat exchanger plates. Snap-On is shown in Figure 4.2.

Figure 4.2 Clip-on feature

There are specific standards for the QC method, and they are:

- Any alteration on the clip-on is permitted, but it can happen only at a 2mm distance from the gasket body. There is a limit of a maximum two clip-on to be repaired on each gasket in terms of alteration.
- The clip-on must be cut within 1mm to 3mm from the gasket body in terms of complete cut-off.
- Any clip-on inside the critical area must not be altered.

iii. Flash

The rubber outside the gasket body has specific restrictions in terms of QC. These rests from manufacturing are trimmed away, but some residuals will remain. The remains are called flash. Loose rubber residual is not allowed on the gaskets. The proper flash height for critical areas must lie within specified limits. The contamination due to flash on the gasket body is shown in Figure 4.3.

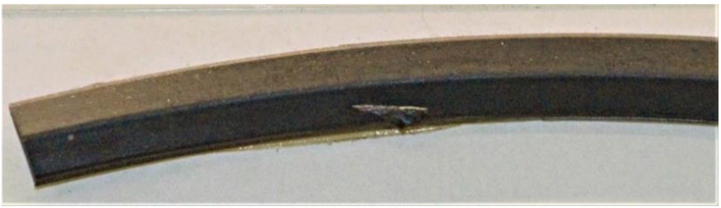


Figure 4.3 Flash Contamination

The Profilometer device can determine the flash height to ensure that the side flash lies within the range. This setup is shown in Figure 4.4, and the flash height is shown in Figure 4.5.

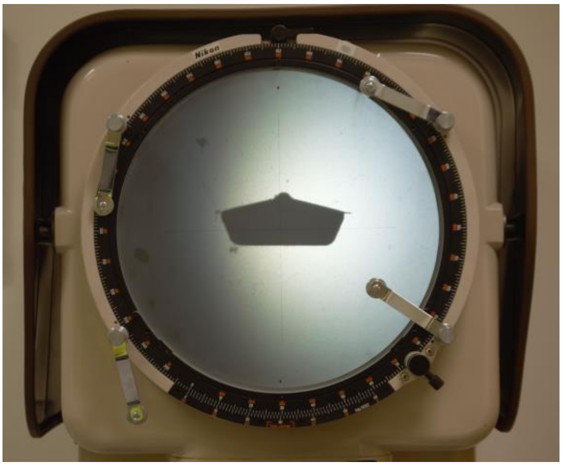


Figure 4.4 Profilometer view of the gasket cut section.

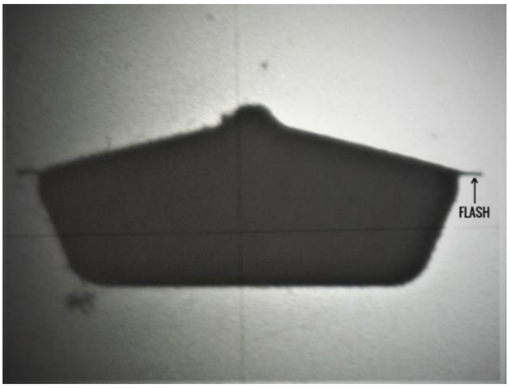


Figure 4.5 Cross-section of the gasket and flash height

iv. Surface Defects

Surface in gaskets can get protrusions or cavities formed during the manufacturing process. This can happen due to damages to the mold. Too significant surface defects can be seen in Figure 4.6.

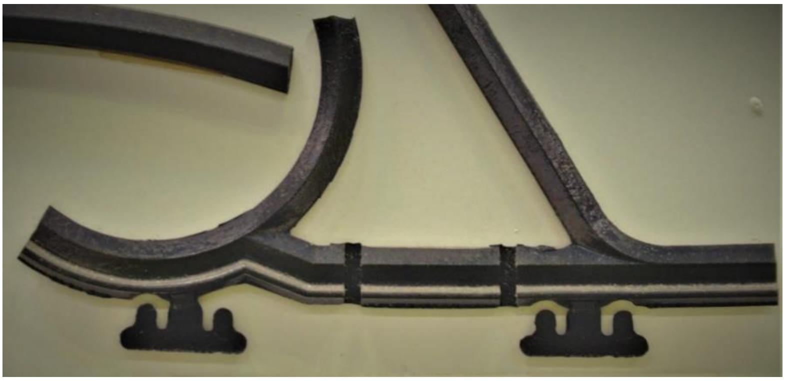


Figure 4.6 Poor surface on the gasket

Surface defects are considered minor defects if protruding from the surface but must follow the standards set

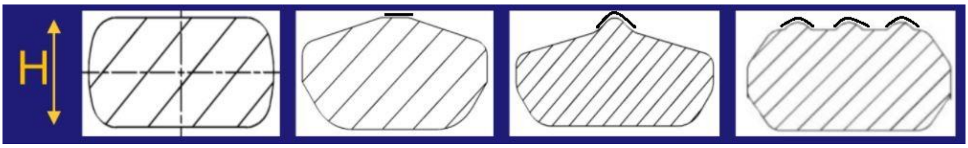


Figure 4.7 Lined for the standards for Hight measurement [44]

Any change in dimensions beyond the limit would be considered a significant defect and rejected if the surface defects are repeated. This will also result in the inspection of the mould, which can be the possible reason for the repeatable surface defect.

Another Surface defect during the manufacturing can be misalignment between moving tool parts, as shown in Figure 4.8.

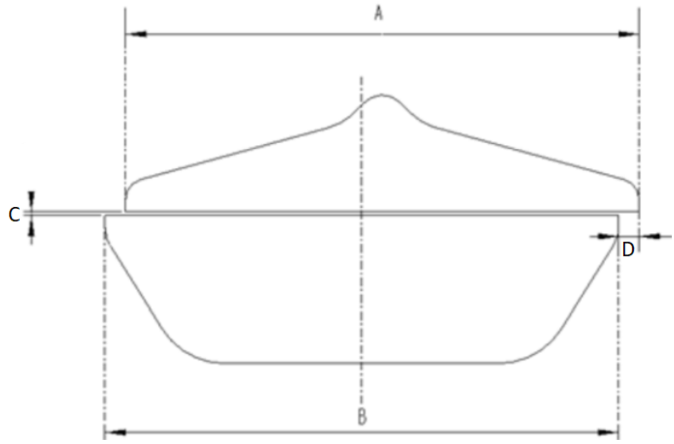


Figure 4.8 Moving tool part defect [44].

v. Gasket Dimensions

The other key inspection area of the gaskets would be the dimensions of the gaskets. The dimension checks are done using instruments like measuring gauges, dial indicators, and profilometers to check different geometries in the gasket cross-sections. The R&D dept sets the dimension tolerance and is represented in the 2D drawing. The parameters shown are measured in various sections on the gaskets.

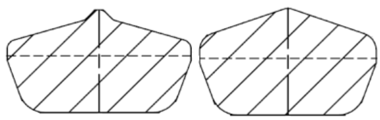


Figure 4.9 Cross-section of the gasket [44].

4.2 QC process

The quality standards are one of the highest priorities at Alfa Laval. The department's primary daily assessment process is the technical requirement for approval and test methods in terms of shape and appearance for the initial gasket sample. The quality department consists of experienced personnel to approve the gasket sample. Based on the above section on the technical requirements, execution of assessment takes place.

At first, the quality department receives the initial samples from the supplier. The number of gasket samples can differ between the suppliers based on the exotic material and unique features. The usual number of gasket samples is five from each cavity but reduced by the supplier to three in the particular table case mentioned above.

Inspection of the gaskets takes place in terms of various contaminations and defects visually. If any critical feature is damaged and critical areas having contamination or defects might result in the disapproval of the samples. If the gaskets have no issue in that step, then the dimensions assessment takes place. In this step, the checking of length dimension occurs and is verified against drawing tolerance. A ruler is used to perform the measurements and then the assembly to the heat exchanger plate if accepted in the previous step. Once assembled, the assessment is conducted in terms of distortion and flatness.

If accepted in this step, the gasket height(thickness) is assessed with the digital dial gauge shown in Figure 4.10 Dial indicator measurement. Assessment of height of gasket compared with the tolerance mentioned. A thickness measurement outside the tolerance will not be accepted.

Figure 4.10 Dial indicator measurement

After the assessment of height, the flash height is assessed by visual inspection. Suppose there is a flash, the section of a gasket slit by a customized cutter for gasket shown in Figure 4.11. A custom-made blade cuts a tiny gasket area, and this cut section is held under a profilometer to determine the flash height. The flash height is assessed in the profilometer to check if it lies within the given standards mentioned above and shown in Figure 4.4. If not within tolerance, the sample results in disapproval. The misalignment between moving or non-moving tool parts is assessed the same way as the flash measurements.In cases where there is a significant issue with the cross-section, it can be evaluated in the Tool factory at Alfa Laval. The cross-section is verified with the CAD model to check the cross-section matches the 3D model. Comparison is made with the help of a Photographic scanner that Alfa Laval possesses.

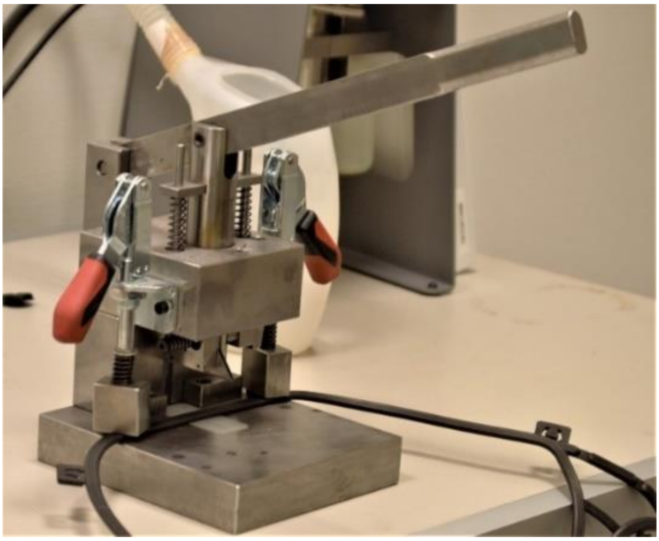


Figure 4.11 Customized cutter for gasket cross-section verification

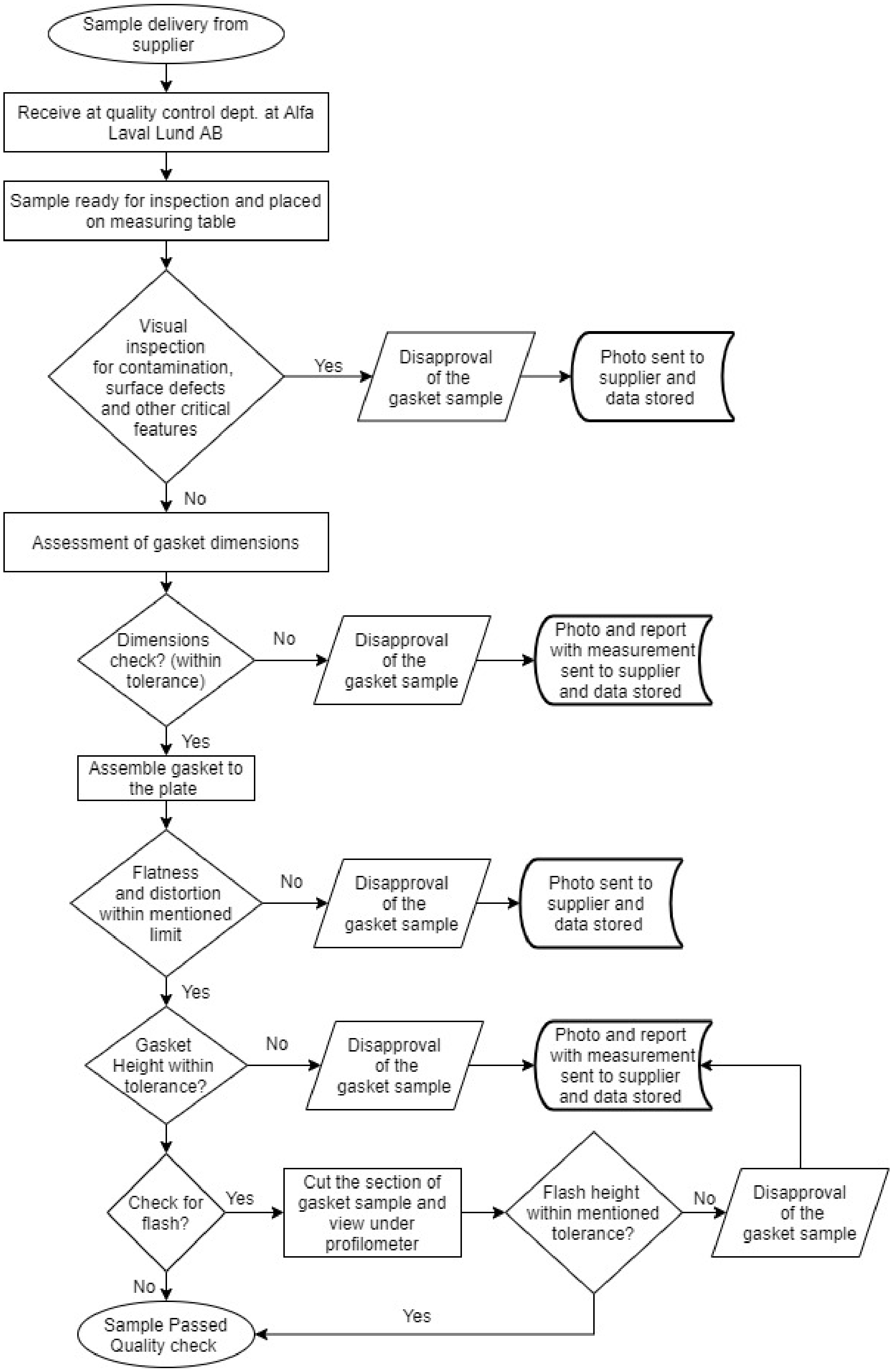


Figure 4.12 Flowchart of current method at Alfa Laval

4.3 Key features of Existing methods

Alfa Laval's existing process in the Quality department for the QC of gaskets is a manual method. The features found during the evaluation of the current methods are:

- Quality of gaskets assured using simple gauges such as dial indicator, profile projector, and measuring the gasket's length using a simple linear distance measurement technique.
- The process is easy to understand in terms of complexity and has simple steps to follow.
- The use of a Photographic scanner can make an accurate assessment of the cross-section.
- The length evaluation method uses the marking on the gaskets to measure the distance between them. For fit to plate measurements, a pressed plate is used. Here, the critical dimensions can be measured by referencing the gasket not to change its position in the plate during the course. The technique is inexpensive and has good repeatability of the specification within its tolerances.
- Defects on the gasket can visually notice with ease based on observation and experience. To solve problems on defects like distortion, twisting, lifting, angle gauge can be used. The use of the angle gauge helps in solving the problem with good efficiency.
- Dial indicator gives fast and effective results in quick time concerning thickness. Users can measure the section of the gasket for flash containments in the profile projector.

4.4 Drawbacks of the Existing methods

During our investigation of the current quality assessment methods and interview of Marija Fazekas working as a metrology inspector at the PHE-LA Quality Department, we formulated the gaps in the current methods. The following points are the challenges considered during the gasket measurement:

- When measuring the thickness, it is a fact that the thickness could be within tolerance, but the geometry could still differ from the desired design, and the fit to gasket groove be bad and cross-section area wrong.
- The photographic scanner report is more time-consuming as there is an involvement of a different department.
- No accurate, reliable, and non-destructive method exists for checking the geometries of attachment features. A lot of cuts need to be taken from a Clip-on and measured in a laboratory microscope.

- When measuring the cross-section area of the gasket, it is not always feasible to cut the gasket and measure the area. A destructive technique is currently followed where the gasket is cut at a random point to determine the cross-section of the gasket. Errors could be added during the cutting. This method can also be used to assess the flash containment and tool part misalignment at that point. The cross-section is viewed on a magnified scale in a profile projector or laboratory microscope
- Challenges associated with measuring the transition areas, if there were any significant deviation in the transition area, the gasket would not fit into the grooves in the heat exchanger plates. If the varying area is less or more than the groove area in the plates, then leakage of the fluids can occur.
- Calibration of measuring equipment takes time as the calibration process is time-consuming and can delay the QC process.

5 Evaluation of gasket cross-section

This section will discuss how the Quality control department in Alfa Laval can be modernized by implementing various techniques by scanning the gasket cross-section. This can help avoid the destructive method of measurement which is presently performed by cutting the gaskets. These methods can also help in performing accurate and repeatable measurements.

During our investigation of cross-section measurement at Alfa Laval, we came across various laser instruments to measure the cross-section without taking the gaskets apart. The technique mentioned is being investigated in the thesis work to measure various gaskets to understand the capabilities and perform a SWOT analysis of the techniques.

- Laser line Triangulation (LLT)
- Hand-held 3D scanning

We perform numerous trials for the measurement of various sections on the gaskets. We use the same section and measure the parameters on different techniques mentioned above. During the investigation, we used three types of gaskets with varying cross-sections and used three samples of each gasket to understand the repeatability of the measured results.

The gaskets used in the investigation are listed in Table 4.

