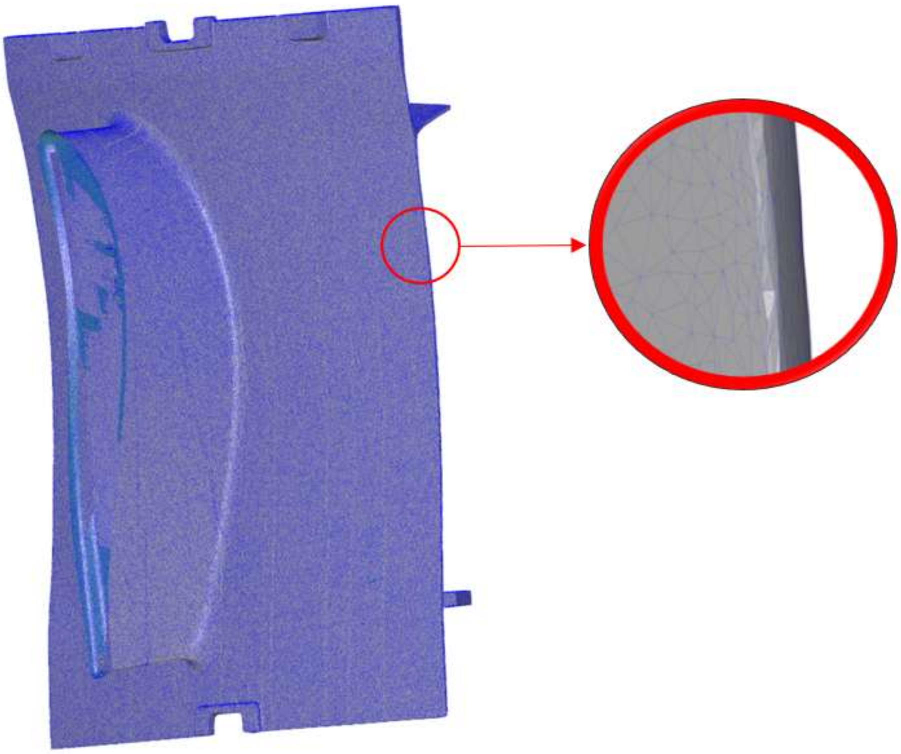

# Strategies for Robust Fabrication using RD&T

Bachelor Thesis in Mechanical Engineering

ANNA JÖNSSON
ANTON LANQVIST

**DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE**

CHALMERS TEKNISKA HÖGSKOLA
Göteborg, Sverige 2024
www.chalmers.se

REPORT NO.

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ABSTRACT

The aerospace industry requires precision in manufacturing to ensure high-quality, reliable components. This thesis investigates strategies for robust fabrication at GKN Aerospace, focusing on optimizing welding joint preparation methods. Specifically, it compares one-sided and three-sided machining strategies to minimize geometric variations and deformations during welding.

GKN Aerospace, a leading supplier of aerospace components, faces challenges in maintaining tight tolerances and reducing weight in complex assemblies. Virtual geometry assurance using RD&T simulation software is crucial in early development phases. This study evaluates geometric variations and fixture stability to aid decision-making for welding joint preparations.

A comprehensive literature review on geometrical variation, robust design principles, and RD&T applications in manufacturing sets the foundation. Simulations and analyses, including variation simulations and Finite Element Analysis (FEA), predict non-rigid parts behavior during assembly and welding, providing insights into optimal fixture design.

Interviews with production, design, and tool design engineers at GKN Aerospace reveal diverse perspectives. Production engineers prioritize efficiency and cost-effectiveness, often favoring one-sided machining. Design engineers emphasize precision and adaptability, advocating detailed simulations. Tool design engineers focus on creating versatile fixtures for various machining strategies.

The study identifies key factors influencing welding joint preparation: material properties, component geometry, and production efficiency. One-sided machining is less costly and simpler but may lead to higher quality control and rework expenses. Three-sided machining, while more complex and expensive, offers superior precision and stability.

Case studies demonstrate RD&T simulations practical application in evaluating fixture designs and predicting clamping forces. Results indicate that simulations with physical prototypes, or digital twins, provide more reliable data than purely theoretical models.

This study recommends a structured decision-making framework for welding joint preparation in aerospace manufacturing, combining RD&T simulations with engineers’ practical expertise. The thesis concludes with directions for further research, including integrating welding simulations and exploring virtual fixturing techniques to enhance aerospace components' precision and reliability.

The report is written in English.

**Keywords:** Welding joint preparation, Geometric variation, RD&T simulation

# Acknowledgment

This thesis report presents the work and results produced in the course IMSX20 (15 credits) at the Department of Industrial and Materials Science, Chalmers University of Technology. The thesis was carried out during the spring semester of 2024 by students in the Bachelor of Science in Mechanical Engineering (180 credits) on the behalf of GKN Aeorospace.

The examiner and supervisor for the thesis was Kristina Wärmefjord deputy head of department and professor at the department of Industrial and Materials Science at Chalmers University of Technology. Manager Design and Definition at GKN Aerospace Sweden AB Johan Lööf acted as external supervisor. We wish to extend our sincere appreciation to the individuals listed above, as well as to our additional advisors Hans-Olof Svensson and Pär Nordström for guiding us along the way with valuable insights and knowledge during the thesis work. A big thank you to the individuals who participated in our interview study and to the people who have given us valuable information and knowledge at GKN Aerospace which has contributed to a successful result. We would also like to thank Lars Lindkvist at the department of Industrial and Materials Science at Chalmers for providing insights in the simulation software RD&T.

# Table of Contents

# 1 Introduction

This section provides the background of the research alongside a description of its distinctive features, research questions and limitations to the thesis work.

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## 1.1 Background

GKN Aerospace is the aerospace operation of GKN plc, serving a global customer base and operating in North America and Europe. With sales of £3,85 billion in 2019 [1], the business is focused around three major product areas – civil airframes, engines and defence, plus several specialist products - electro-thermal ice protection, fuel and flotation systems, and bullet resistant glass. The business has significant participation in most major civil and military programs. GKN Aerospace is a major supplier of integrated composite structures, offers one of the most comprehensive capabilities in high performance metallics processing and is the world leading supplier of cockpit transparencies and passenger cabin windows [2].

Fabricated engine structures are built up by using optimized combinations of castings, forgings, and sheet metals of one or more different materials that are welded together. This solution leads to decreased weight, but it also implies more complex assemblies, advanced fixtures, longer tolerance chains and deformations due to more parts and more welding operations. Therefore, it is important to implement virtual geometry assurance activities in early development phases to assure that final product tolerance requirements are fulfilled.

Geometry assurance is a concept that can be a guidance for minimizing the variation before a part is assembled and manufactured. This necessitates a demand to alter the manufacturing process and divide the structures into smaller parts. More parts in the structure lead to complications in terms of strength and variation in the structure. Through research on different alignment methods and the simulation software RD&T, this can be investigated at an early stage [3].

## 1.2 Aim and Research questions.

Welding strategies used today at GKN are non-rigid (one-sided machining) and rigid (three-sided machining) and rigid best fit. The focus in this thesis work is to investigate and compare these strategies to fulfill requirements prior welding and minimize total variation and deformation to optimize fixturing for improved geometric quality. Which leads to the following research question:

*RQ1: Which factors influence the choice of joint preparation?*
*RQ2: How can simulation software be an aid in the choice of joint preparation?*

## 1.3 Delimitations

Limitations have been imposed to enhance project focus on one-sided machining and three-sided machining. The strategy involving rigid best fit and full-scale real test is abandoned due to complexity. Welding simulation is treated as a secondary focus, considering time constraints.

# 2 Theoretical Framework

In this section, the foundational theory underpinning the research presented in this thesis is introduced.

## 2.1 Geometrical variation

A manufactured part always has a geometrical variation compared to the created CAD and drawing. It is important to take this into account when creating the design of fixtures, to understand how the imperfections influence the variation [4]. Geometrical variations in individual manufacturing and assembly processes can spread and build up, leading to products that fail to meet functional, aesthetic, or assembly requirements. By simulating and foreseeing geometry problems early, robust concepts can be developed, tolerances and assembly sequences optimized, and key inspection features selected. This proactive approach minimizes the risk of production delays and defects, thereby reducing waste and cost, while optimizing the manufacturing process to achieve higher quality and consistency in the final products [3].

## 2.2 Locating schemes

The locating scheme is important for the geometrical robustness. Figure 1 shows a locating scheme with six location points. The first three points A1, A2 and A3 are the primary locating points, these will control three degrees of freedom. Translation in Z-direction, rotation around Y-axis and rotation around X-axis. Next is the two secondary location points, B1 and B2, these will control 2 degrees of freedom. Translation in X-direction and rotation around Z-axis. C1 is the tertiary locating point and it controls the last degree of freedom, translation in Y-direction [5].

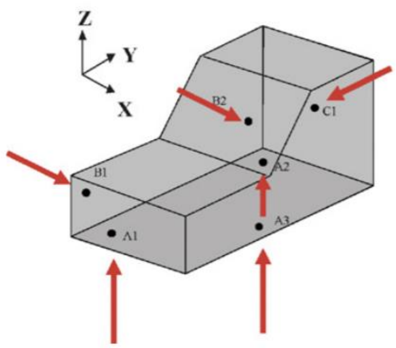


*Figure 1 3-2-1 locating scheme*

A robust locating scheme had a significant value in this thesis to acknowledge the variations between two parts that should be fixture before welding. Non-rigid part is used, therefore additional points should be used to support the clamping before welding. The locating scheme used called “6 directions” in RD&T and are similar to 3-2-1. “6 direction” positioning system is used when the positioning planes are not perpendicular, each point can have an individual steering direction. [6] Support points are also added alongside the welding line in order to get the part in the right position.

## 2.3 Robust design

A robust design is one that remains unaffected by variations in the manufacturing and assembly processes [7]. The concepts of robust design and enhancing quality were initially introduced by Taguchi. The methodology behind robust design is to without eliminating the sources of variation make the design insensitive to variation. The locating schemes are a key to obtaining a robust design concept [8].

In figure 2 a comparison is made between a robust locating scheme and a non-robust locating scheme visualizing the effects of the position of B2.

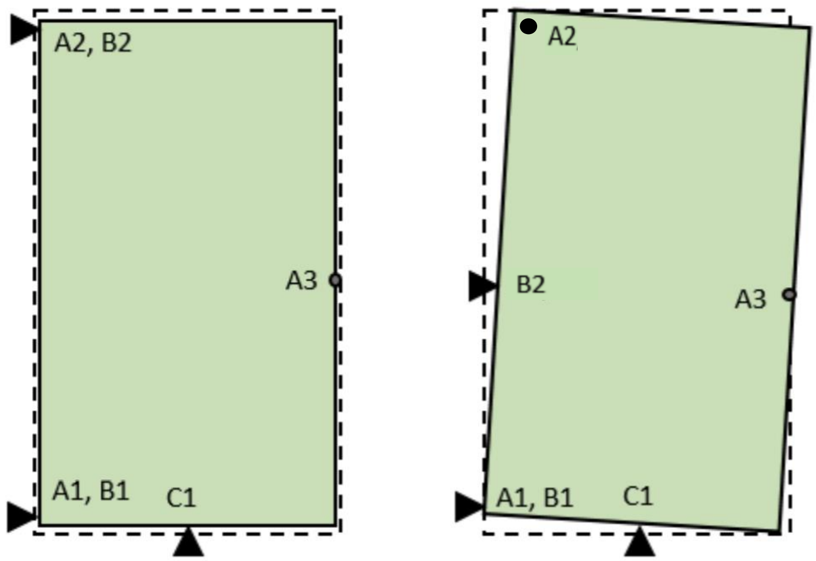


*Figure 2 Comparison of the effects of a robust locating scheme*

## 2.4 RD&T (Robust design & Tolerancing)

RD&T (Robust design & tolerancing) is a simulation software for evaluating geometrical variations, input to the software can be tolerances and locating schemes from drawings. The software can handle both rigid and non-rigid simulation. For the non-rigid simulation, a mesh is generated to achieve a model with nodes that can be deformed in RD&T [9]. In this thesis, the simulation with non-rigid parts is performed to evaluate the deformation and forces when a part is clamped before welding.

## 2.5 Geometry assurance

Geometry assurance involves minimizing the impact of variation in geometry on the final product, this through various activities across the product process. During the design phase product and production concepts are developed, optimized, and virtually tested for variation in manufacturing. Physical testing and arrangement for inspection using coordinate measurement machines (CMM) is being handled in the verification phase. During the production phase adjustment is made to production processes and inspection data is crucial for controlling production and identifying errors [9].

## 2.6 Variation simulation

In RD&T Monte Carlo simulations is used for tolerance analysis. The idea of a Monte Carlo simulation is to predict the behavior of a simulated system using random samples [10]. With these samples, a mathematical technique can predict the statistical distribution of the deviation of an assembled product. When incorporating non-rigid variation simulations with Monte Carlo analysis the tolerance analysis significantly enhances, especially in aerospace component manufacturing. This method considers the flexibility and deformation of parts during assembly. This is crucial for accurately predicting geometric variations that results from joining methods for example welding. Using simulations to study how parts are joined, the order they are assembled in, and the forces applied can help us to better understand and reduce mismatches in shapes and sizes, improving how well parts fit together [11].

## 2.7 FEA-model

FEA (Finite Element Analysis) is a numerical method that is used to solve complex mathematical models, often used for analyzing structural and thermal problems [12]. To retrieve the deformation when clamping a component in RD&T the FEA is considered in the calculations.

The FEA software Ansys is used to simulate the stresses in the component in this thesis work. Both shell and solid mesh are created to simulate the forces and stresses in the materials. Shell elements refer to a type of finite element used to body thin-walled structures such as car bodies, aircraft fuselages, or other surfaces that require structural analysis but are too thin relative to their other dimensions to be modeled as solid elements efficiently. Shell elements combine properties of both plate and membrane elements, which means they can withstand forces in their plane like membrane elements and out of the plane like plate elements [13].

## 2.8 Fabrication

In aerospace development, especially when constructing large engine components, fabrication involves welding smaller pieces to form the final structure. This method, highlighted by the pressing need to reduce $CO_2$ emissions and the weight of aircraft components, offers enhanced design flexibility also leads to more suppliers being available. It enables weight optimization and supports diverse product needs through material and process reuse. Such a shift towards more sustainable and efficient manufacturing practices is crucial in meeting the stringent quality and reliability demands of the aerospace industry [14]. Fabrication processes in this context involve managing the geometrical variation of every part to ensure proper fit at the interfaces, essential for maintaining the high precision required in aerospace manufacturing. Moreover, this approach utilizes geometry assurance methodologies and advanced computational tools to predict outcomes and adjust processes proactively, ensuring the precision and reliability of the final products [15].

## 2.9 Welding joint preparation

Joint preparation in welding refers to the process preparing the edges of the parts to be welded in a way that facilitates optimal welding conditions. This involves shaping edges to specific geometric contours and ensuring proper alignment gap and step between the parts. The choice of joint preparation type depends on various factors, including the material thickness, welding process parameters, and accessibility of the joint [16]. In this thesis one-sided and three-sided welding joint preparations are in focus. One-sided machining in welding joint preparation involves shaping the edge of the parts to be welded from only one side. This technique is used when only one side of the material is accessible or when welding very thin material. Three-sided machining in welding joint preparation involves shaping the edges of the materials to be welded from three sides to create a specific geometric profile. The complex preparation is used to enhance weld penetration and joint strength often used in thicker materials. By machining the edges from three sides it allows for a more detailed and tailored joint geometry. This ensures a robust welding area that can withstand higher loads and stresses [16]. In figure 3 and 4 the two types of machining is visualized.