Table 4 Gaskets used for cross-section measurements

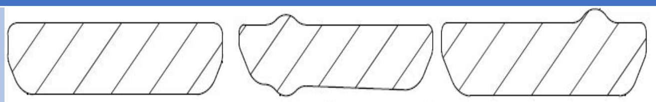
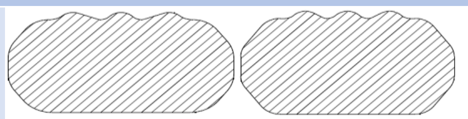
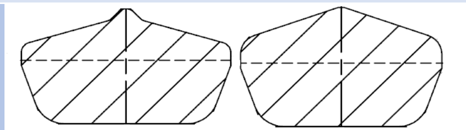
No.	Gasket title/Name given	Gasket cross-section
1	HR4-P (End plate gasket)/ A	
2	DR-15M (Field gasket Wedge grip)/ B	
3	PHE CLIP10/ C	

Table 4 shows three different gasket cross-sections, which will help investigate various parameters that can be recorded and tabulated. By accessing different sections of gaskets, we can help select the best method that can be implemented in Alfa Laval's gasket quality control department, which will positively impact the quality control. The cross-section measurement is essential in gaskets because the simulations for gaskets are performed for a particular cross-section. If there is a massive variation in the gasket cross-section, it can directly affect the performance of the gasket and can affect the heat exchanger process as a whole. Hence, we perform an in-depth capability analysis of the measuring instruments.

5.1 Laser Line Triangulation (LLT)

Laser line triangulation (LLT) is a non-contact measuring method used in 3D metrology, which has features like fast scanning, high precision, and an accurate measuring system [45]. The setup consists of a laser triangulation sensor (LTS) mounted on a motorized linear system (MLS) to scan a line on the 3D object [46]. The setup is shown in Figure 5.1.

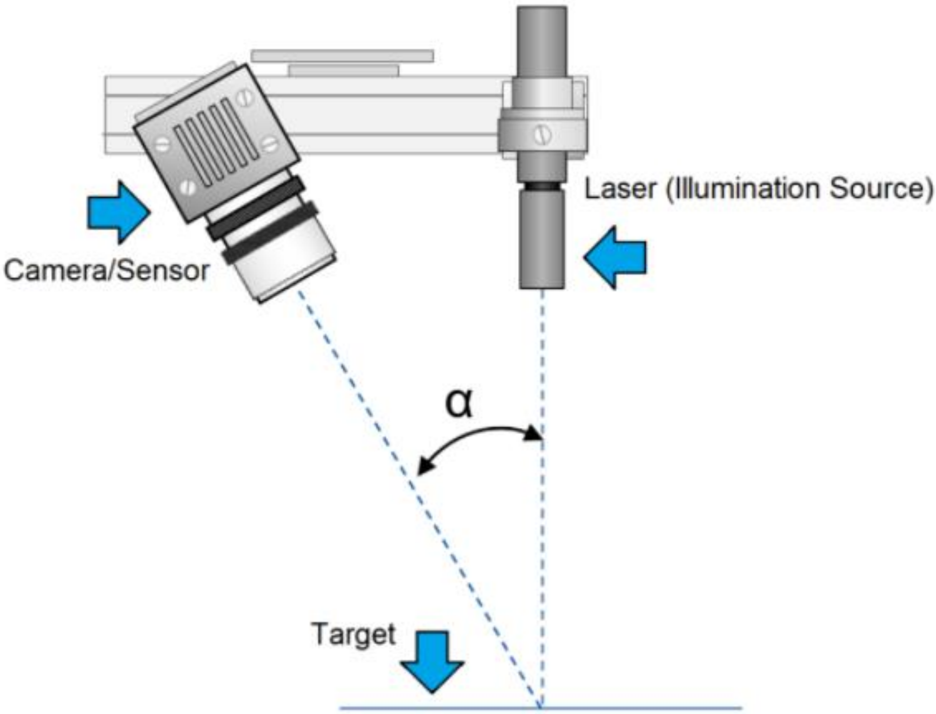


Figure 5.1 Setup of LTS system [47]

The LTS system consists of a laser diode that emits a laser line on a specific area in the 3D space [46][48] called target in Figure 5.1. The camera/sensor captures the image of the laser light. Here α is the angular offset between the camera and laser [47]. The profile height, i.e., the z-axis, can be adjusted to get the proper focus. The inspection area between the laser and the measurement surface where the parameters are to be measured produces a laser line based on the shape of the surface [46]. The image can be recorded on the camera and will be displayed for further measurement.

Figure 5.2 The laser line on the target surface (left), Sensor matrix when laser light is recorded by a high-quality sensor (center), Calibrated x/z measuring point on the measuring software (right) [49].

The LTS is connected to a computer via a LAN port which transfers images and data to a computer where measurements can be made.

5.1.1 Prototype Construction

In this sub-section, we shall discuss the sensor setup and perform different trails to measure different gaskets of different cross-sections shown in Table 4. We shall be giving how the construction is made to set up the line triangulation measuring system.

5.1.1.1 Hardware Setup

The setting up of the hardware for the measurement of the gaskets has a straightforward construction with a universal mounting arm, sensor holder plate, tightening screws for clamping, MLS of LTS. The arm should be mounted very firmly to make sure there is no vibration in the system, which can cause inaccurate measurement. The MLS is mounted on the sensor holder plate firmly by screwing it to the plates. The gaskets are placed on the table and can be handheld by the operator or by using duct tape to make sure there is no movement of the gasket. The mounting arm is moved to a specific position to ensure the sensor camera focuses on the gasket image. The connection to the sensor is provided by the main power supply cable and is connected to the measuring software by a LAN cable for the data processing. The setup is shown below

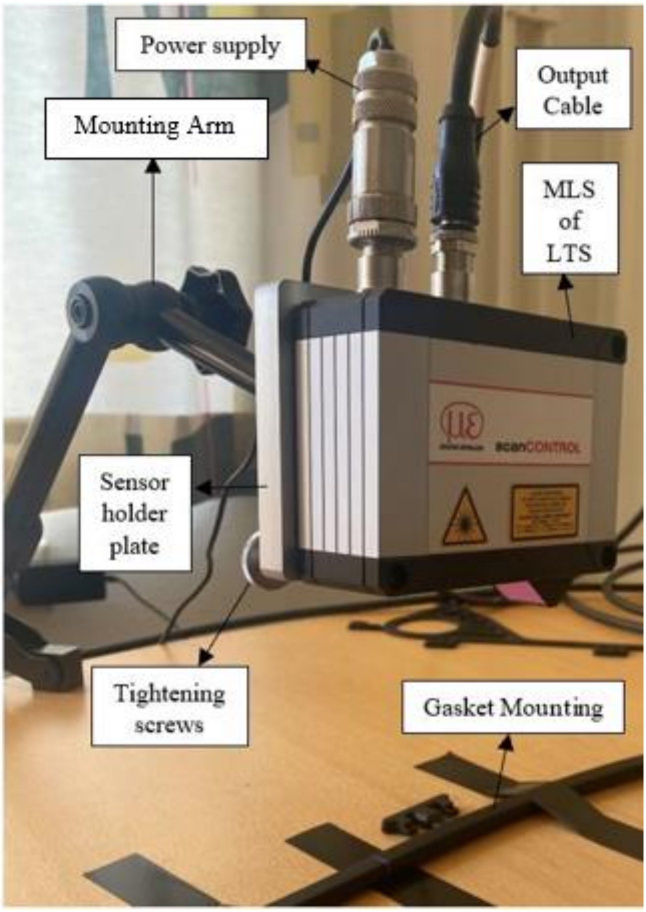


Figure 5.3 Setup of the measuring instrument of MLS system

In our investigation, we have used Micro-Epsilon scanCONTROL LLT3060-25/BL. This MLS device consists of a blue laser source and a charged coupled device (CCD) camera used in laser triangulation. We use a universal mounting arm that houses a sensor holder plate.

We mark the section where the laser line falls, and that point is placed over a black surface to help to avoid reflection and the image captured has better resolution.

5.1.1.2 Software Setup and output

We use the scanCONTROL configuration tool, a software tool used to configure the scanCONTROL sensors' results on the Windows PC [50]. It helps in viewing the profile and setting up the sensors. It helps in parameterizing complex measuring tasks on the profile of the measuring target [50]. The software provides a direct mage of the sensor matrix at the target, as shown in Figure 5.4.

Figure 5.4 Sensor matrix on scanCONTROL configuration tool.

The calibration is performed based on the amount of the angle deflection. Based on the deflection, the sensor is aligned to the laser line on a straight-line matrix. Once the calibration is performed, we start the measurement process. Based on the different parameters to be measured, we can select eight programs for measuring out of 30 programs available. The main programs are shown in the below Figure 5.5. For some cases where the measuring method can get complicated, different programs can be selected, and Boolean operations can be performed to get the output. We used this method in determining the flash height, where we selected the first point within a specific area and the last point in that area. By performing the Boolean operation, we determined the flash height of the gasket. This is well represented in Figure 5.6.

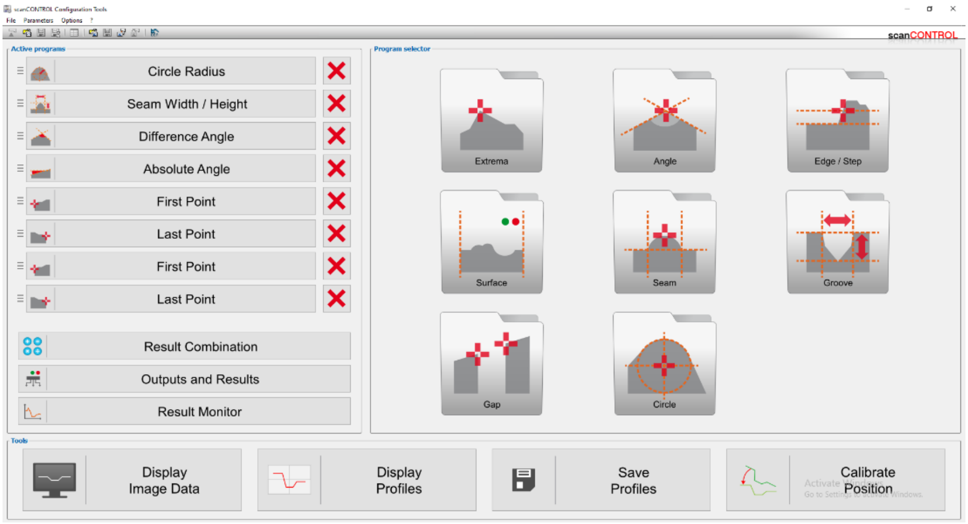


Figure 5.5 Main programs available in scanCONTROL

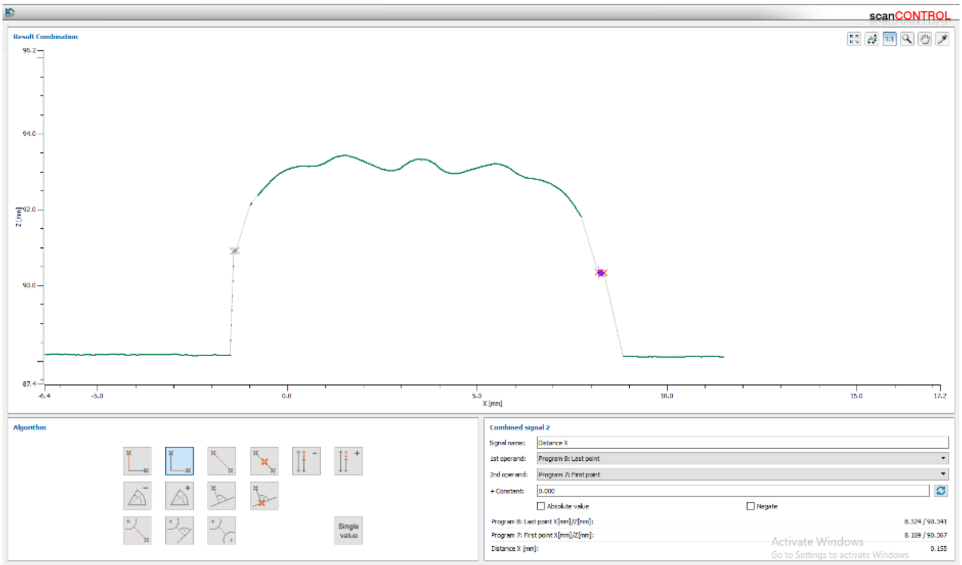


Figure 5.6 Flash measurement using two programs.

Some parameters can be set to measure other parameters like area, angle, radius, width, etc. We can see the results of other parameters in the below Figure 5.7, Figure 5.8, Figure 5.10, Figure 5.10.

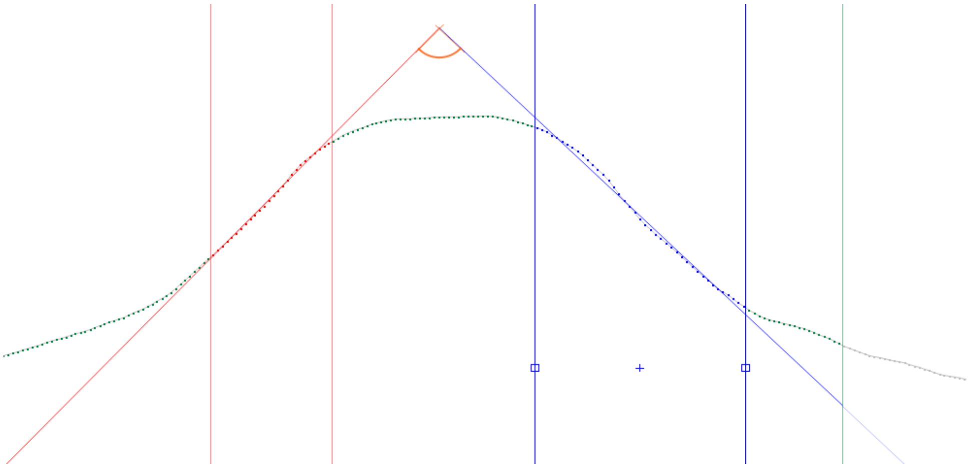


Figure 5.7 Angle Measurement.

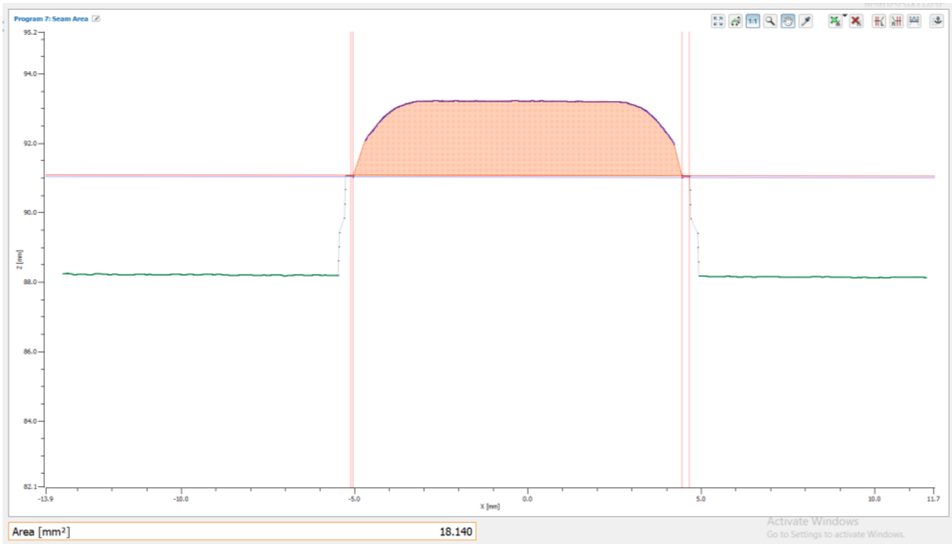


Figure 5.8 Area measurement of the upper surface.

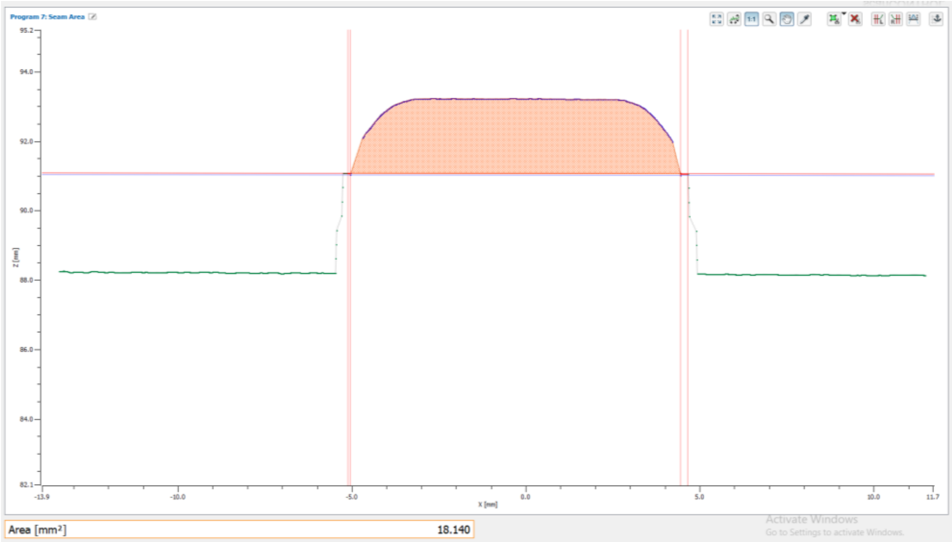


Figure 5.9 Area measurement of the lower surface.