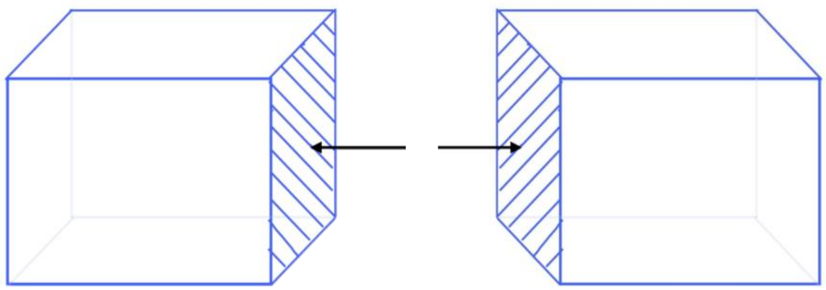

*Figure 3 Visualization of one-sided machining*

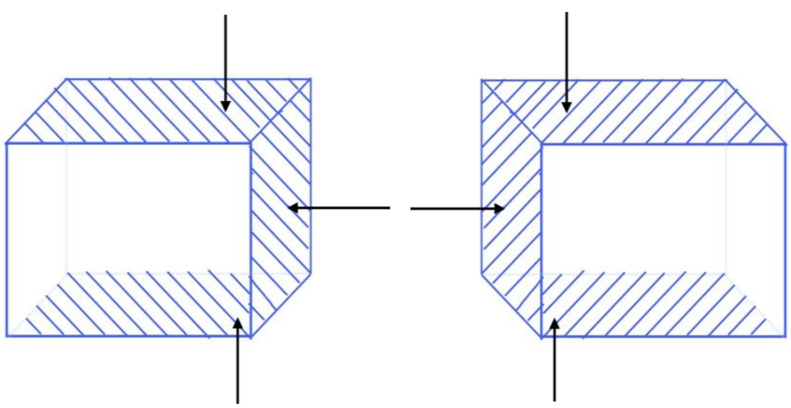

*Figure 4 Visualization of three-sided machining*

## 2.10 Digital Twin & Scan data

The Digital Twin concept is key to connecting what the simulation on computers shows with what happens on the manufacturing floor. It involves creating a highly accurate virtual replica of a physical system or product, primarily facilitated through the scanning of manufactured parts to capture geometrical variations arising during production. This model, often represented as a Finite Element Analysis (FEA) mesh, is enhanced with detailed inspection data to reflect real-world conditions accurately [17]. By simulating and analyzing the effects of welding and geometrical variations, the Digital Twin significantly enhances the precision of fabrication and minimizes the risk of errors. The integration of 3D scan data allows for the dynamic simulation of how individual parts will behave when welded together. This capability enables real-time adjustments during the manufacturing process, thereby ensuring products meet high-quality standards and adhere to stringent aerospace regulations [15]. Through these advancements, the Digital Twin becomes an essential tool in modern manufacturing, providing a reliable solution for enhancing product quality and manufacturing efficiency.

Zeiss Inspect (previously known as GOM Inspect) is the software that is used in this thesis to scan the real parts to get a digital copy. The scanning method used is optical 3D-scanning, that uses a blue light equalizer to capture the surfaces. 3D scanning technology facilitates the collection of scan data by projecting light onto the surface of a part and measuring the reflected beams to generate a point cloud. This point cloud is an aggregation of data points that delineates the surface geometry of the scanned object. Sophisticated software algorithms then process this point cloud to construct a virtual model that mirrors the physical part with high geometric accuracy [15], see figure 5.

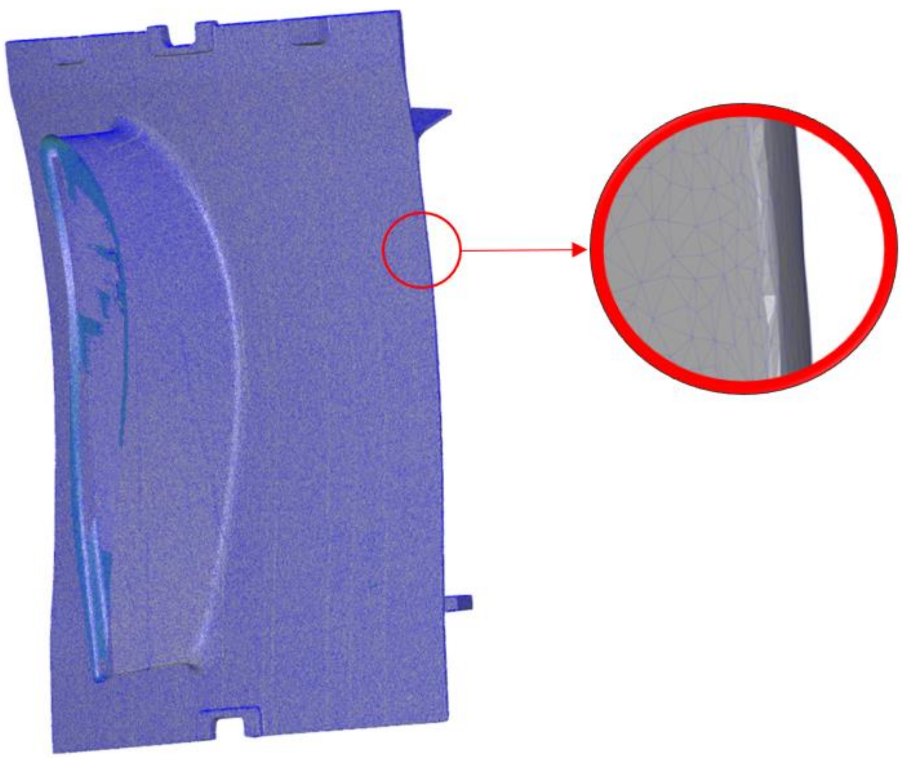

*Figure 5 Point cloud of the scanned part*

## 2.11 Product realization loop

The product realization loop encapsulates the journey from design to production, with geometry assurance as its guiding principle as illustrated in figure 6. In the initial concept phase, designs are virtually tested against potential manufacturing variations, establishing a foundation for geometric resilience. This foundation is then rigorously examined in the verification phase, where designs undergo physical testing to refine and confirm their geometric fidelity. Finally, the production phase sees these designs come to life, with ongoing adjustments ensuring that the finished product remains true to its precise geometric specifications. This process iterates as needed, enhancing the product's geometric integrity with each cycle [18].

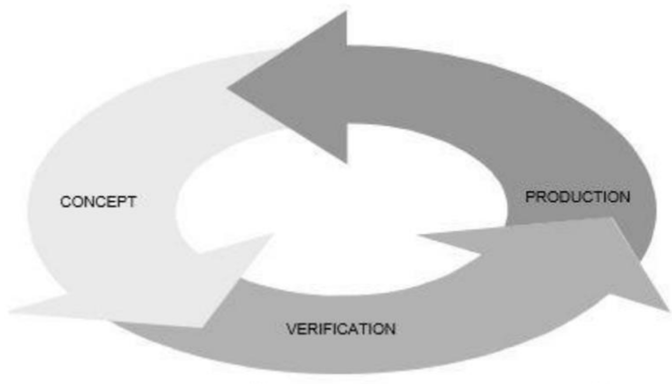


*Figure 6 Product realization loop*

# 3 Methodology

This section will explain the methods to fulfill the thesis work's aim and answer the research questions. The research strategy includes different methods. First literature research was done to find current published literature on the subject. Followed by qualitative research including interviews and a quantitative part using the simulation software RD&T.

## 3.1 Literature research

In this study, primarily, previous course literature, books, and scientific journals were utilized to gather information. The search for relevant literature occurred continuously throughout most of the study, utilizing the Chalmers library database and Chalmers library. The search on the Chalmers library database was narrowed down by employing keywords such as: geometric assurance, welding, fabrication, and manufacturing.

## 3.2 RD&T

The software RD&T focuses on geometrical assurance and statistical variation simulation [9]. RD&T can be used to identify geometric variations between two parts that should be welded and how the parts should be fixtured. The input to the software is a CAD-file or deformed mesh, rigid or non-rigid, with specific tolerances and variations. The output will be data on the geometrical variations of the parts. The output and result of the simulation will benefit to determine in an early stage whether the used locating scheme and part tolerances fulfil the product requirements. Chalmers and PE Geometry collaborated and provided educational materials and training sessions for software knowledge.

## 3.3 Input RD&T

The locating scheme is important when building a model in RD&T before simulation. In this project a 6-direction scheme is used to replicate how the part is fixtured before welding, see figure 7**.** For the coordinates see figure A3 in the appendix. Support points are added to simulate the clamping before welding, see figure 8.

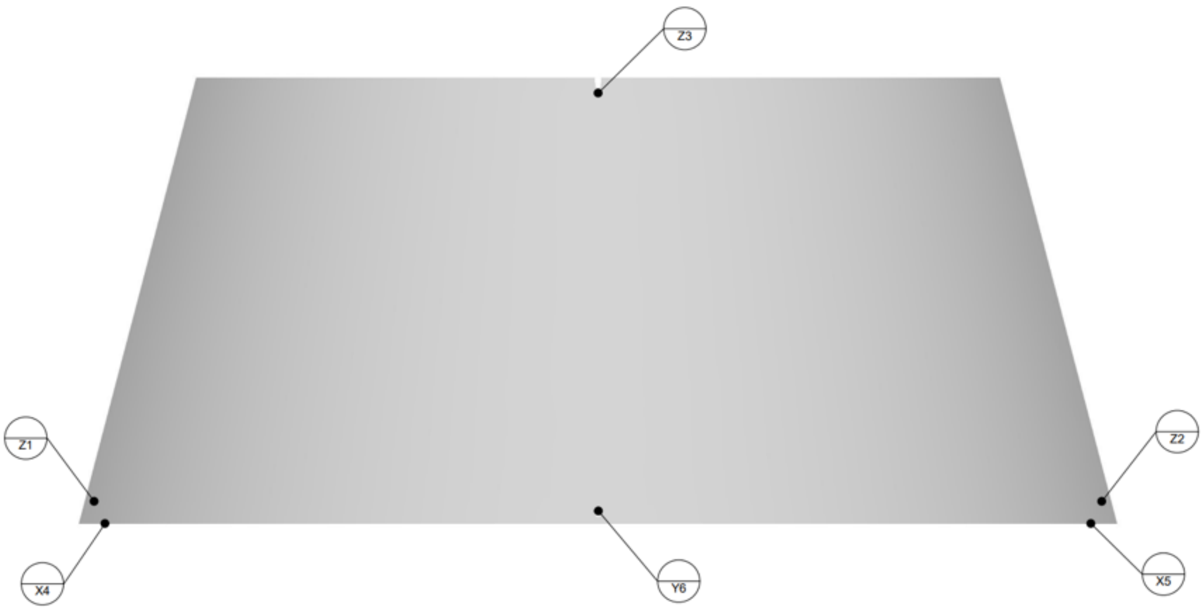


*Figure 7 Reference system for the part*


*Figure 8 Support points in Z-direction*

A replicate of an actual component was generated in RD&T by deforming the nominal CAD-file. For the initial analysis a surface model was used in RD&T, this model had a thickness of 9.525 mm. A tolerance of 1 mm was allocated to the part, and simulations were conducted for 1000 iterations, the resulting deformed parts were then exported to further analysis. The deformed parts were then used to compute the force required to repositioning the parts to nominal state. These force measurements provided valuable insights into the clamping force necessary to fixture a part that has undergone machining on one side.

These simulations concerning clamping and repositioning the part also contributes information about the geometrical variation that occurs, which needs to be considered in the decision about one-sided or three-sided machining.

Further analysis about clamping a detail was concerned and to replicate a real part even better a manufactured part was scanned using a 3D-scanning system to create a scanned copy. The scanning creates an STL-model that can be aligned against the nominal CAD-model, using the same points as the fixture. The locating scheme used to imitate the fixture was “Reference point system” (RPS), this method is similar to 6-direction in RD&T. Three points in Y-direction creates a plane that constrains two rotations and one translation, two points in Z-direction locks the last rotation and one translation and the last point in X-direction constrain the last translation. See figure 9.

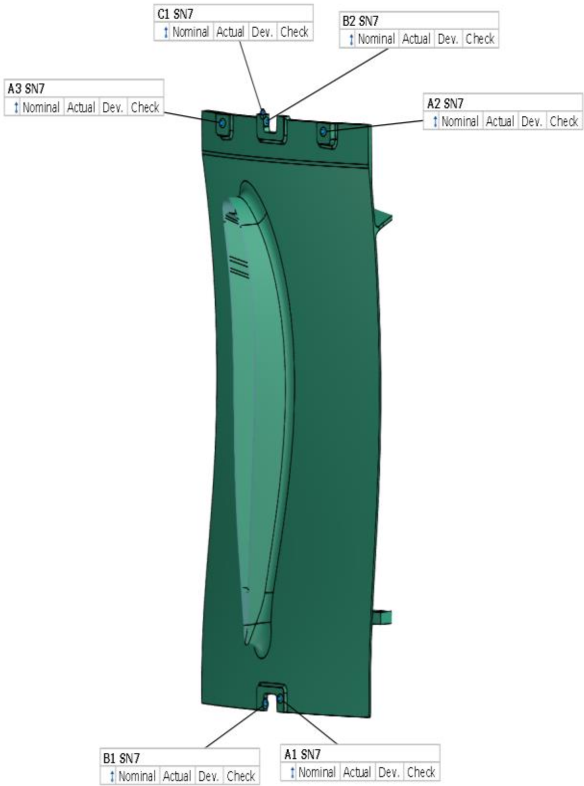


*Figure 9 Locating scheme for part*

Deviation analysis was inspected using “Surface Comparison” in GOM Inspect to understand the deformation forces needed in the fixture. This analysis compares the nominal CAD to the actual mesh at every node on the part and shows the value using deviation labels. See figure 10.

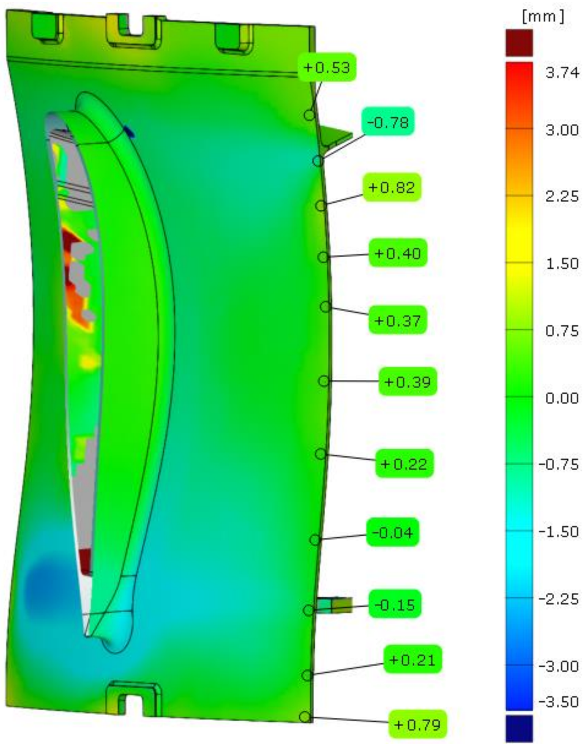


*Figure 10 Deviation labels in GOM Inspect*

The STL-model was exported from GOM Inspect and imported to RD&T, to achieve the deviations from the real part. In RD&T the nominal mesh can be compared to the scanned mesh and the nominal mesh with FEA adds the deviation in every node. To evaluate the clamping forces the measure method “locator force” is used in RD&T.

## 3.4 Output RD&T

Through simulations conducted in RD&T the forces that occurs when fixturing the part are calculated. These results can then be evaluated to understand if the forces are reasonable for the fixture. Within this project it is possible to observe the influence of support material and geometry, leading to higher force values at support point S12 and S13 has a larger value, see figure 11.