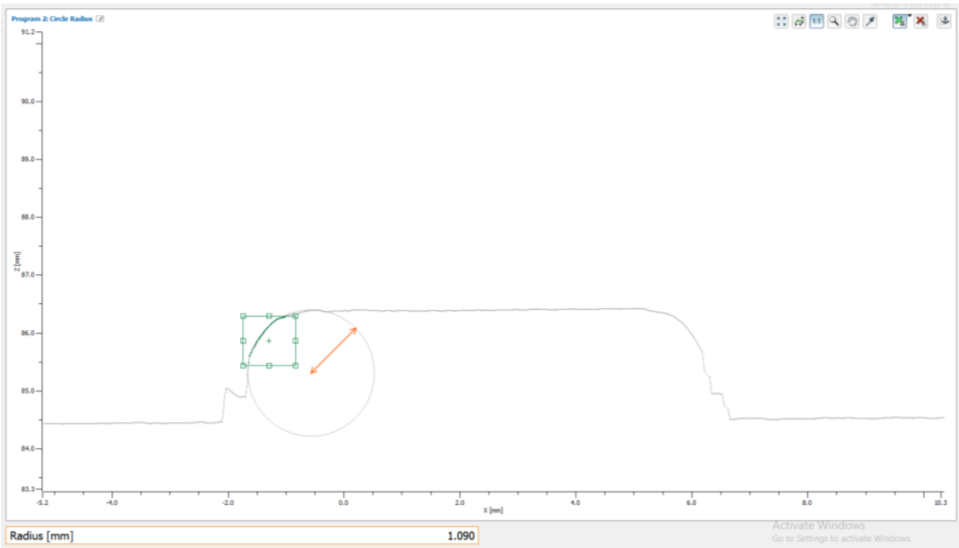


Figure 5.10 Radius Measurement.

The result will be immediately displayed below. But during our study, we performed a dynamic measurement where we tried to understand some disadvantages due to the effect of vibration and clip to be held firm. The result obtained during the dynamic measurement will have a graph that will show the deflection during the measurement. This can be seen in Figure 5.11.

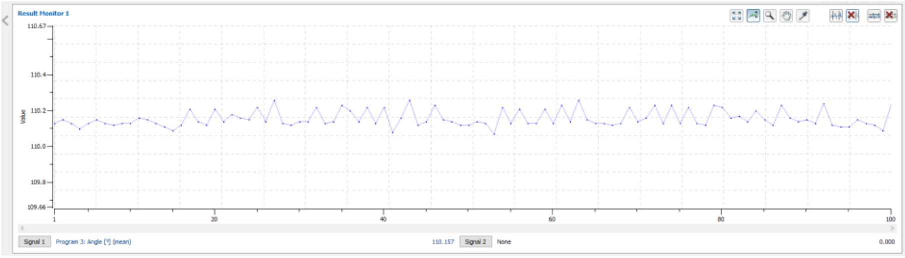


Figure 5.11 Dynamic result monitor.

Here, we have seen that the result was not linear during the angle measurement of Clip 10/gasket C. This was due to the gasket movement during the measurement. This is discussed in subsection 5.1.3.

The data obtained can be exported into an excel file to use for tabulating or processing. We have attached an Appendix that gives all the results obtained and tabulated.

5.1.2 Observations of MicroEpsilon

In this section, we shall observe some key results that we obtained during our investigation. We provide a scatter graph of the tabulated data and can use the data for comparison with other techniques investigated in section 5.2.

5.1.2.1 Gasket A

In this section, we shall observe the cross-section of the gaskets with sections A-A, B-B, C-C, D-D with nominal measurements are shown in Figure 5.12. Other data are listed in Appendix 11.1.

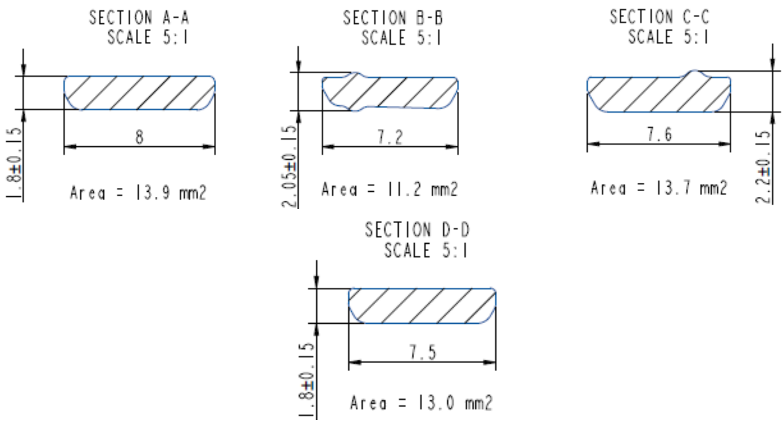


Figure 5.12 Gasket nominal measurement drawing for different sections

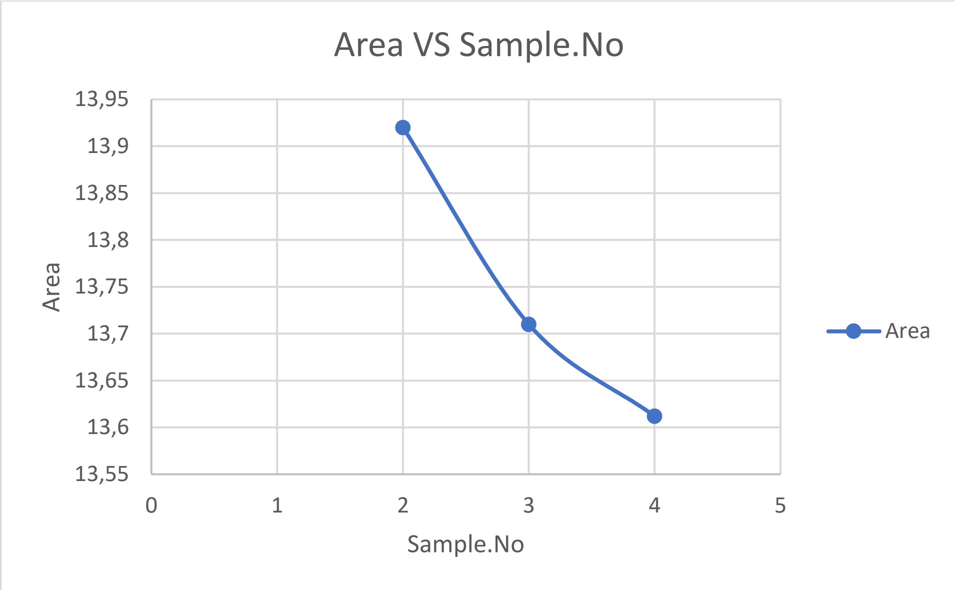


Figure 5.13 Area of gasket on Section A-A (Nominal: 13.9mm^2, Measured: 13.612mm^2-13.92mm^2)

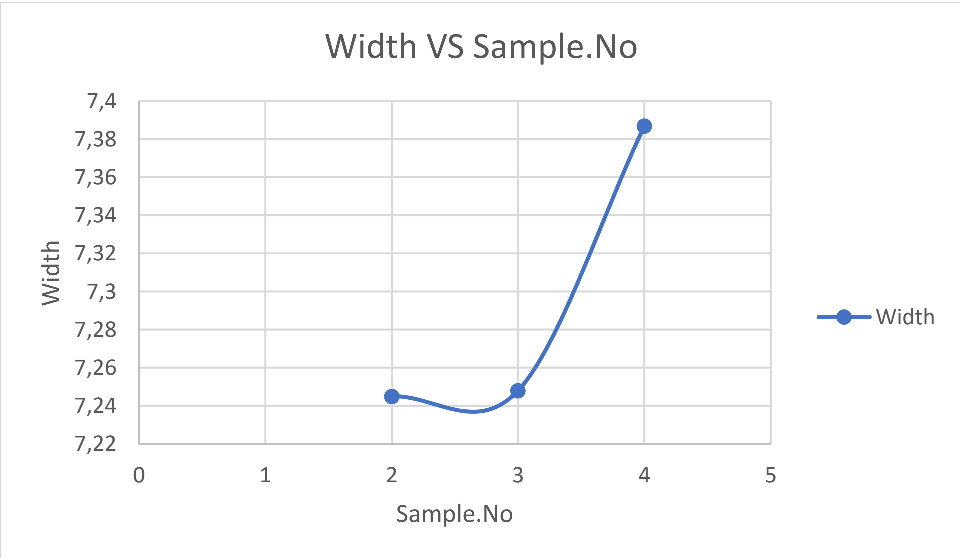


Figure 5.14 Width of the gasket on Section B-B (Nominal: 7.2mm, Measured: 7.245mm-7.387mm)

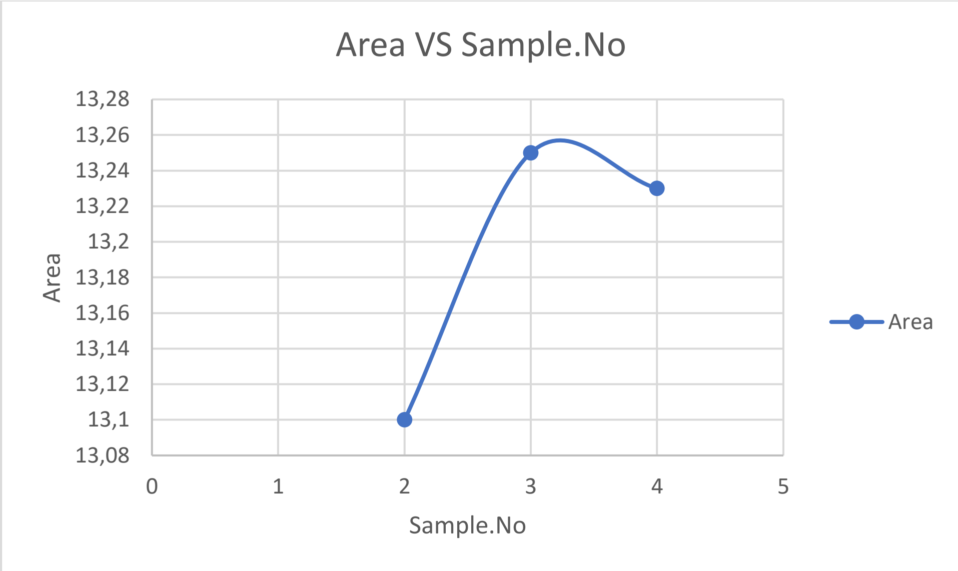


Figure 5.15 Area of the gasket on the section C-C (Nominal: 13.7mm^2, Measured: 13.1mm^2-13.25mm^2)

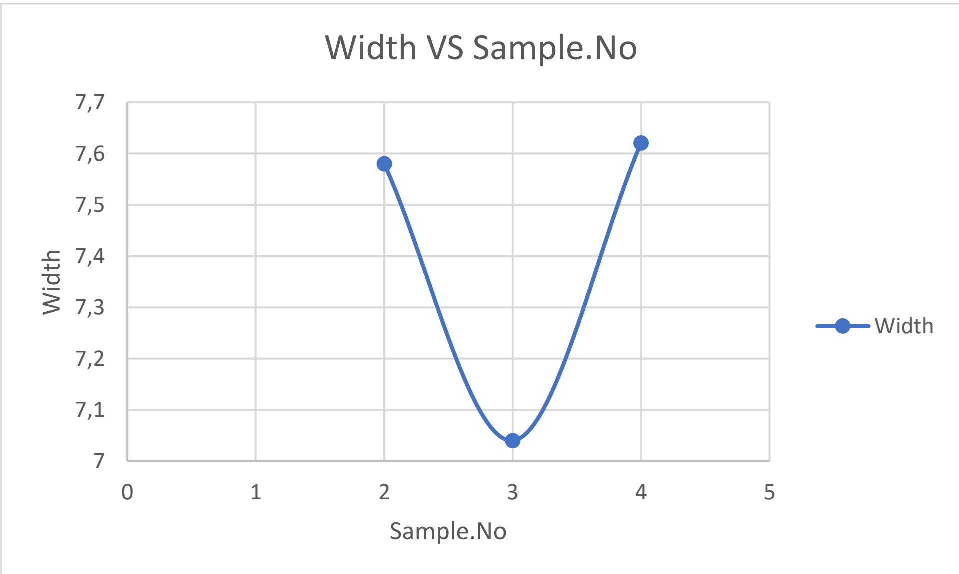


Figure 5.16 Width on section D-D (Nominal: 7.5mm, Measured: 7.04mm-7.621mm)

In Figure 5.15, we can see that the area has variation compared to the nominal measurement. There can be an error when measuring as we take the reference as a flash to measure the area, which is more manual. This will be validated in Chapter 6.

5.1.2.2 Gasket B

In this gasket, we have measured three different samples and two sections of the gaskets. We have measured the gasket section A-A and B-B. The data is mentioned in Appendix 11.2. The nominal measurement of the sections is shown in Figure 5.17.

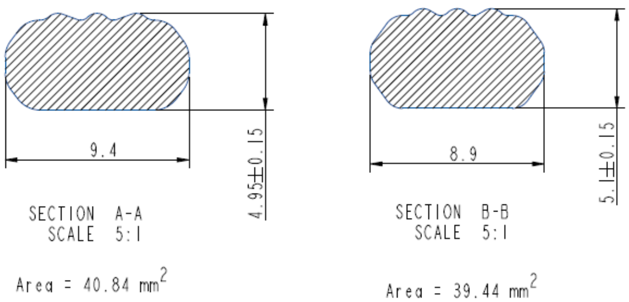


Figure 5.17 Gasket B nominal measurement

The below graphs will show some of the observations made during our investigation. The graph shows some variations between 3 different samples.

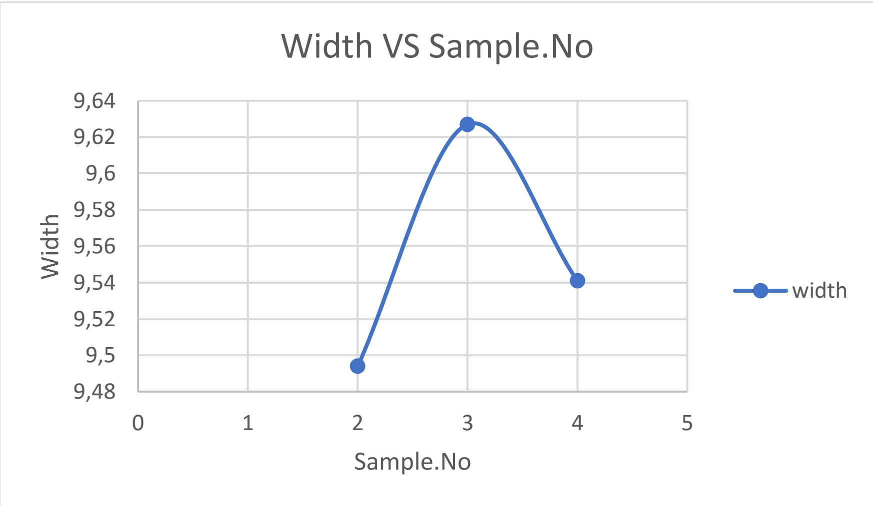


Figure 5.18 Gasket width on section A-A (Nominal: 9.4mm, Measured: 9.494mm-9.627mm)

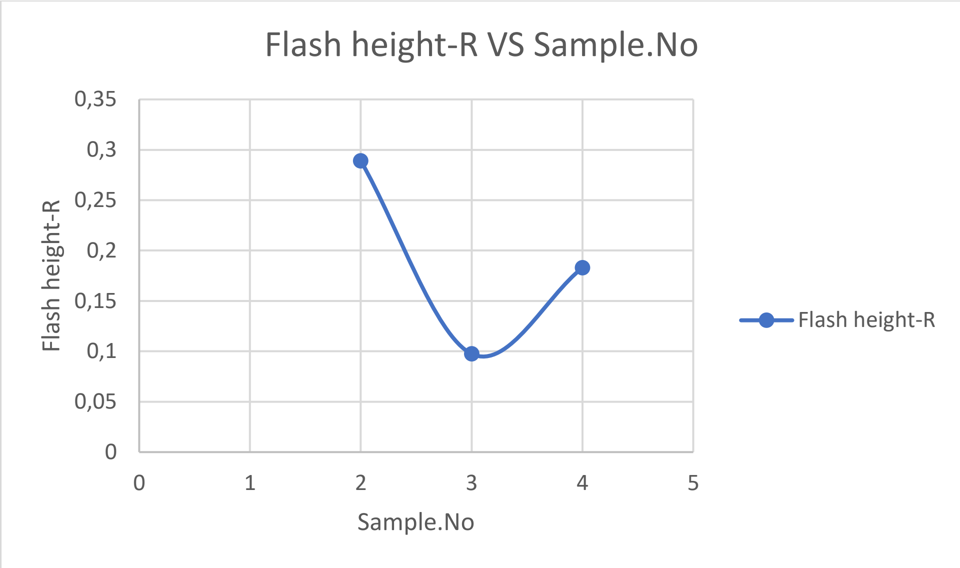


Figure 5.19 Flash height right side on Section A-A (Measured: 0.0975mm-0.289mm)