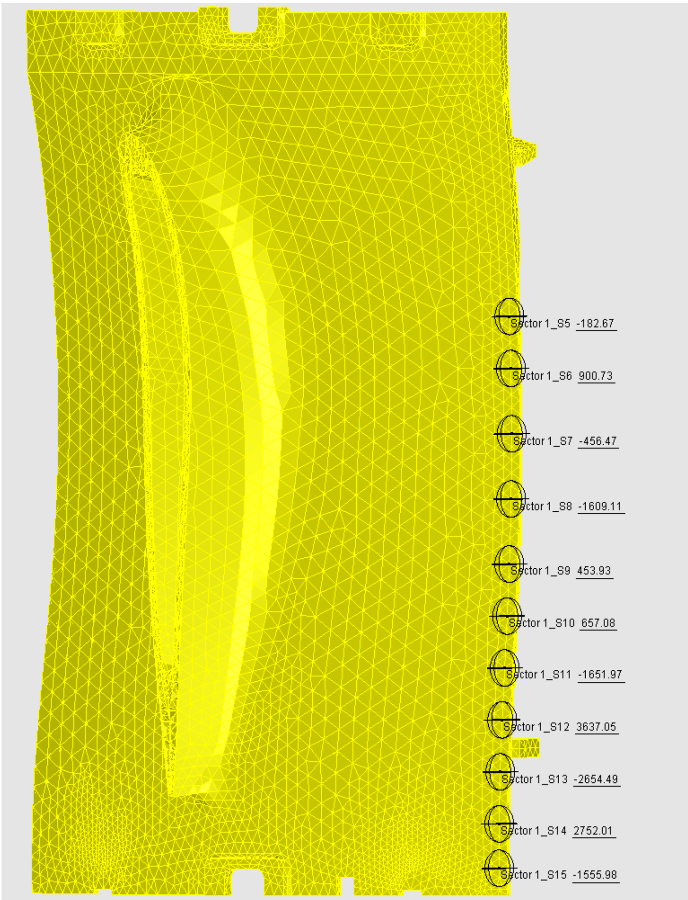


*Figure 11 Resulting forces in the support points*

## 3.5 ANSYS

After using RD&T to simulate the geometrical variation and clamping forces, the software ANSYS was utilized to simulate the stresses. To ensure consistency in part alignment throughout the project, the same locating scheme used in GOM Inspect and RD&T was applied in ANSYS. The forces achieved from simulations in RD&T were then input into ANSYS to evaluate the von-Mises stress within the material. The maximum von-Mises stress occurs at the same area as the highest clamping forces, suggesting a rational correlation between applied forces and resultant stress distribution, see figure 12.

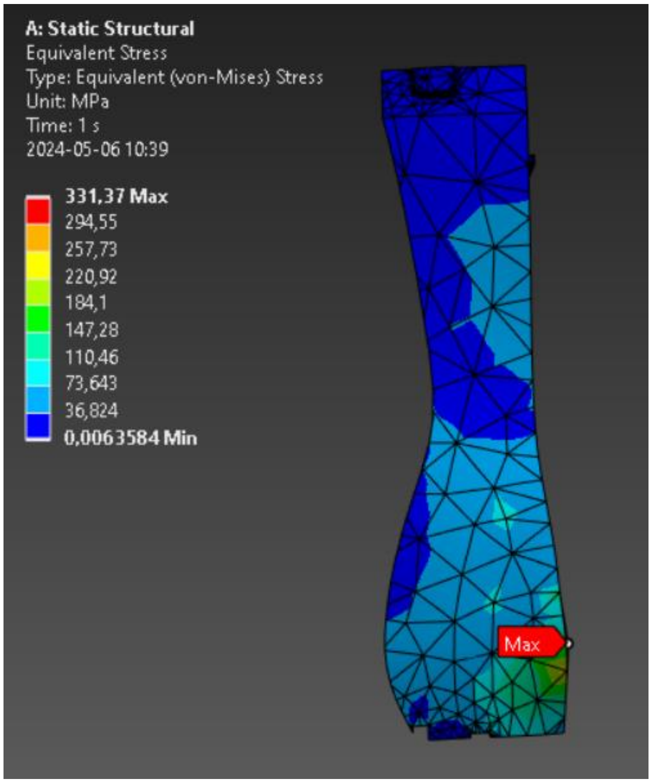


*Figure 12 Stress result in Ansys*

## 3.6 Collection of data

To obtain a wide understanding of the subject different methods of gaining knowledge can be used. To produce a description of the status at GKN interviews and internal documents were used.

### 3.6.1 Interviews

The interviews were conducted to gather knowledge about when the various fixturing and welding methods were used. All interviews were conducted face-to-face and, if consented, recorded. The interviews were conducted with experts in manufacturing and design who had experience in both one-sided machining and three-sided machining. A list of the interviewees can be found in table A1. It was also essential to interview experts in welding simulation to gain a deeper understanding of how the heat flow from welding impacted the material structure.

Before the interviews, a list of questions was prepared in the form of a script, as outlined in table A2. This script allowed the interviewee to respond in their own words, contributing to a low degree of standardization in the interviews, which is typical in interview settings [19]. Additionally, there was room for follow-up questions from both the interviewers and the interviewees.

### 3.6.2 Internal documents

In this study, relevant internal documents were examined to understand the current situation GKN. Documents such as procedures, process maps, and quick reference guides were scrutinized. These documents were utilized to gain a deeper understanding of GKN’s products and how they are manufactured.

# 4 Current knowledge

As part of this thesis, an in-depth study was conducted to understand the current development process of components GKN Aerospace focusing on the choice of weld joint preparation. This study involved structured interviews with specialists from different areas within the organization, including engineers, project managers, and quality assurance experts. These interviews aimed to gather first-hand insights into the practical challenges and operational nuances of fixture design and manufacturing. In addition to interviews, this research also involved a review of internal documentation at GKN Aerospace. The primary documents examined included process descriptions and product planning documents. These sources provided valuable insights into the current methodologies and planning stages used in the development of fixtures, enriching the context and depth of the analysis presented in this thesis.

## 4.1 Development process for components

In the initial stages of developing a new component, the design phase critically evaluates whether to apply one-sided or three-sided machining. This decision is based on a thorough understanding of several key factors and begins with brainstorming sessions involving a cross-functional team of production engineers, design engineers, tool design engineers, and operators. Both the design and production teams work in close collaboration to determine essential elements such as material choice and weld positioning, crucial for ensuring the structural integrity and manufacturability of the final product. The early involvement of design teams is essential in defining the industrial function and ensuring that fixtures are adaptable to variations in component manufacturing and welding needs. The choice between one-sided or three-sided weld preparations is significantly influenced by material properties, component geometry, and overall design requirements. These decisions are typically finalized early in the process to ensure seamless integration into production lines.

Material selection plays a significant role as it not only influence the cost but also dictates the choice of joint preparation based on the material properties. The thickness and overall geometry of the material are equally vital; variations here may determine if one-sided machining or tree-sided machining is appropriate. For instance, geometries that are too thin may not be suitable for more complex joint preparations like three-sided machining. With thicker materials sometimes demands more robust three-sided approach to accommodate variations and ensure stability in weld joints. The material used also dictates certain limits due to how differently each reacts under welding conditions. Another key factor when deciding between weld joint preparation is the accessibility for the milling process, three-sided machining can be excluded because of the lack of accessibility. Additionally, it is also important to gain insights into how these different methods impact the stress in the materials. The anticipation of stresses can be challenging due to the complex geometry when using three-sided machining.

## 4.2 Economic considerations of weld joint preparations

Economic considerations are essential with decisions on weld preparations often driven by cost-effectiveness and the practicality of altering the production processes. The decision impacts not only the immediate costs associated with the production process but also has broader implications for long-term financial planning and efficiency.

Three-sided machining, while offering superior precision and potentially higher quality, typically at a higher production cost due to more complex setups and longer machining times. The equipment required for this type of machining is often more specialized, leading to greater capital investment and higher maintenance expenses. In addition, three-sided machining tends to use materials less efficiently which can increase waste and consequently raise material costs.

On the other hand, one-sided machining is generally less costly in terms of both equipment and operation. One-sided machining offers a reduction in machining time due to its simpler setup and fewer operational steps. The reduced material use compared to three-sided machining is also a factor that reduces cost with one-sided weld joint preparation. However, the initial cost savings with one-sided machining might be canceled out by potential increases in quality control and rework expenses. If the reduced precision of one-sided machining fails to meet quality standards, the additional costs required to rectify defects could overthrow the initial cost savings. Moreover, the long-term economic considerations, such as the potential need for more frequent maintenance or replacement of components due to lower quality, must also be factored into the decision-making process.

The decision between one-sided and three-sided machining also involves evaluating opportunity costs related to design flexibility. Limiting machining can restrict design options and uses for the parts, possibly leading to missed opportunities where adaptability and innovation are crucial. Ultimately, the choice between the different types of machining is a strategic choice that requires thorough analysis of both short- and long-term economic impacts balanced against the company’s operational needs and goals. This decision must be made with a comprehensive understanding of how each option aligns with the broader objectives of maximizing efficiency, reducing costs, and ensuring product quality and reliability.

## 4.3 Simulation and modelling

The initial design of the component is forwarded to a tool designer. At this stage, the use of RD&T (Robust Design & Tolerancing) software has a central role. RD&T is used to simulate various manufacturing and assembly conditions to predict performance using variation simulations. These simulations help in understanding how slight variations in the production process might affect the final product. This leads to the development of an optimal target system for the fixture, which serves as a foundational blueprint. The target system defines critical parameters and tolerances that the fixture must meet to ensure it effectively supports the component during manufacturing. By basing the fixture design on comprehensive RD&T simulations, the team ensures that the final setup not only meets the precise requirements of the component but also contributes to overall production efficiency. This approach minimizes the risk of production delays and defects, thereby reducing waste and cost, while optimizing the manufacturing process to achieve higher quality and consistency in the final products.

Structural strength calculations and simulations are performed in certain cases where there might be high loads to refine the design. This approach helps managing risks associated with design changes as well as enhances the ability to plan effectively. Simulations support the design process by allowing teams to visualize the effects of different weld preparations and material behaviors before actual production begins.

Simulations that is time consuming but very important is welding simulations to predict the outcome of the fabrication. Welding simulations are an integral tool in modern manufacturing, providing crucial insights that enhance both the efficiency and quality of welding processes. These simulations are primarily used for heat management, allowing engineers to control the heat affected zone to prevent material weakening during welding. They also enable the optimization of weld sequences to minimize distortions and reduce residual stresses, ensuring that the final weld is strong and free of defects.

## 4.4 Diverse perspectives on weld joint preparations

Depending on which area you work in you have approaches to weld joint preparations. There are key opinions from production engineers, design engineers and tool design engineers. Each group’s unique insights, individual goals and priorities shape their approach to welding, which reflects their distinct roles within the manufacturing. Analyzing these perspectives offers insight into how each contributes to the overall strategy and execution of weld joint preparations which ultimately impacts the efficiency and quality of the outcome.

### 4.4.1 Production engineers

Production engineers focus on the efficiency and safety of the manufacturing process. Their primary concern is ensuring that welding operations are streamlined and cost-effective without compromising the product quality.

During interviews with employees within this area insights were given on the production engineers perspective. Production engineers generally prefer straightforward, efficient machining strategies that facilitate rapid assembly and reduce downtime. They highlight the importance of quality and although increasing production speed is essential for operational efficiency, it must not compromise the quality of the product. They can favor one-sided machining for its faster setup and lower complexity but have concerns if the quality standards are not met. Therefore, with more complex assemblies where precision and mechanical properties are crucial, they advocate for three-sided machining, supported by welding simulations to ensure structural integrity, and minimize defects.

### 4.4.2 Design engineers

Design engineers are involved in the initial and detailed design phases of components, ensuring the design are manufacturable and optimized for functionality. Their tasks can include simulations such as strength simulations.

Design engineers prioritize precision and adaptability in the welding process. Based on prior experience with either three- sided or one-sided machining design engineers may prefer either one. Design engineers, often specializing in components that are compatible with only one type of machining may exhibit a preference that reflects their specialization. They support the use of detailed simulation that enable deep understanding of material behavior under different welding scenarios. By combining design and manufacturing in the early stages of the development of a component is crucial to ensure that weld preparations are doable and effective without compromising the end products quality.

### 4.4.3 Tool design engineers

Tool design engineer focuses on developing fixtures and tools that support the manufacturing process. Their focus is on reliability and functionality of these tools during production.

The tool design engineers values robust and versatile fixture concepts that can accommodate various machining strategies. Emphasizing the importance of fixture adaptability to both one-sided and three-sided machining, depending on project specific needs, to maintain high production flexibility and reliability.

## 4.5 Comparative analysis and conclusion

The exploration of diverse perspectives of different engineering roles alongside material and economic consideration reveals the complexity of choosing weld joint preparation. The perspectives of production engineers, design engineers and tool design engineers on weld joint preparations show distinct priorities shaped by their roles within the manufacturing process. The analysis underlines the interconnectedness of production efficiency, material properties, design precision and economic practicality.

Production engineers typically lean towards methods that streamline operations, while design engineers look for accuracy and quality, often showing a preference for more complex preparations like three-sided machining. The tool designer, meanwhile, bridges these approaches by focusing on creating versatile tooling solutions that can support diverse welding strategies.

The differing perspectives from various engineering roles at GKN Aerospace underscore the complexity of decisions in weld joint preparation. By integrating these diverse viewpoints, more innovative solutions that enhance both the efficiency and quality of the manufacturing process can be achieved, leading to more reliable and higher-quality aerospace components.

# 5 Results

In this section the results of the thesis work will be presented. Using different cases towards the establishing of a working process for the selection of one-sided or three-sided machining. This should be recommendation for which method to utilize. Software used during the thesis is RD&T and especially new test functions in an upcoming version. The output from RD&T are confirmed and used in other software such as ANSYS as stated in the methodology section.

## 5.1 Introducing the case

The following figures illustrate how the software RD&T conducts the force simulation. The software utilizes support points and integrates tolerances from technical drawings to accurately simulate the effect of variations typically seen in manufactured parts. Such methodology enables RD&T to create virtual representations of parts with different variations, which then will be adjusted to their nominal shape again to ensure correct assembly as seen in figure 13 and 14.