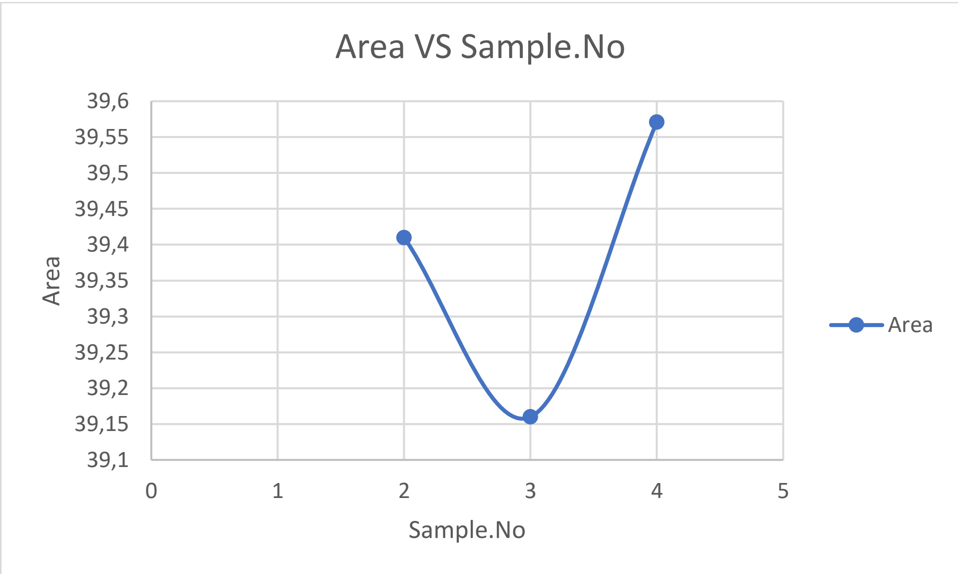


Figure 5.20 Gasket Area on Section B-B (Nominal: 39.44mm^2, Measured: 39.16mm^2-39.571mm^2)

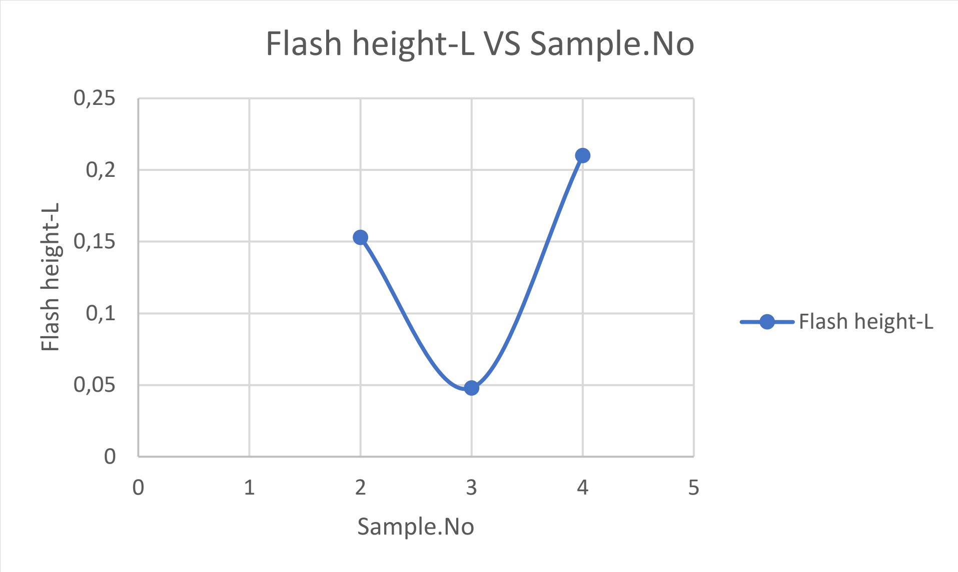


Figure 5.21 Flash on left side Section B-B (Measured: 0.048mm-0.2102mm)

The above graphs show all the measured values within the expected limit, and therefore the gasket cross-section can get the green light in terms of measured values compared to the nominal values shown in Figure 5.17.

5.1.2.3 Gasket C

In this gasket, we have measured different sections on the gasket. We have concentrated our measurements on the sections A-A, B-B, C-C shown in Figure 5.22. The data can be seen in Appendix 11.3.

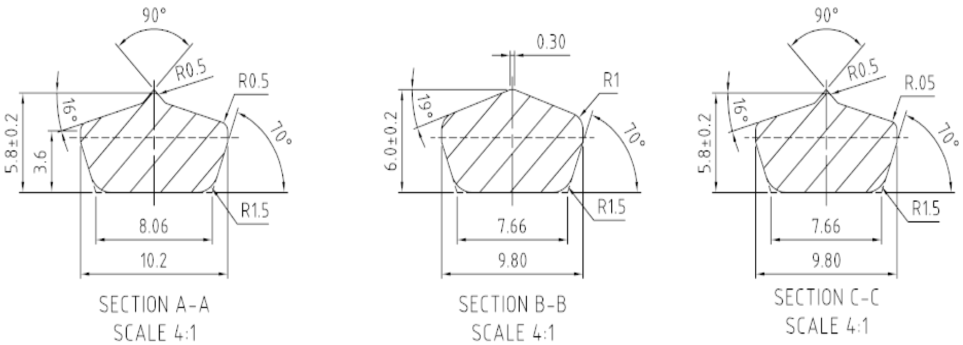


Figure 5.22 Sections on the Gasket

When the sections were measured by the LLT method, we made the following observations. Sample 2 on the A-A, B-B and C-C sections significantly differ from samples 3 and 4.

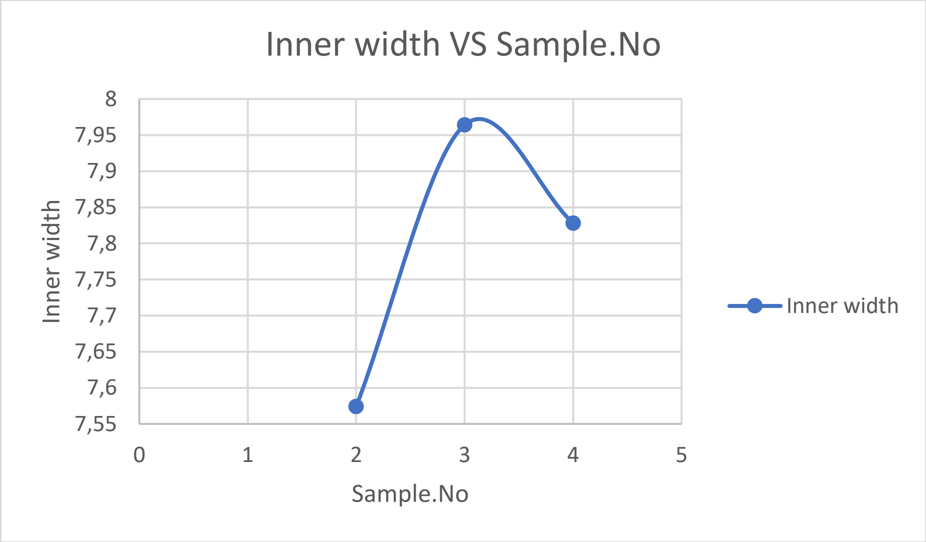


Figure 5.23 Inner width for section A-A (Nominal: 8.06mm, Measured:7.574-7.964)

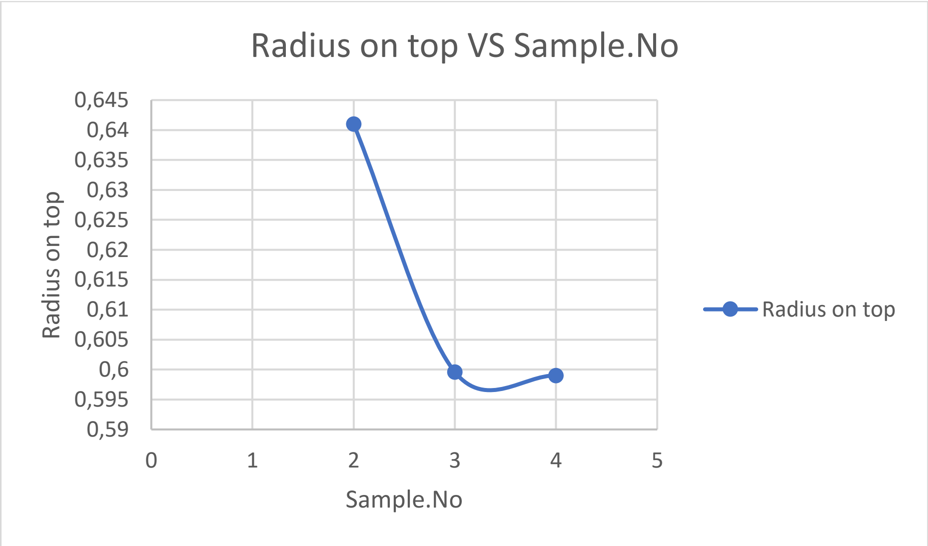


Figure 5.24 Radius on top for section A-A (Nominal: 0.5mm, Measured: 0.599-0.641mm)

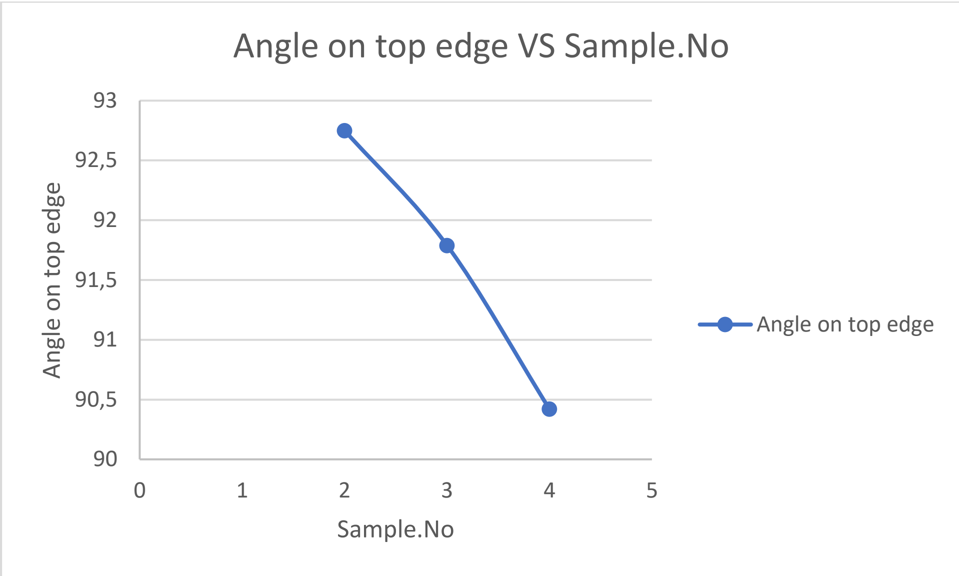


Figure 5.25 Angle on top for Section A-A (Nominal: 90⁰, Measured: 90.42⁰-92.75⁰)

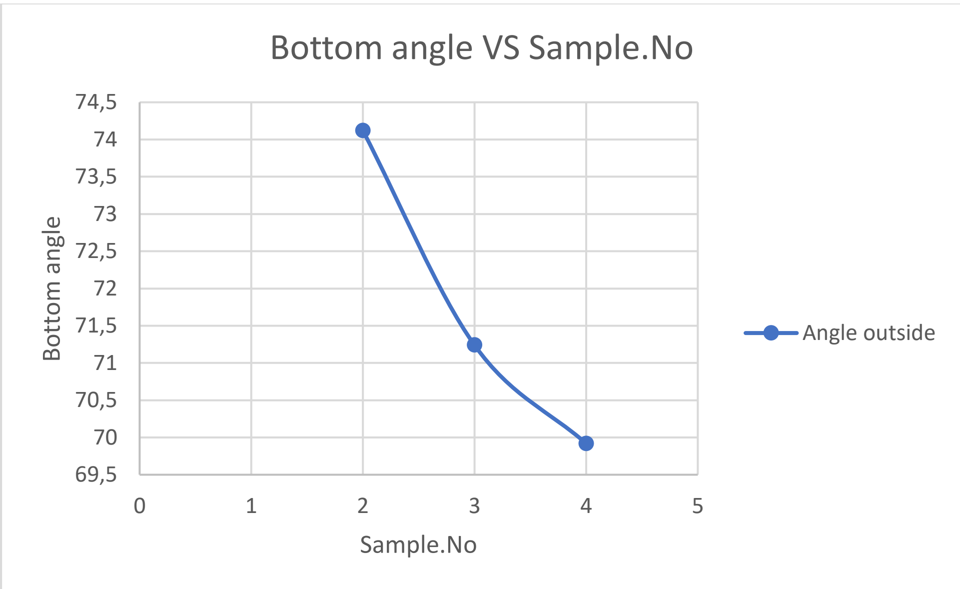


Figure 5.26 Bottom angle on Section C-C (Nominal: 70⁰, Measured:69.92⁰-74.12⁰)

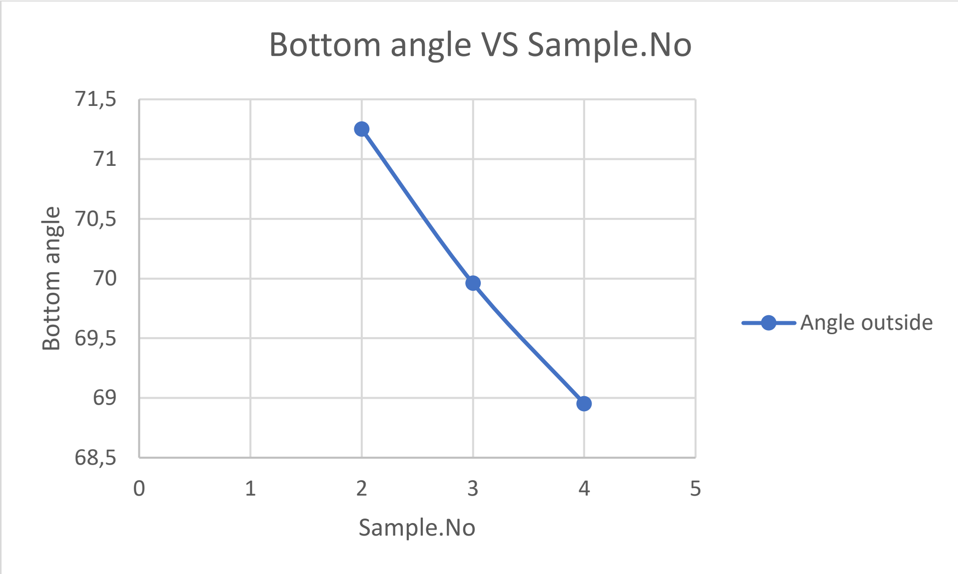


Figure 5.27 Bottom Angle on section B-B (Nominal: 70⁰, Measured: 69.96⁰-71.25⁰)

The above figures show that sample 2 seems to have varying measured values compared to sample 3 and 4. When the values of sample 2 are compared to the nominal, the difference is comparatively higher. Hence, sample 2 can have issues in terms of manufacturing in terms of the cross-section.

5.1.3 Features of LLT method

In this subsection, we shall be discussing the critical observation made during our investigation of the LLT method. These observations can help in understanding the feasibility of this technology for the gasket cross-section measurement. These features can also help in providing the base for the following subsection 5.1.4.

The key features of LLT that were observed during the assessment of the devices are:

- The point matrix of the laser line falling on the gasket can keep shifting during the measurement if there is any slightest vibration on the table. This can affect the accuracy of the measurement method. Hence, by taking a dynamic result, the average can be considered, and the effect of vibration can be nullified to a certain extent.
- The clamping of the gasket in a fixed position is a key. Any movement of the gasket causes an inaccurate measurement. Hence, finding the best way

to clap the gasket using a jig will be another focus area for implementing this method.

- In this method, the laser line can scan only a single profile at a time. But in some instances, like area measurement, etc., there is a requirement of measuring two sides, and therefore the scanning must be performed twice.
- During the measurement of the area of the cross-section, we found that flash was a key. For measuring the gasket cross-sectional area, the top surface is measured until the flashpoint. Similarly, the bottom surface is also measured until the same flash point by scanning the lower section of the gasket. By adding the results, the area of the cross-section can be obtained. This can be seen in Figure 5.8 and Figure 5.9.
- The cross-section can be zoomed in to a specific point, and the geometry can be assessed with the 2D drawings of the cross-sections.
- The width can be measured efficiently, but two different scanning's must be performed for measuring height.
- The radius of the gasket in a cross-section can be measured smoothly. But the region of selection should be well defined.

5.1.4 SWOT Analysis

Here, we shall be discussing the strength, weaknesses, opportunities, and threats of using the LLT method. This can support the LLT method's feasibility and be used in performing a ranking method for the process. Below Table 5 gives a detailed analysis. This analysis helps in finding better methods that can be used within Alfa Laval.

Table 5 SWOT Analysis of LLT technique.

	Helpful	Harmful
Internal	**i.** Can scan the cross-section of the gaskets efficiently. **ii.** Angle and width measurements can be performed accurately and efficiently. **iii.** Software is straightforward and easy to use. **iv.**The results can be generated in a graph and can set tolerances to obtain a complete test report.	**i.** Two scans to perform measurements like Area, height, etc. This can lead to time consumption. **ii.** Vibration and the slightest movement of gaskets can alter results. **iii.** The geometrical comparison must be performed manually and cannot be directly compared with the 3D model. **iv.** Not all the parameters can be measured using this process
External	**i.** The process is cheaper as the software is free and easier to implement. **ii.** It requires very little time in terms of training. **iii.** The gasket quality by Alfa Laval can have better assurance.	**i.** Added investment for setting up. This can include a vibrating damped table and a separate project to design and prototype a jig to hold the gasket intact. **ii.** The time consumption of the measurement can cause scheduling issues.