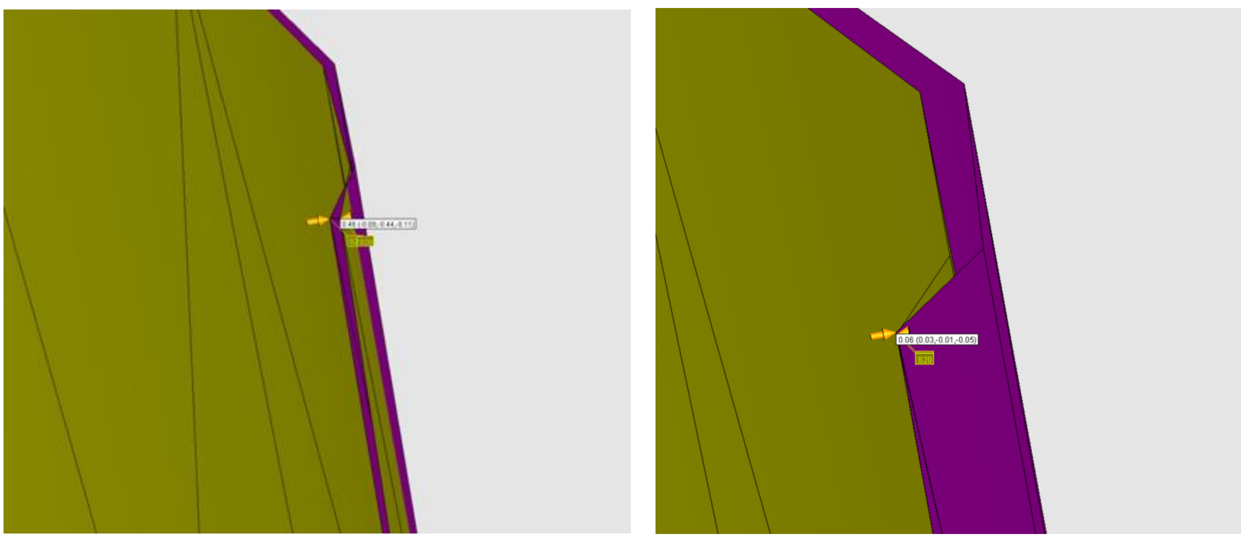

*Figure 13 Comparison between the nominal shape and a disturbed part*

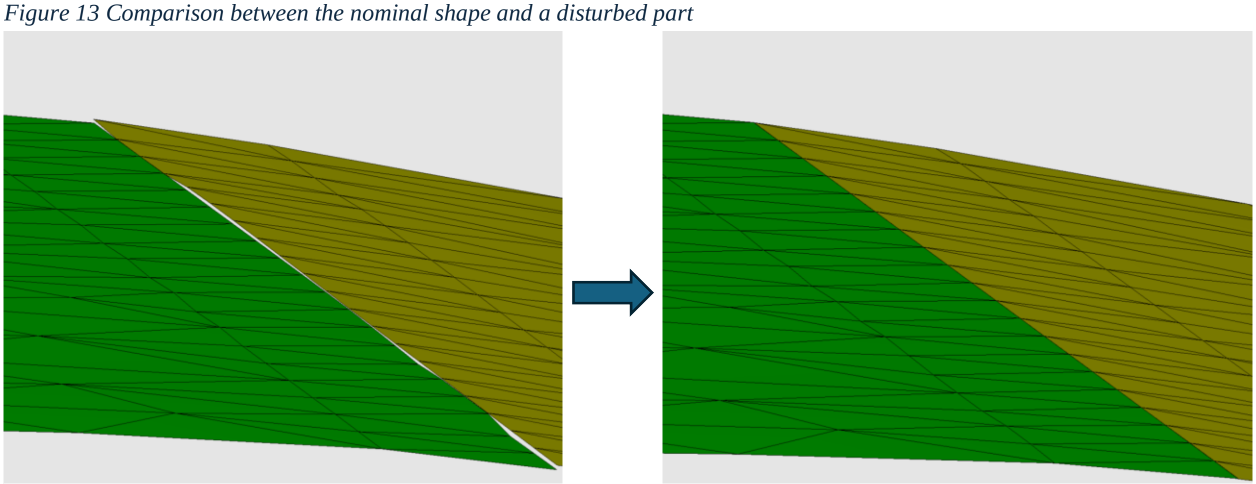

*Figure 14 Vizualisation of the clamping in RD&T*

The primary reason for doing this case is through simulations predict the forces that will be applied during the assembly process. Understanding these forces is crucial because it allows for the prediction of how the material will behave under actual manufacturing conditions. Specifically, it helps determine the joint preparation method. Whether one-sided or three-sided machining is most appropriate for ensuring that parts can be deformed and assembled correctly without introducing stresses that could compromise the quality of the final product.

### 5.1.1 Simulation without a physical part

In the initial phases of a new project, before any physical components are manufactured, simulations in RD&T can be helpful. By using support points and integrate tolerances from technical drawing, it is possible to replicate the variation expected in a manufactured part. This process enables the software to generate parts with different variations which then can be clamped to nominal again. Through these simulations it is possible to anticipate the locations where the largest forces and stresses are likely to occur, which is the primary aim for this study.

However, when using only tolerances as the basis of these simulations, the forces exerted can be unpredictable. This unpredictability arises because the tolerances are not grouped but treated individually. As a result, the simulated forces can vary in a manner that does not directly correlate with the realistically behavior. In scenarios where tolerances are applied individually, the resulting force on any given point can differ significantly from what might be expected if the tolerances were considered in a grouped or collective manner. This can lead to a misrepresentation of real-world physical behaviors and potentially misalign the outcomes of the simulation from the realistic result. This is visualized in figure 15 below, the

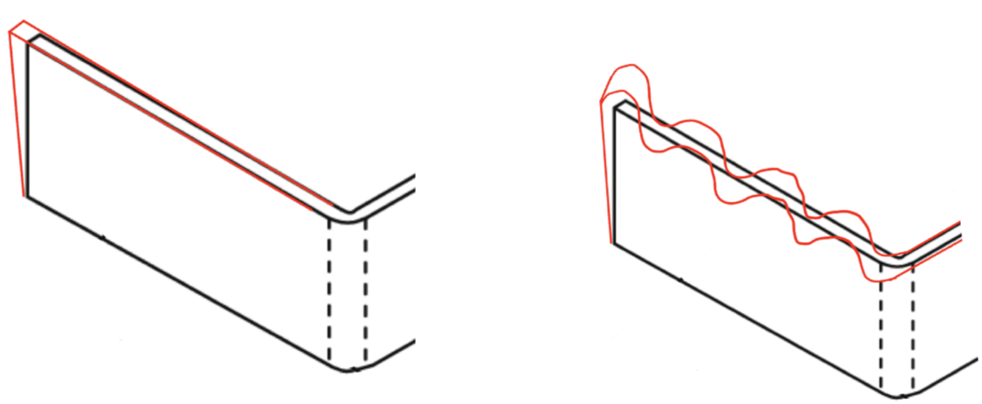

*Figure 15 Grouped tolerance vs individual tolerance when calculating force*

drawing on the left being the variation with the tolerances grouped and the individual interpretation of the tolerances to the left.

Understanding this will help in conducting a simulation that is as close to reality as possible which is crucial when simulating without a physical part. Grouping tolerances can help approximating a more realistic interaction between components as they would occur in an actual manufacturing scenario. This approach enhances the reliability of the simulation results but without a physical part it is still a hypothetical behavior since the real behavior is not established yet.

The result will be an average force in each support point that indicates how much force required to clamp the part to the nominal shape. This result will indicate if there are tools that are able to handle such forces which will rule out one-sided machining if the tools are insufficient. Another factor to consider is if the amount of force will introduce stress in the material where there also should be a limit for. Considering these factors will indicate if one-sided or three-sided machining is the proper choice.

### 5.1.2 Simulation with a physical part

When the first real prototype is created further analysis can be made. With the creation of the first physical part a digital twin can be constructed using 3D-scanning. This digital twin can be analyzed further in RD&T to accomplish a greater perception of the reality. The manufactured prototype is scanned to capture the deviations and then create a mesh-structure with FEA data. The simulation is then performed where the part is clamped in RD&T to assess the forces required to restore the nominal shape and the geometrical variations that occurs caused by the forces. This result will be as in the simulation with no physical part an average of the required force but more reliable since the part is a digital twin that reflects the real manufactured behavior.

It is important to note that the scanned prototype is an early model that may be in worse condition than parts manufactured at full production speed, or alternatively, it could be in better condition than what would be expected in a real manufacturing environment. Therefore, the results are only an indication of the required force and may not fully represent the actual forces needed. Despite this, simulating with a digital twin is still more reliable than simulations using only theoretical tolerances.

While the force simulations provide valuable insights it is important to assess the stress simulations caused by the clamping force to ensure that the material is not compromised. By integrating these force and stress analyses, we can make informed decisions that optimize the machining process while maintaining the integrity and quality of the material.

## 5.2 Factors guiding selection of joint preparation

This thesis work interviews with experts in the area and review of internal documents have provided a solid foundation for researching the factors that influence the choice of weld joint preparation. Six interviews were conducted with production engineers, design engineers and tool design engineers, as stated in earlier sections. Through these interviews valuable insights were gained. Internal documents offered detailed information on the established practices and guidelines within the organization. The combination of qualitative data from interviews and quantitative data from internal documents has allowed for a comprehensive understanding of the key factors that determine the selection of weld joint preparation methods.

Listed below are the key factors that influence the choice:

- Material properties
    - Material selection influence the cost and dictates the joint preparation method based on material properties such as the stiffness of the material.
    - Thickness and geometry: Thinner materials may not be suitable for three-sided machining, while thicker materials may require it for stability.
- Component geometry:
    - The shape and dimensions of the part are limiting the choice of machining.
    - Accessibility for milling, limited access may exclude the use of three-sided machining.
- Overall design requirements
    - Design considerations such as structural integrity and manufacturability impact the choice between one-sided and three-sided machining.
- Production efficiency
    - The machining strategy should facilitate rapid assembly and reduce downtime.
    - The need to balance production speed with product quality, favoring methods that streamline operations without compromising standards.

These are key factors to consider when developing fabricated structures and understanding them will simplify the decision-making process.

## 5.3 Working process for recommendation for joint preparation

By implementing simulation methods, a structured decision-making framework for joint preparation machining is established. This working process serves as a guide for future projects, combining fact-based data and practical expertise to ensure more informed and effective decisions and is visualized in figure 16. When a new part is introduces, a systematic process is followed to decide the appropriate machining method, divided into two main pathways: a part during development only existing on the drawing board and a part during development with an existing pre-runner.