5.2 Hand-held 3D scanning

A hand-held 3D scanner is a non-contact 3D contour measuring device that provides a highly accurate, efficient measurement of a 3D object and can be used for reverse engineering [51]. The setup generally consists of CCD cameras and laser devices, and light sources [51].

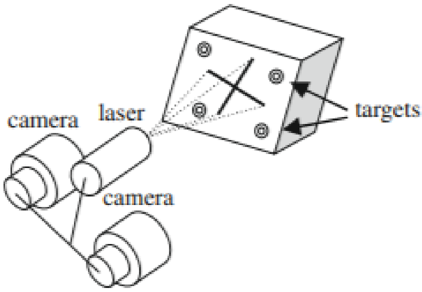


Figure 5.28 Hand-held 3D scanner basic construction [52].

The target in the Figure 5.28 shows reference or the point cloud on the measuring surface. This principle is based on target based registration method where the scanning uses artifacts to merge multiple point clouds to produce a complete scan [53]. The point cloud is transformed into a mesh, which is the different triangles joined together to form the corners and edges of a model [54].

The HandySCAN is based on Photogrammetry technology, one of the most powerful technologies in measuring accurately individual points on the part [55]. The image captured during the scanning by laser is recorded on software like VXelements. The data transfer takes place using a USB port.

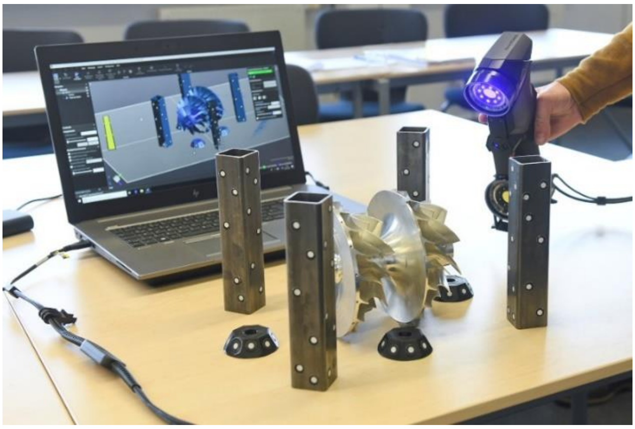


Figure 5.29 Basic set up of scanning at Allianz center of technology [56]

5.2.1 Prototype Construction

In this sub-section, we shall be discussing how hardware and software setup is performed and how data is collected. We shall be providing the details on why the hardware is set up for better scanning. We shall be providing insights on software and its user-friendliness and accuracy in measuring data in terms of software.

5.2.1.1 Hardware Setup

In our investigation, we have used HandySCAN black series. The technical specification of the scanner is shown in Table 6. Below Figure 5.30, we can see the hardware setup of the HandySCAN system for efficient scanning.

Table 6 Technical Specification of HandySCAN black Elite [57]

Technical Specification	HandySCAN Black Elite
Accuracy	Up to 0.025 mm
Volumetric Accuracy	0.02 + 0.04mm/m
Measurement Resolution	0.025mm
Mesh Resolution	0.1mm
Light source	11 Blue Laser crosses
Measurement rate	1,300,000 measurements/s
Scanning area	310x350 mm
Standoff distance	300mm
Depth of field	250mm
Part size range	0.05-4m
Software	VXelements/(InnovMetric Software PolyWorks)
Output format	.dae, .fbx, .ma, .obj, .ply, .stl, .txt, .wrl, .x3d, .x3dz, .zpr, .3mf
Compatible software	3D Systems (Geomagic® Solutions), InnovMetric Software (PolyWorks), Metrologic Group (Metrolog X4), New River Kinematics (Spatial Analyzer), Verisurf, Dassault Systèmes (CATIA V5, SOLIDWORKS), PTC (Creo), Siemens (NX, Solid Edge), Autodesk (Inventor, PowerINSPECT)
Weight	0.94 kg
Dimension (LxWxH)	79 x 142 x 288 mm
Connection standards	1 X USB 3.0
Operating temperature range	5-40 °C
Operating humidity range	10-90%

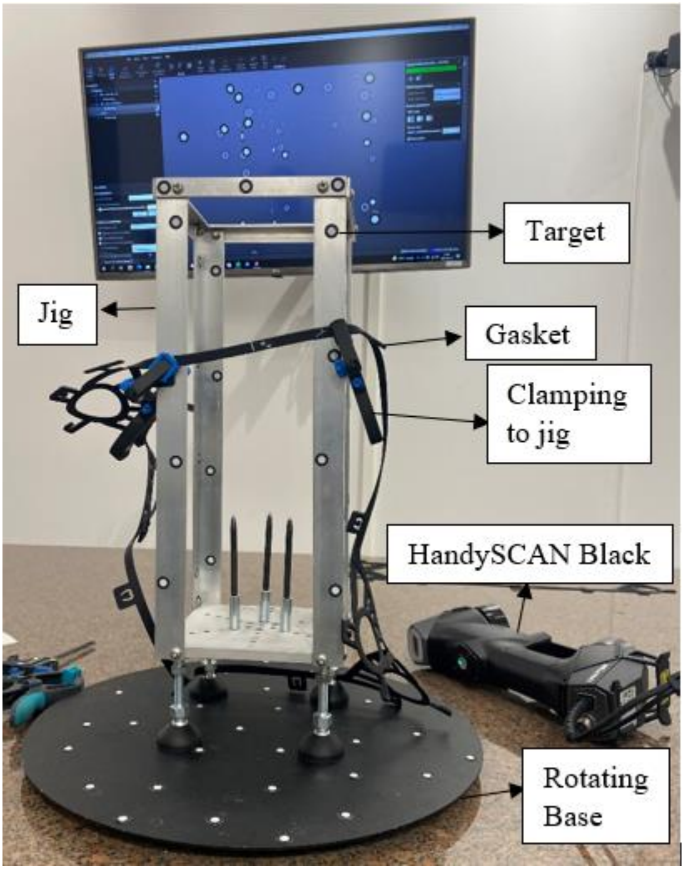


Figure 5.30 HandySCAN hardware setup

We perform scanning on the different sections of the gaskets. Initially, we perform an easy calibration of the HandySCAN using the different motions of the scanner on the calibration board, and the motion will be displayed in the software VXelement shown in Figure 5.31. The target points are placed as a reference to the scanner to consider the target points are the starting point for scanning. The gasket is clamped on the cuboidal jig, which can hold the gasket intact. The scanning of the section is done by moving the scanner to all places so that laser light falls on gaskets at each point on the gaskets section. The camera captures where the laser light falls, and the model is displayed on the software. The scanned image would then be generated by a large number of triangles and generated into .stl format. The image generated after the scanning would look like Figure 5.32.

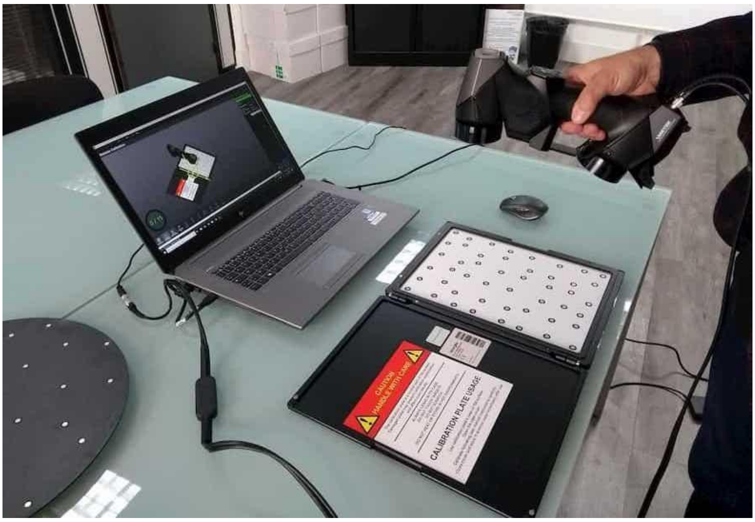


Figure 5.31 Calibration set up [54]

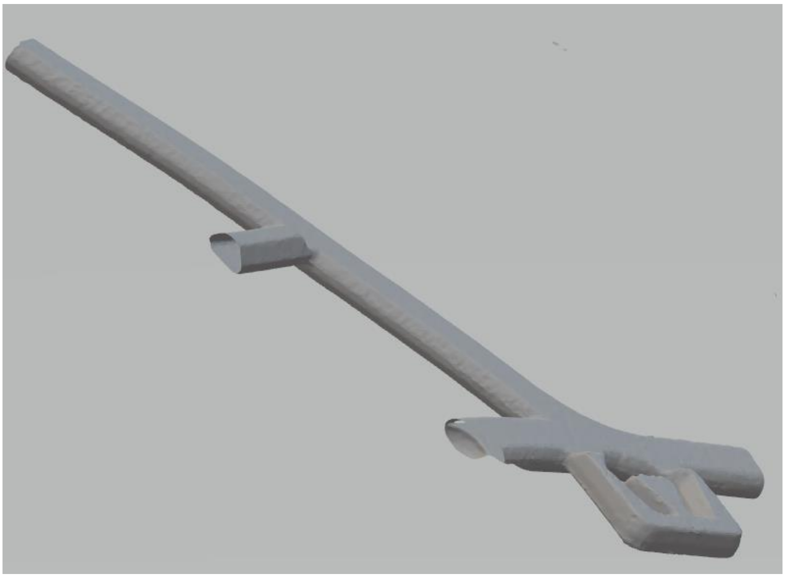


Figure 5.32 Result after scanning

5.2.1.2 Software Setup

In this process, there is two software used for scanning and measuring. The process works as shown in Figure 5.33.

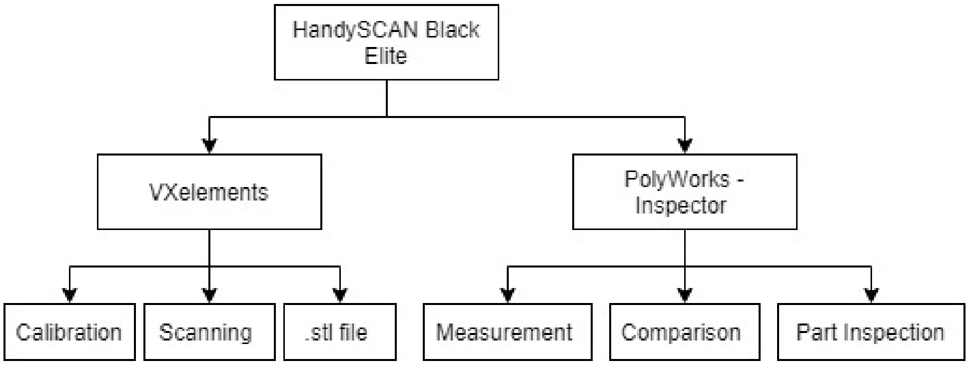


Figure 5.33 Software workflow

Initially, the calibration of the HandySCAN is performed, as shown in Figure 5.31. Then, the data scanning is performed, which is transferred via USB cable to the software VXelement. Then the scanned data is generated by the VXelement and can be converted into .stl format.

The scanned data is then used as an input in the software PolyWorks-Inspector used to further analyze the cross-section in our study. There is an option to merge CAD and the scanned model, which can help compare the measurement of the gasket cross-section. The CAD must be imported into software in .igs format. The measurement is started by alignment of the scanned and the CAD data. Once the alignment is done, there is an option to check the scanned model deviation to CAD as a reference of the CAD and scanned data in the form of colour coding, and from each colour, there is a value linked with it. This can be seen in Figure 5.34. We then proceed with a detailed measurement of the cross-section data to get the values. The parameters can be selected from the CAD model, which can be compared with the scanned data. The tolerances can be set and verified if the parameters lie within the tolerance range. The parameters measured can be seen in Figure 5.36.

After performing the measurements of required parameters, a detailed report can be generated within the software. This can provide the information in a table or picture that is very easy to understand. Some unique results for the process are shared in the following sub-section 5.2.2.

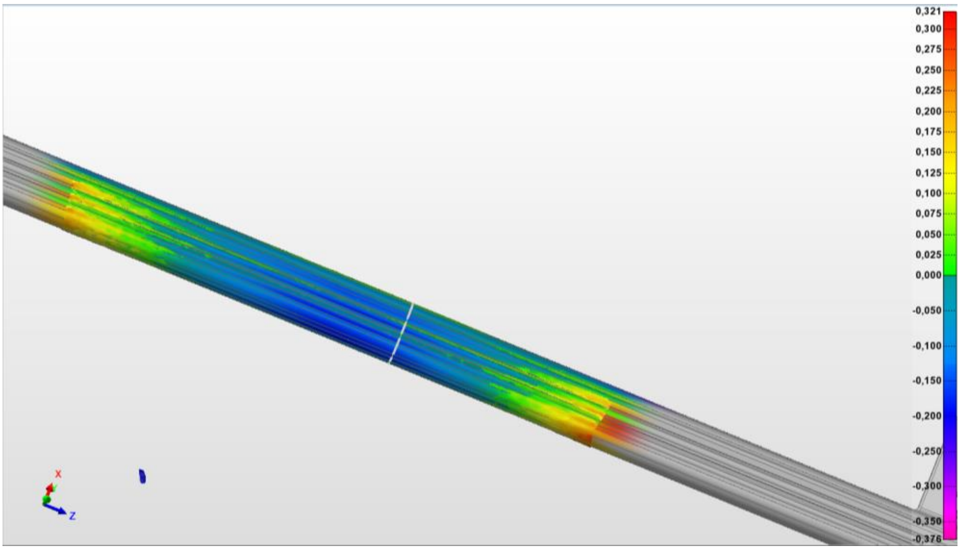


Figure 5.34 Scanned model deviation to CAD as a reference

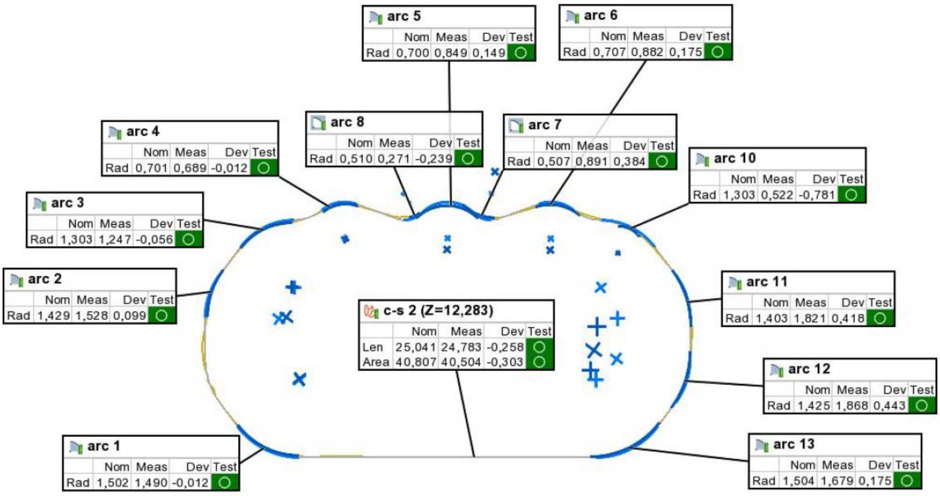


Figure 5.35 Parameter evaluation and comparison

5.2.2 Observations of HandySCAN

In this section, we shall be providing a detailed report of the blue laser measurement. We shall be providing the information of few unique results and exposing some of the issues that occurred during the manufacturing.

5.2.2.1 Gasket A

We have selected this section to understand the issues that occur when manufactured and why measuring cross-section measurement is essential. As seen in Figure 5.36.

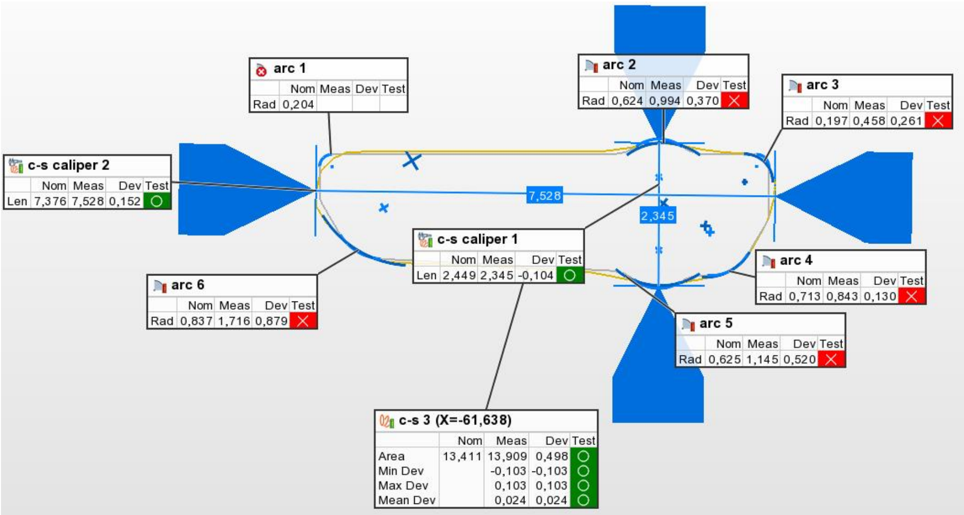


Figure 5.36 Measurement of cross-section parameters for Gasket A

Table 7 Feature's measurement for Gasket A

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
arc 1	Radius	N/A	N/A	N/A	N/A	N/A	N/A
arc 2	Radius	0,624	0,994	±0,100	0,370	Fail	0,270
arc 3	Radius	0,197	0,458	±0,100	0,261	Fail	0,161
arc 4	Radius	0,713	0,843	±0,100	0,130	Fail	0,030
arc 5	Radius	0,625	1,145	±0,100	0,520	Fail	0,420
arc 6	Radius	0,837	1,716	±0,100	0,879	Fail	0,779

Table 8 Cross-section measurement for Gasket A

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
c-s 3 (X=-61,638)	Area	13,411	13,909	±0,800	0,498	Pass	
	Min Deviation		-0,103	±1,000	-0,103	Pass	
	Max Deviation		0,103	±1,000	0,103	Pass	
	Mean Deviation		0,024	±1,000	0,024	Pass	

Table 9 Width Table for Gasket A

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
c-s caliper 1	Length	2,449	2,345	±1,000	-0,104	Pass	
c-s caliper 2	Length	7,376	7,528	±1,000	0,152	Pass	

As we can see from Table 7, the arcs are out of tolerance and have failed the tolerance test. There is one arc that had problems during the measurement, which we will be discussing below:

- **Arc 1 issues:**

In below Figure 5.37, we can see that the curve does not match the CAD model. It is completely off when we compare the manufactured gasket and the CAD model.

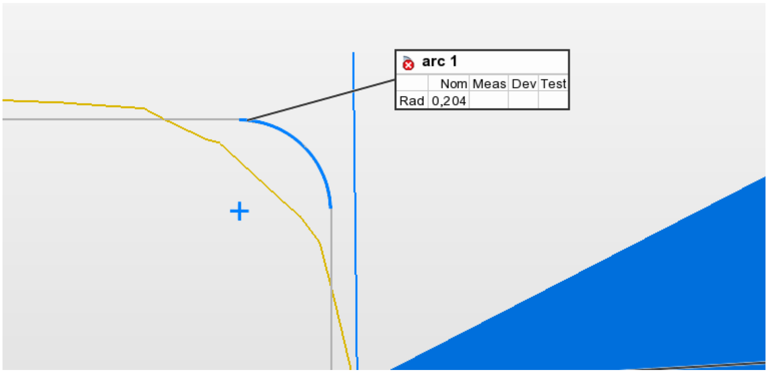


Figure 5.37 Issue in arc 1

Due to such significant variation, the manufactured part has an issue measuring the arc radius.

- **Arc 2- Arc 6 issues:**

From Table 7, we can see that the arc radius 2, arc radius 3, arc radius 4, arc radius 5, arc radius 6 are not within the tolerance limit as we have assumed the tolerance to be ±0.1. We see that Arc 4 has the least and arc 6 has the highest deviation. Arc 4 is almost within the tolerance. We can see in Figure 5.38 that the CAD and scanned parts are almost matching.

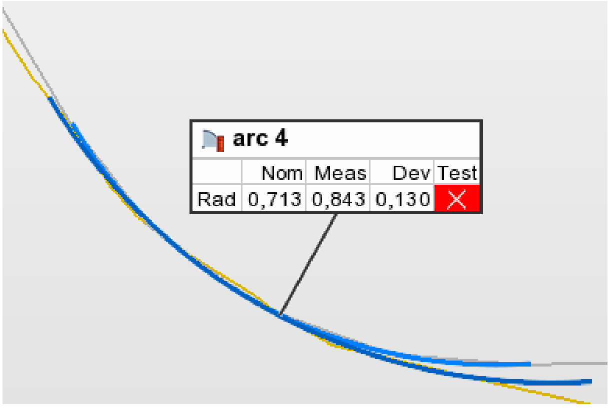


Figure 5.38 Arc 4

In the case of Arc 6, We can see a considerable difference in CAD and scanned models. The curve not matching the CAD and has a much larger radius. This can be seen in Figure 5.39.

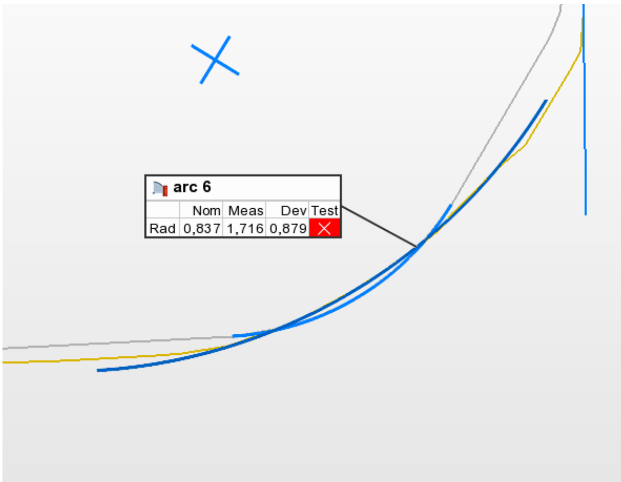


Figure 5.39 Arc 6

The issues mentioned above can have severe repercussions on regular usage when considering fit to gasket grove and leakage performance of the gaskets in the heat exchangers. During our investigation, we found that the FEM calculations are performed considering the CAD model (nominal), and in terms of arc 1 and arc 6, we can see that there is a huge difference.

5.2.2.2 Gasket B

The below Figure 5.40 and below tables gives the critical measurements of the cross-section information of the gaskets.

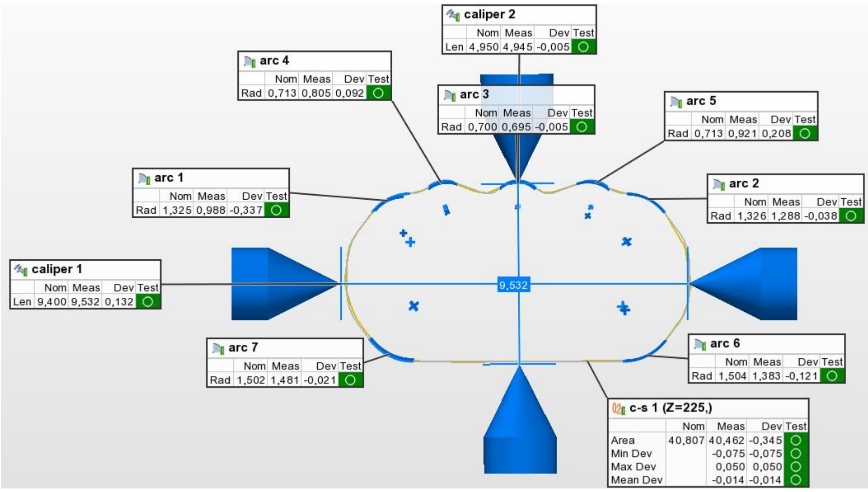


Figure 5.40 Measurement of cross-section parameters for Gasket B

Table 10 Feature's measurement for Gasket B

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol	Warn Test
arc 1	Radius	1,325	0,988	±0,500	-0,337	Pass		Pass
arc 2	Radius	1,326	1,288	±0,500	-0,038	Pass		Pass
arc 3	Radius	0,700	0,695	±0,500	-0,005	Pass		Pass
arc 4	Radius	0,713	0,805	±0,500	0,092	Pass		Pass
arc 5	Radius	0,713	0,921	±0,500	0,208	Pass		Pass
arc 6	Radius	1,504	1,383	±0,500	-0,121	Pass		Pass
arc 7	Radius	1,502	1,481	±0,500	-0,021	Pass		Pass

Table 11 Cross-section measurement for Gasket B

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
c-s 1 (Z=225,)	Area	40,807	40,462	±1,000	-0,345	Pass	
	Min Deviation		-0,075	±1,000	-0,075	Pass	
	Max Deviation		0,050	±1,000	0,050	Pass	
	Mean Deviation		-0,014	±1,000	-0,014	Pass	

Table 12 Width Table for Gasket B

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
caliper 1	Length	9,400	9,532	±1,000	0,132	Pass	
caliper 2	Length	4,950	4,945	±0,150	-0,005	Pass	

We can see some critical parameters measured and compared. Based on the tolerances, the test results are displayed in the report. We can see that all the parameters have passed the quality test in this case.

5.2.2.3 Gasket C

In this type of gasket, we did not have the CAD model available. Therefore, we had to make the comparison by referring to the available drawing. We assessed the parameters mentioned in the drawing, and the measurement results and tables are listed below.

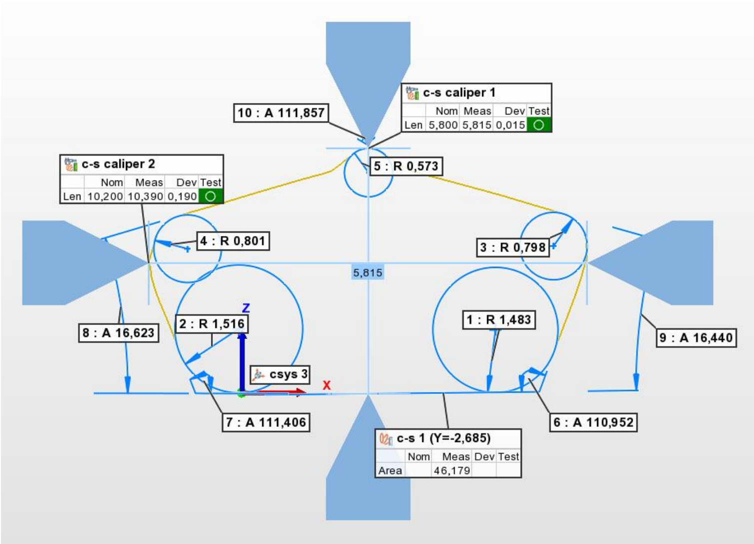


Figure 5.41 Measurement of cross-section parameters for Gasket C

The measurement process for the scanned model without CAD would differ from the conventional method. In this process, the coordinate system will not be appropriate as it does not merge with the CAD and take up the coordinates of the CAD. Hence, we must create a new coordinate system to create a section of the model. The measured parameters are listed in the below table.

Table 13 Length measurement for Gasket C

Caliper Table

Units	Millimeters
Coordinate Systems	csys 3
Data Alignments	original

Name	Control	Nom	Meas	Tol	Dev	Test
c-s caliper 1	Length	5,800	5,815	±0,200	0,015	Pass
c-s caliper 2	Length	10,200	10,390	±0,500	0,190	Pass

Table 14 Radius and angle measurement for Gasket C

Name	Index	Type	Nominal	Measured	Deviation
radius 1	1	Radius	1,500	1,483	-0,017
radius 2	2	Radius	1,500	1,516	0,016
radius 3	3	Radius	0,500	0,798	0,298
radius 4	4	Radius	0,500	0,801	0,301
radius 5	5	Radius	0,500	0,573	0,073
angle 1	6	Angle	110,000	110,952	0,952
angle 2	7	Angle	110,000	111,406	1,406
angle 3	8	Angle	16,000	16,623	0,623
angle 4	9	Angle	16,000	16,440	0,440
angle 5	10	Angle	90,000	111,857	21,857

Table 15 Area measurement for Gasket C

Name	Control	Nom	Meas	Tol
c-s 1 (Y=-2,685)	Area		46,179	±1,000

We observed during our investigation that angle on top is supposed to be 90º, but the measured angle is 111.857º, as shown in Table 14. This can be due to manufacturing problems or fault tooling models.

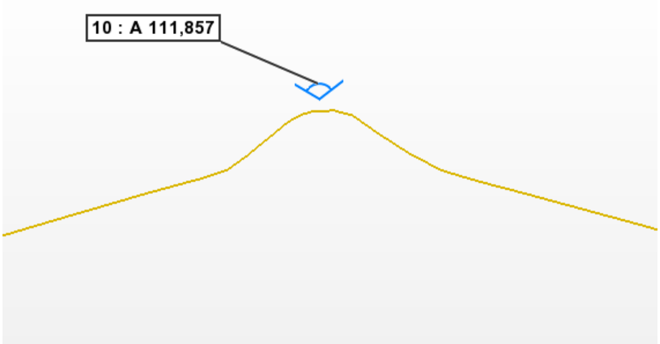


Figure 5.42 Top angle.

5.2.3 SWOT Analysis

This sub-section gives the SWOT analysis of the handheld 3D scanning based on the observations made above.

Table 16 SWOT analysis of Hand-held scanner

	Helpful	Harmful
Internal	S **i.** Parameters can be selected on the CAD, which makes it easy to select and compare. **ii.** All the cross-section parameters can be measured by this method. **iii.** The report generated is easy to understand, and a template can automatically generate quality reports. **iv.** Portable device and can be used in the manufacturing area if there are any problems.	**i.** The flash measurement is tough to measure due to the resolution of the scanner. **ii.** For the best scanning, the jig to hold the gasket is essential. **iii.** Some curves are photographed as a line due to resolutions. This can be seen in Figure 5.37. **iv.** The target points must be placed in the right positions, and once the scanning starts, the gasket position must not change. The scanner can be rotated, but the gasket must be stationary.
External	O **i.** This provides all the parameters measurements of the cross-section. **ii.** This can help ensure that the measured parameters are within tolerance range so that the FEM analysis can be replicated in the manufactured gaskets. **iii.** This can help Alfa Laval get secure Quality assurance. **iv.** In terms of accuracy, it is much better compared to other technology.	T **i.** Investment is very high comparatively. The software license is an extra added cost. **ii.**Training is time-consuming and requires four days, as proposed by the supplier.

6 Data Validation

When data is obtained from any experimental process, it is necessary to check the accuracy of data. We are testing the reliability of data obtained in the experimental process by comparing the results with another much-advanced process of accuracy and precision. Data validation is required so that the working team may have complete confidence in the results. There is a risk of an imperfect picture that does not reflect the actual condition of the case if data is not validated. In measurement systems, data validation is defined as gathering and evaluating data that will give scientific evidence that the system can consistently give quality outputs [58].

Data validation is done for data obtained using laser triangulation technique and hand-held 3D scanning devices in this thesis work. This is achieved by comparing the data of the above measurement techniques with the results obtained from Light Optical Microscope (LOM).

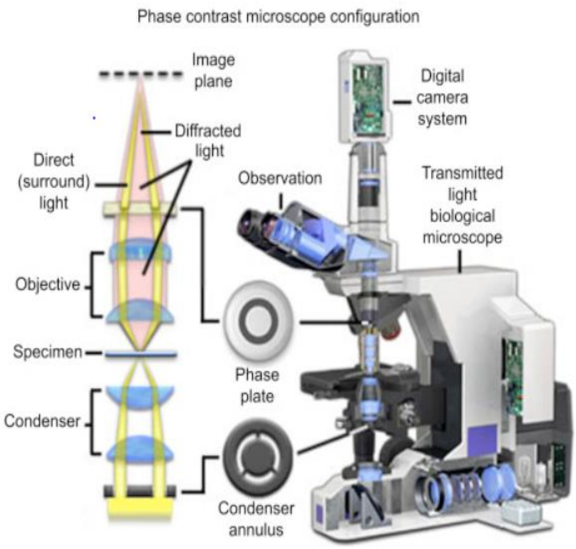


Figure 6.1 Schematic diagram of LOM

Manufactured by Leica microsystems, this microscope is known as a Light Optical Microscope because it magnifies the picture of the object using visible light and a couple of lenses. It creates a magnifying image using no. of lenses that focus the beam of light on the object, and convex objective lenses are used to magnify the image [59]. When light passes from one medium to another, it bends at the interface due to refraction. The Refractive index will determine the speed of light.

LOM is an incredibly versatile tool for many different applications. They can be used in many varieties of applications with minimal preparation. These microscopes provide a wide range of information on physical and chemical attributes. Images obtained can be easily transferred to the computer, where further analysis is performed. These instruments are relatively less expensive and require very low maintenance [60]. Magnification ranges from x10 – x1000 [59]. With better magnification, better image quality is obtained, and measurements can offer high levels of observational quality with better accuracy and precision.

When it comes to Leica M205C, it is the world's first stereo microscope to achieve an optical resolution of 0.952µm. It can consistently deliver calibrated and similar images. System settings can be saved with images and can be recalled whenever required. This will make the results accurate and reliable. Fusion optical technology from Leica will combine the best information of the depth of field and high resolution. It also has a wide variety of choices on how the light falls on the sample, making a difference. We have ring light illumination, which will provide bright and uniform illumination over a large object field. It also has spotlight illumination where high contrast lighting falls directly on the sample [61].

Table 17 Technical specifications of Leica M205 C [61]

Technical Specification	Leica M205 C
Zoom	20.5:1
Magnification	7.8x – 160x
Resolution	Max. 525lp/mm
Working distance	61.5mm
Object field	Ø29.5mm – 1.44mm
PC interface	USB
Software used	Leica Application Suite X software

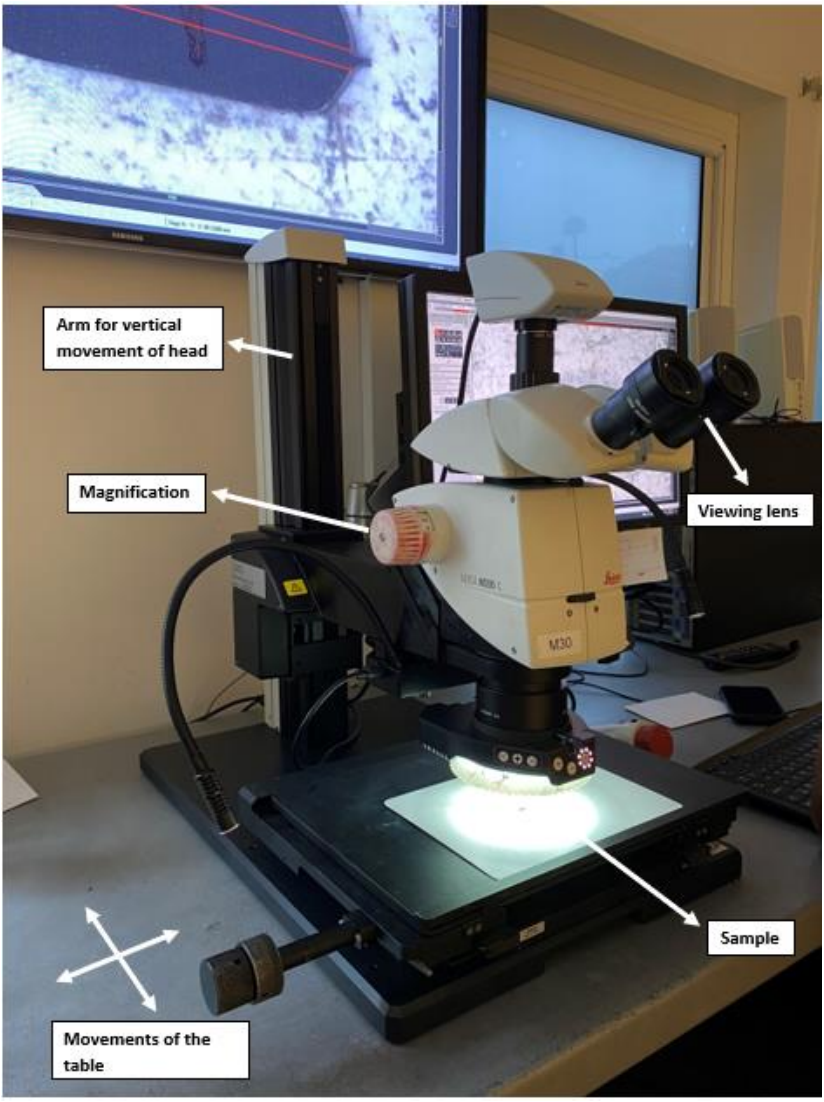


Figure 6.2 Image of Leica M205 C

Gaskets are used in LLT and handy scanners to obtain measured data, and the same gaskets are used to make observations using LOM. But the gaskets are cut using a customized cutter to get a small cross-section. This section is kept under the microscope, and desired results are obtained, as shown in Figure 6.2.

6.1 Comparison of Data

In this section, we will compare the data obtained during our investigation of the cross-section with two different techniques and compare it with the LOM method to check the precision of the measurement.

For the comparison, we have used similar gaskets with a similar section marked on the gasket. The marked point first underwent the measurement of the cross-section using the LLT method. The results are tabulated and are attached in Appendix. Some of the results are shown in Chapter 5, sub-section 5.1.2. We then use the same marked point by scanning the section by HandySCAN Black Elite, and the results are shown in Chapter 5 sub-section 5.2.2, and some results are displayed in Appendix. After the measurement is performed, we then move on to cut the sections of the gaskets using the customized cutter shown in Figure 4.11 chapter 4. After the sections are cut, we place them under the microscope and perform measurements using the microscopic imaging software by Leica. The result of the following process is shown in subsections.

6.1.1 Gasket A

Here we shall be comparing the measurement of 3900840504 HR4-P End Plate Gasket on section A-A. The HandySCAN data is taken from Appendix 11.5.

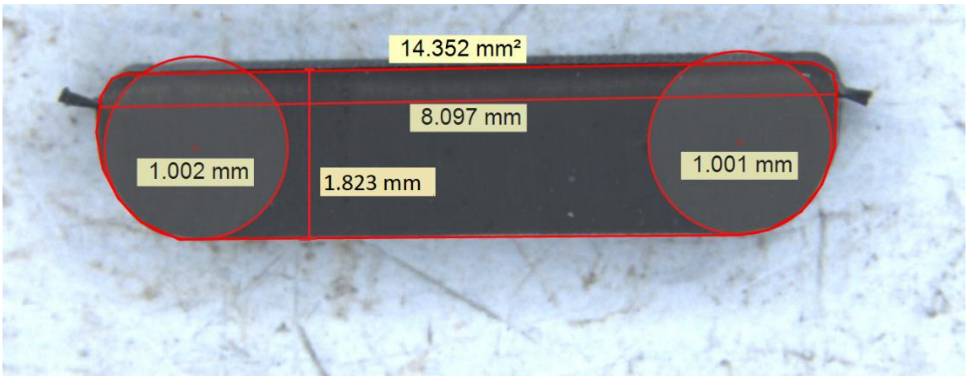


Figure 6.3 LOM measurement result for the gasket A

Table 18 Parameter measured for the gasket A

Measurement method	1. Area (mm^2)	2. Width (mm)	3. Radius Left (mm)	4. Radius Right (mm)	5. Height (mm)
LLT	13.7173	8.09	0.8033	0.80593	
HandyScan	14.325	8.171	0.916	0.975	1.855
LOM	14.532	8.097	1.002	1.001	1.86

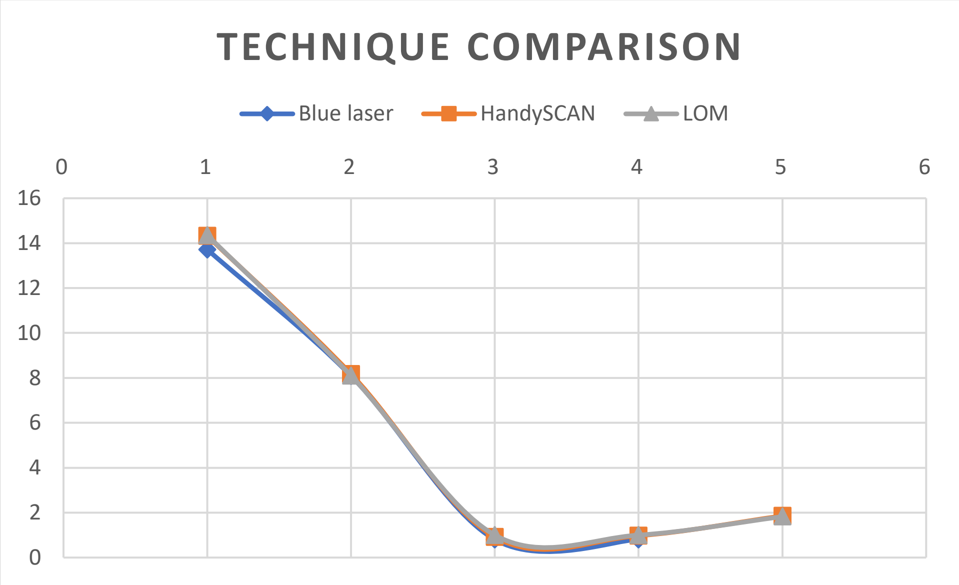


Figure 6.4 Scatter diagram for Technique comparison of gasket A

From *6.4*, it is evident that the HandySCAN is very close to the validation method (LOM). As we can see, the orange curve and grey curve intersecting each other throughout.

6.1.2 Gasket B

Here we are comparing section A-A of the gasket 3900840455 DR15-M Field gasket (WedgeGrip LP). The scatter diagram gives the details regarding the two techniques and how close they are to the LOM method.

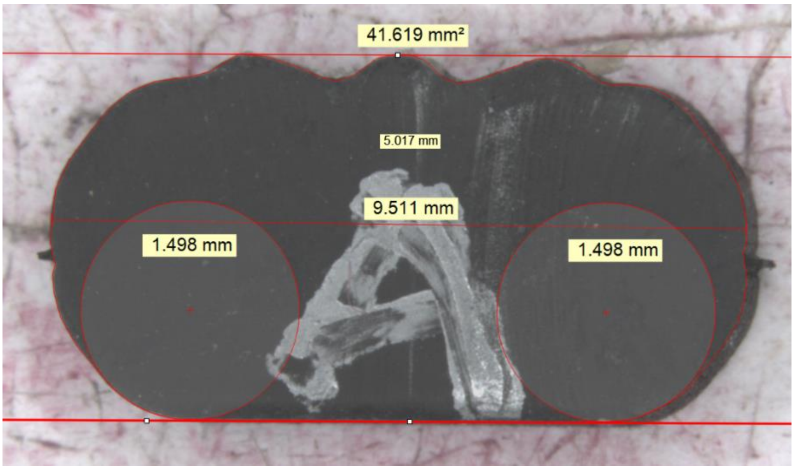


Figure 6.5 LOM measurement result for the Gasket B

Table 19 Parameter measured for the Gasket B

Measurement method	1. Area (mm^2)	2. Width (mm)	3. Radius Left (mm)	4. Radius Right (mm)	5. Height (mm)
LLT	40.123	9.541			
HandyScan	40.462	9.532	1.481	1.383	4.945
LOM	41.619	9.511	1.498	1.498	5.017

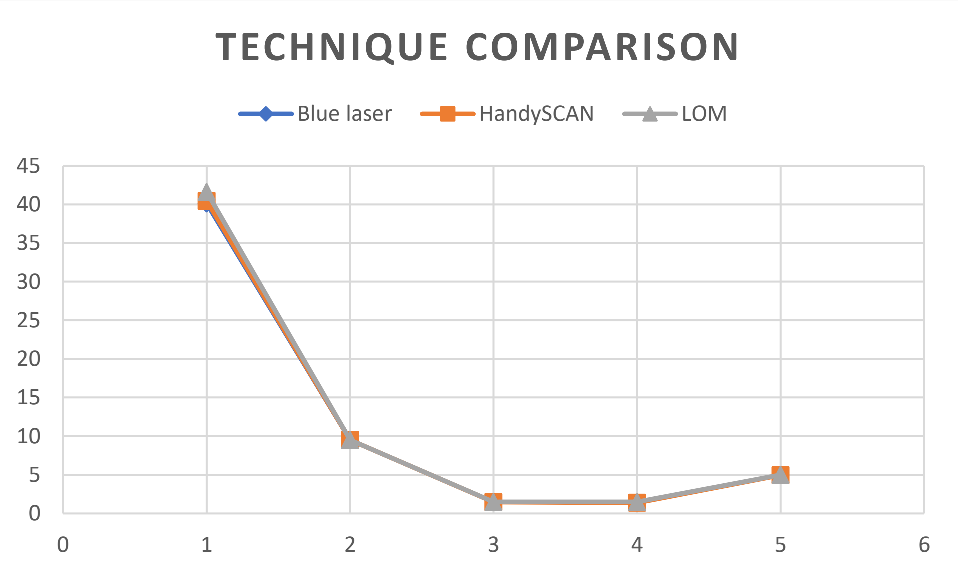


Figure 6.6 Scatter diagram for Technique comparison of Gasket B

From the above graph in Figure 6.6, we can see that the values are pretty close to the method used for validation (LOM) in terms of width, but HandySCAN is slightly ahead in terms of area. The radius can be measured in the LLT method, but the height measurement can be complicated as there is a dependency on Flash, as mentioned in section 5.1.3 in Chapter 5.

6.1.3 Gasket C

Here we shall be performing the validation for the gasket 39005612-27 PHE Clip-10. The below Figure 6.7 shows the measurement of the gasket section A-A on the LOM method by microscopic imaging software.

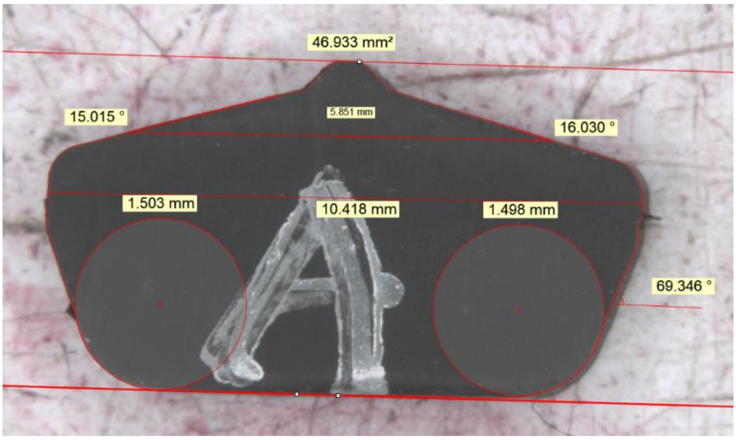


Figure 6.7 LOM measurement result for the Gasket C

Table 20 Parameter measured for the Gasket C

Measurement method	1. Area (mm^2)	2. Width (mm)	3. Radius Left (mm)	4. Radius Right (mm)	5. Height (mm)	6. Angle Left (^{0})	7. Angle Right (^{0})
LLT			1.517	1.517		16.389	16.389
HandySCAN	46.179	10.39	1.516	1.483	5.815	16.62	16.44
LOM	46.993	10.418	1.503	1.498	5.851	15.015	16.03

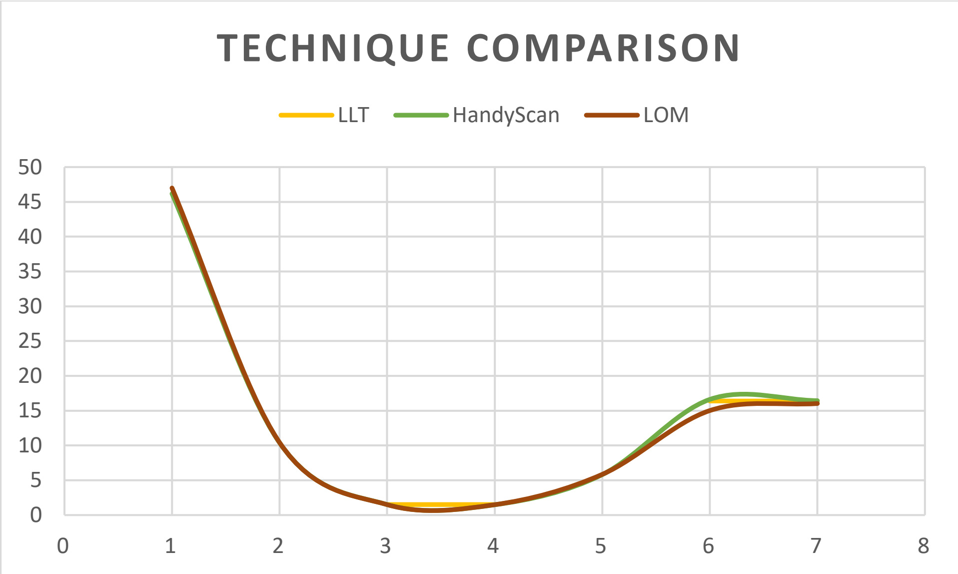


Figure 6.8 Scatter diagram for Technique comparison of Gasket C

In Table *19*, we can see that the LLT method has some empty parameters. This is due to the unavailability of the flash in the gasket, which is critical in measuring the LLT method, as mentioned in Section 5.1.3 in Chapter 5. Otherwise, we can see that HandySCAN matches closely with the LOM and LLT methods with few parameters.

This validation process helps set a base for Chapter 7 and helps further select the best process for measuring the gasket cross-section.

7 Result

This chapter will understand the selection of the fitting process using Multi-Criteria Decision Making (MCDM) called Analytical Hierarchy Process (AHP). By making an analytical study, we select the best process.

Step.1 Determine the goal and list the criteria.

The goal is to determine the best process among the laser triangulation technique and a hand-held scanner. The list of criteria selected to determine the best process is cost, data accuracy, ease of use, and measurement time.

Step.2 Determine the pairwise comparison matrix.

$$W = \left[\frac{w_i}{w_j}\right] = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix}$$

Where i, j= 1,2, …n
w = vector of current weights of alternative

Table 21 Pairwise Comparison matrix

	Cost	Data Accuracy	Ease of use	Measuring Time
Cost	1	1/7	1/5	1/3
Data Accuracy	7	1	2	3
Ease of use	5	1/2	1	3
Measuring Time	3	1/3	1/3	1
Sum	16	1.9728	3.53	7.33

In the above matrix, we have considered four different parameters. By comparing the parameters, the matrix is completed on a scale of 1-9. When we compare the cost with cost, it will have equal importance. This will be the same when we compare the same criteria with each other. These values are given based on the priorities one would consider when implementing a new measurement technique to replace the existing measurement technique.

When cost is compared with data accuracy, data accuracy has been given more importance. On the scale of relative importance, it is seven times more important than cost. Without data accuracy, any process with high cost will result in a wrong solution of the components. With better data accuracy, it will lead to better decision-making and increased productivity.

Similarly, when the cost is compared with the ease of use, ease of use has scaled five-time than cost. A machine with better features to test out the products and user-friendly will significantly impact the results compared to cost. Likewise, measuring time has been scaled three times the cost. The machine which results in quick output in a short period should be given a greater priority.

When data accuracy and ease of use are weighed up, data accuracy has been given twice the priority. If better results can be obtained with a diligent measurement technique, it should be recommended. Time is also a factor to be considered.

Both data accuracy and ease of use have been scaled three times higher than measuring time. Since the above two factors will determine the product's overall performance in terms of customer satisfaction, usefulness, and trust, they are scaled higher than measuring time.

The next step would be to divide each criterion’s value with the sum of the respective column, as shown in the above table.

$$= [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & 1 \end{bmatrix}$$

Table 22 Pairwise comparison matrix

	Cost	Data Accuracy	Ease of use	Measuring Time
Cost	1/16	0.1428/1.9728	0.2/3.53	0.33/7.33
Data Accuracy	7/16	1/1.9728	2/3.53	3/7.33
Ease of use	5/16	0.5/1.9728	1/3.53	3/7.33
Measuring Time	3/16	0.33/1.9728	0.33/3.53	1/7.33

Step.3 Calculate the normalized pairwise comparison matrix and determine the criteria weight.

Normalization matrix

$$a_{ij}^{*} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

For all j= 1,2, …n

	Cost	Data accuracy	Ease of use	Measuring time	Criteria Weights
Cost	0.0625	0.0724	0.0566	0.0450	0.059125
Data accuracy	0.4375	0.5076	0.5665	0.4092	0.4802
Ease of use	0.3125	0.2538	0.2832	0.4092	0.3146
Training	0.1875	0.1675	0.0934	0.1364	0.1462

Criteria weights are calculated as the average sum of the rows.

For e.g.: (0.0625+0.0724+0.0566+0.0450)/4 = 0.059125

When all the criteria weights are added up, the sum should be equal to 1. Hence, we can verify that we are on the right track.

Weight calculation

$$W_i = \frac{\sum_{i=1}^{n} a_{ij}^*}{n}$$

Here we take the comparison matrix to be multiplied with criteria weights of each column as shown below.

Criteria weights	0.059125	0.4802	0.3146	0.1462
	Cost	Data accuracy	Ease of use	Measuring time(MT)
Cost	1 ∗ 0.059125	0.1428 ∗ 0.4802	0.2 ∗ 0.3146	0.33 ∗ 0.1462
Data accuracy	7 ∗ 0.059125	1 ∗ 0.4802	2 ∗ 0.3146	3 ∗ 0.1462
Ease of use	5 ∗ 0.059125	0.5 ∗ 0.4802	1 ∗ 0.3146	3 ∗ 0.1462
Training	3 ∗ 0.059125	0.33 ∗ 0.4802	0.33 ∗ 0.3146	1 ∗ 0.1462

Weighted sum value is sum of the row. For e.g.,
0.059125+0.0685+0.0629+0.0482 = 0.2387

Step.4 Check for consistency of the matrix.

To check for consistency of the matrix, we need to have λ_{max}.

	Cost	Data accuracy	Ease of use	MT	WSV	Criteria weights
Cost	0.059125	0.0685	0.0629	0.0482	0.2387	0.059125
Data accuracy	0.413875	0.4802	0.6292	0.4386	1.9618	0.4802
Ease of use	0.295625	0.2401	0.3146	0.4386	1.2889	0.3146
Training	0.17737	0.1584	0.1038	0.1462	0.5857	0.1462

The next step is to find the ratio between weighted sum value and criteria weights.

$$\textbf{Ratio} = \begin{pmatrix} 4.037 \\ 4.085 \\ 4.096 \\ 4.006 \end{pmatrix}$$

Now, λ_{max} is average sum of the ratio between WSV and criteria weights.

$$\lambda_{max} = \frac{4.037+4.085+4.096+4.006}{4} = 4.056$$

$$CI = \frac{(\lambda_{max} - n)}{(n-1)}$$

CI=0.01866

We have a Consistency ratio, CR

$$CR = \frac{CI}{RI}$$

CR= consistency ratio
RI = random consistency index i.e., 0.9 from

CR=0.0207 < 0.10

The results say that weights are considered as well suitable in our case. Here 0.10 states that 10% consideration is provided for inconsistency ratio. Our result obtained is 2.07%.

The following steps would be to select the best process. We have

$$\begin{pmatrix} Cost \\ Data\ accuracy \\ Ease\ of\ use \\ Measuring\ time \end{pmatrix} = \begin{pmatrix} 0.059125 \\ 0.4802 \\ 0.3146 \\ 0.1462 \end{pmatrix} \begin{matrix} IV \\ I \\ II \\ III \end{matrix}$$

According to the matrix, we can say that cost is given the least priority. High Priority has been given to data accuracy, and the next priority is given to ease of use. The third priority is given to measuring time.

Now that we have two processes to choose from, the next step is prioritizing alternatives concerning each other's criteria.

Table 23 Criterion's data

	Cost	Data accuracy	Ease of use	Measuring time
LLT	100,000	95.39	Better (5)	18min. approx.
Handheld scanner	790,000	97.89	Excellent (8)	12min. Approx.

To select the best process, we need cost to be minimum, data accuracy to be high, ease of use to be high, and measuring time to be less. Data accuracy calculations are attached in Appendix 11.4.

Table 24 Criterion's table

	Cost	Data accuracy	Ease of use	Measuring time
LLT	$\frac{100,000}{100,000}$	$\frac{95.39}{97.89}$	$\frac{5}{8}$	$\frac{12}{18}$
Handheld scanner	$\frac{100,000}{790,000}$	$\frac{97.89}{97.89}$	$\frac{8}{8}$	$\frac{12}{12}$

In Table 24, we are trying to normalize the matrix. So, with the most negligible value, we will be making the ratio of the data.

Table 25 criteria weights for alternatives normalized matrix

Criteria weights	**0.059125**	**0.4802**	**0.3146**	**0.1462**
	Cost	Data accuracy	Ease of use	Measuring time
LLT	1	0.974	0.625	0.6667
Hand-held scanner	0.125	1	1	1

Now, criteria weights from the earlier normalized matrix will be multiplied with the normalized matrix of alternatives form.

LLT = (0.059125*1) + (0.4802*0.974) + (0.3146*0.625) + (0.1462*0.6667) = 0.8204 = 82.04%

Hand-held scanner = (0.059125*0.125) + (0.4802*1) + (0.3146*1) + (0.1462*1) = 0.94847 = 94.847%

Overall priority of the alternatives can help conclude that a hand-held scanner is a better option than the LLT.

8 Discussion

Investigation of the current method resulted in minimum emphases given to the cross-section, which was a massive gap in the current QC process. The current destructive method is rarely used due to destroying techniques and time-consuming. We have found that the assemblers have faced issues while assembling the gaskets during our study, the gaskets batch which had passed the quality check had the issue, and when backtracked, it was found that the issue was with the cross-section geometry. Due to some out-of-tolerance in the gasket, geometry could affect the performance of the gasket in terms of leakage. By analyzing the cross-section parameters, the issues with these regards can be avoided. Hence the research topic is significant in terms of the performance of heat exchangers.

The main aim of our thesis was to find the most feasible method of measuring the gasket cross-section parameters used in heat exchangers. By investigating different techniques, we have concluded. We performed various trials to understand the system's user-friendliness by in-depth studying LLT and handheld 3D scanning methods. We successfully measured gaskets of different geometry to measure different parameters like radius, angles, area, width, height, etc. We conclude that the data is reliable and accurate by validating the data acquired by techniques like LLT and the handheld 3D scanning method. Introducing the method of decision-making model and successful implementation of the AHP process has provided analytical proof of the capabilities of the best process that can be selected.

In the decision-making model like AHP used in Chapter 7 where we compared the LLT and Handheld 3D scanning method in terms of four features listed below:

- Cost
- Data Accuracy
- Ease of use
- Measuring time

According to the company's priorities, we have set the weight for each criterion to select the best technique, as shown in Table 23. This is explained in detail in Chapter 7. Based on the weights used for each criterion, a normalized pairwise matrix is generated. This helped us determine the best technique that is more relevant for Alfa Laval in terms of quality. We have found that the best way to measure the gasket cross-section will be by scanning the cross-section using Handheld 3D scanning, which is explained in Chapter 5 and Section 5.2. The handheld scanner used by us in the thesis, Creaform’s HandySCAN Black Elite, and the software package of Polyworks are effective in terms of user-friendliness, measuring accuracy, and time for measurement. It is seven times more expensive concerning cost, but Alfa Laval can use it for many other requirements in terms of metrology and heat exchanger valves. The scope of the scanner is high for various applications, and this can help the department in terms of modernization by digitalizing the quality practice.

To implement this technique as routine in Alfa Laval, it will be essential to train the workforce in the scanning equipment. MLT Maskin & Laser Teknik AB's training team will offer the training program, the authorized reseller of Creaform HandySCAN Black Elite. The training in terms of Polyworks software must be offered to a dedicated person who can be responsible for the same. Training the workforce in the quality department will also help in modernizing, which can lead Alfa Laval towards a technologically advanced future.

The main strength of the thesis is that it provides a detailed comparison of the two techniques and how these processes obtain the result. The comparison and selection of the proper technique are justified with analytical proof, which helps validate the result. These measurement processes have a much larger scope in terms of quality assurance. The details given in the thesis can be used to make other future studies for measuring other components. The SWOT analysis gives details regarding the positives and negatives of the equipment, which can be used as a base to work on for improvement in the future. The limitation of the thesis is that analysis is performed for gasket cross-sections, as we have set the limitations. There can be ways to scan the gasket thoroughly and analyze more features like length, radius, overall volume, etc.

In terms of the future, there must be some additional investigation in some critical regards to implementing the technique successfully. The future scope of the thesis is listed below:

- The plan for implementation of personnel and training must be performed, and the economic analysis must be analyzed to implement the investment process. Personnel cost and overheads must be performed to understand the return on investment (ROI).
- To perform the scanning better, there must be work by implementing a customized Jig that can hold the gasket to get all the details during the scanning process.
- Setting standards in terms of tolerances must be something that should be worked on in the future. Some parameters in the cross-section have very tight tolerance, and some have no mention of tolerance. This can help in making the process of measuring and analyzing much easier.

- A study must be performed for the various applications so that the technology is limited to gaskets and can also be used for other components.
- Some quality practices must be implemented in the quality department to help find the common issues by suppliers and document the issues. Using cause and effect charts and processes like Statistical process control (SPC) can help find common issues and avoid them.
- FEM calculation simulation can be performed for out-of-tolerance models of cross-section scanned by Handheld 3D scanning to understand the effects of variation.
- It is also vital that gaskets have 3D models in Creo parametric so that analyzing the phase of the gasket can be done much quicker.

9 Conclusion

In this master thesis, the problem under investigation was to find a way to measure the cross-section geometries as this can directly impact the heat exchangers in terms of leakage and the gasket's performance. The geometrical difference can have a significant impact in terms of quality and performance. Today's methods are destructive and have a long lead time. The most commonly used non-destructive technique is to measure the thickness alone.

Our analysis of the various measuring instruments can be used for a detailed analysis of the cross-section. The research question is successfully answered and validated by performing a decision-making model. We have provided a detailed analysis of why the investment in this particular technique is essential and listed all the pros and cons of the technology.

The implications of the thesis work can directly impact the quality department and R&D department as they can understand the problems and the gaps in the manufacturing process. The R&D department can use this technology to understand and analyze the capabilities of the moulding technique used in manufacturing the gaskets and from a design perspective. The quality department can use this technique in the assembly line due to its portable abilities when there is a problem in assembly so that the gasket issues can be analyzed.

10 References

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11 Appendix

11.1 Blue lasers LLT excel (Gasket A)

3900840504- End plate gasket

CAD model Spec's	A-A	B-B	C-C	D-D
Cross-section area	13.9	11.2	13.7	13
Width	8	7.2	7.6	7.5
Height	1.8±0.15	2.05±0.15	2.2±0.15	1.8±0.15

Sample-2				
Blue laser results (mean values)	A-A	B-B	C-C	D-D
Cross-section area	13.92	10.76	13.1	12.644
Width	8.02	7.245	7.641	7.58
Height	*can be measured*			
Flash height-R (mm)	0.2678	0.095	0.202	0.2149
Flash height-L (mm)	0.156	0.122	0.1079	0.368

Sample-3				
Blue laser results (mean values)	A-A	B-B	C-C	D-D
Cross-section area	13.71	10.77	13.25	12.291
Width	8.09	7.248	7.605	7.04
Height	*can be measured*			
Flash height-R (mm)	0.286	0.081	0.1341	0.0238
Flash height-L (mm)	0.166	0.041	0.2271	0.2355

Sample-4				
Blue laser results (mean values)	A-A	B-B	C-C	D-D
Cross-section area	13.612	10.91	13.23	12.874
Width	8.15	7.387	7.662	7.621
Height	*an be measured*			
Flash height-R (mm)	0.182	0.202	0.095	0.425
Flash height-L (mm)	0.1122	0.04	0.27904	0.159

11.2 Blue lasers LLT excel (Gasket B)

3900840455-06 Field gasket WedgeGrip LP		
CAD model spec's	A-A	B-B
Cross-section area(mm2)	40.84	39.44
width (mm)	9.4	8.9
Height (mm)	4.95±0.15	5.1±0.15
Sample-2		
Blue laser results (mean values)	A-A	B-B
Cross-section area(mm2)	39.55	39.41
width (mm)	9.494	8.993
Height (mm)	***can be measured***	
Flash height-R (mm)	0.289	0.12
Flash height-L (mm)	0.06	0.153
Sample-3		
Blue laser results (mean values)	A-A	B-B
Cross-section area(mm2)	40.123	39.16
width (mm)	9.627	8.975
Height (mm)	***can be measured***	
Flash height-R (mm)	0.0975	0.1985
Flash height-L (mm)	0.08132	0.048
Sample-4		
Blue laser results (mean values)	A-A	B-B
Cross-section area(mm2)	39.573	38.751
width (mm)	9.541	8.932
Height (mm)	***can be measured***	
Flash height-R (mm)	0.1829	0.0593
Flash height-L (mm)	0.1122	0.2102

11.3 Blue lasers LLT excel (Gasket C)

39005612-27 PHE Clip-10			
CAD Model Spec's	A-A	B-B	C-C
Area (mm2)	*Not specified in the CAD drawing*		
Inner width (mm)	8.06	7.66	7.66
Outer width (mm)	10.2	9.8	9.8
Radius on top(mm)	0.5	1	0.5
Radius at bottom (mm)	1.5	1.5	1.5
Angle on top	16	19	16
Angle outside	70	70	70
Angle on top edge	90	***NS***	90
Sample-4			
Blue laser results (mean values)	A-A	B-B	C-C
Area (mm2)	*Not specified in the CAD drawing*		
Inner width (mm)	7.828	7.389	7.65
Outer width (mm)	*not measured but can be measured*		
Radius on top(mm)	0.599	*not measured but can be measured*	
Radius at bottom (mm)	1.517		
Angle on top	16.389	19.3405	16.47
Angle outside	69.45	68.952	69.92
Angle on top edge	90.42	NS	*can be measured*
Sample-3			
Blue laser results (mean values)	A-A	B-B	C-C
Area (mm2)	*Not specified in the CAD drawing*		
Inner width (mm)	7.964	7.368	7.658
Outer width (mm)	*not measured but can be measured*		
Radius on top(mm)	0.5966	*not measured but can be measured*	
Radius at bottom (mm)	1.89		
Angle on top	15.85	19.8	15.46
Angle outside	69.85	69.96	71.24
Angle on top edge	91.79	NS	*can be measured*
Sample-2			
Blue laser results (mean values)	A-A	B-B	C-C
Area (mm2)	*Not specified in the CAD drawing*		
Inner width (mm)	7.574	7.241	7.661
Outer width (mm)	*not measured but can be measured*		
Radius on top(mm)	0.641	*not measured but can be measured*	
Radius at bottom (mm)	1.535		
Angle on top	15.67	19.09	16.93
Angle outside	70.97	71.25	74.12
Angle on top edge	92.75	NS	*can be measured*

11.4 AHP calculation for data accuracy

AHP Calculation for Data Accuracy						
3900840504 HR4-P	Area	Width				
LLT	13.7173	8.09	LLT/LOM	94.39375172		
Handy scanner	14.325	8.17	Handy scanner/LOM	98.57555739	Avg. Of LLT/LOM	95.39962
LOM	14.532	8.097			Avg. Of Handyscanner/LOM	97.89779
3900840455 DR15-M	Area	Width				
LLT	40.123	9.541	LLT/LOM	96.40548788		
Handy scanner	40.462	9.532	Handy scanner/LOM	97.2200197		
LOM	41.619	9.511				

11.5 HandySCAN Gasket A (Data)

Feature Table

Length Units	Millimeters
Coordinate Systems	world
Data Alignments	best-fit to ref 1

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
arc 1	Radius	0,800	0,975	±1,000	0,175	Pass	
arc 2	Radius	0,802	0,916	±1,000	0,114	Pass	

Cross-Section Table

Units	Millimeters
Coordinate Systems	world
Data Alignments	best-fit to ref 1

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
c-s 1 (Z=68,011)	Area	13,842	14,325	±1,000	0,483	Pass	

Caliper Table

Units	Millimeters
Coordinate Systems	world
Data Alignments	best-fit to ref 1

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
c-s caliper 1	Length	1,800	1,855	±0,150	0,055	Pass	
c-s caliper 2	Length	8,000	8,171	±0,500	0,171	Pass