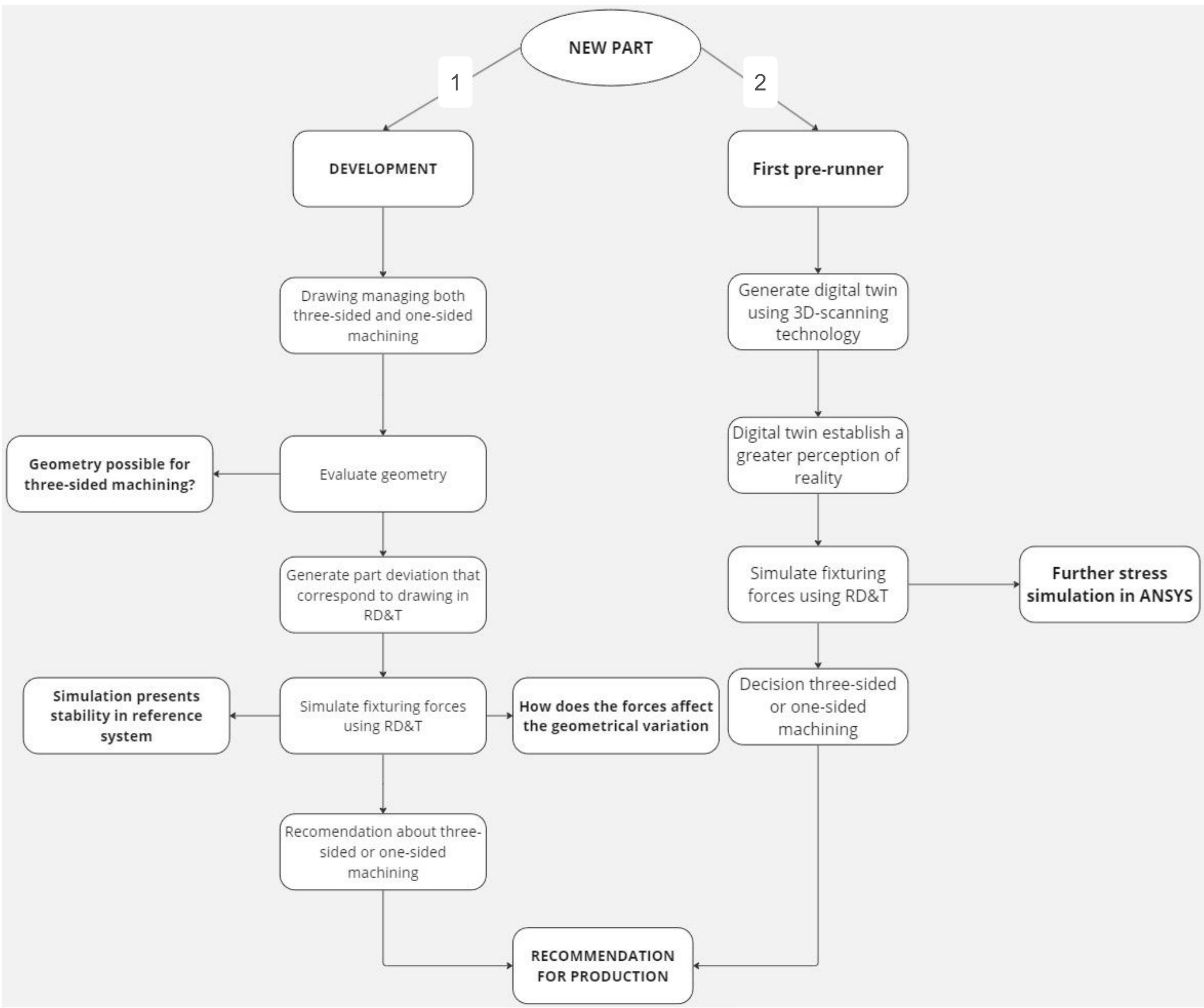


*Figure 16 Working process for recommending weld joint preparation*

The development pathway begins with creating a drawing that accommodates both three-sided and one-sided machining to ensure design flexibility. The next step is to evaluate the geometry of the part to determine if it is suitable for three-sided machining. If the geometry is suitable, part deviation that correspond to the drawing are generated using RD&T to understand potential variation during manufacturing. Simulations are then done to understand the forces used during fixturing mainly to understand if one-sided machining is possible.

The stability of the part in the reference system is analyzed through simulation to ensure that the part remains stable during machining and that the geometrical variations are within acceptable limits. Based on the simulation results a recommendation is made regarding whether three-sided or one-sided machining is to be preferred.

In the pre runner pathway a physical prototype of the new part is created. Using 3D-scanning technology, a digital copy of the part is generated, providing a precise detailed replica of the actual manufactured part. This digital twin is used to establish a greater perception pf reality allowing for detailed visualization and understanding of the part. Similar to the development pathway the digital twin is used to simulate fixturing forces using RD&T to understand the impact on the part and its stability in the reference system.

Further stress simulations are conducted using ANSYS providing deeper insights into the stress distribution and potential deformation of the part under various conditions. Based on these simulations and analyses, a recommendation on machining method is made, with more confidence after further simulations with the digital twin.

After completing the steps in both pathways, the final recommendation for production is made, based on a comprehensive evaluation of the part's geometry, stability, and the impact of machining forces. The chosen machining method, whether three-sided or one-sided, is determined to be the most suitable for ensuring the quality and stability of the part during production. This structured process ensures that all factors are thoroughly considered before deciding, leading to more reliable and efficient manufacturing outcomes.

# 6 Discussion and Conclusion

In this chapter the discussion will be focusing on validating the research questions posed at the beginning of this study. It will evaluate optimization of fixturing for improved geometric quality in welding, the factors influencing the choice of joint preparation and the role of simulation in these processes. This chapter will also acknowledge any uncompleted sections and address potential sources of error encountered during this thesis work. This discussion aims to solidify the recommendations for future applications and improvements in machining practices.

## 6.1 Validation of result and research questions

To validate whether the research questions have been answered, we need to assess the findings in relation to each question posed at the beginning of the study. The research questions were:

*RQ1: Which factors influence the choice of joint preparation?*

*RQ2: How can simulation software be an aid in the choice of joint preparation?*

### 6.1.1 RQ1: Which factors influence the choice of joint preparation

This research identified several factors influencing the choice of weld joint preparation. These factors are thoroughly discussed in sections covering current knowledge and results. The following points summarize the findings:

- **Materials properties:** The stiffness, thickness and overall geometry of the material significantly dictates the type of joint preparation to utilize. For instance, thinner materials may not support three-sided machining due to instability, while thicker materials might require it for enhanced robustness.
- **Component geometry:** The shape and dimensions of the parts to be welded influence the choice of joint preparation. Complex geometries may need more intricate preparations to ensure proper alignment and welding quality.
- **Accessibility for milling:** limited access can exclude the use of three-sided machining, making one-sided machining the only option.
- **Design requirements:** Structural integrity and manufacturability are crucial. The design phase involves evaluating whether the design can accommodate the necessary joint preparation techniques without compromising on quality.
- **Production efficiency:** Methods that streamline operations and reduce downtime are preferred. However, this must be balanced against the need for high quality results.
- **Economic considerations:** Cost-effectiveness plays a crucial role. Three-sided machining, while offering higher precision, typically incurs higher costs due to complex setups and longer machining times. Conversely, one-sided machining is less expensive but may lead to increased quality control and rework expenses if not managed properly.

These factors were derived from a combination of literature research, interviews, and practical insights from GKN Aerospace, ensuring an understanding of the elements that guide joint preparation decisions.

### 6.1.2 RQ2: How can simulation software be an aid in the choice of joint preparation

The study extensively explored the use of simulation software, particularly RD&T (Robust Design & Tolerancing), in aiding the choice of joint preparation. The key contributions of simulation software identified in the study include:

- **Predictive analysis:** RD&T enables the simulation of various manufacturing and assembly conditions allowing for the prediction of the performance outcomes through variation simulations and the addition of contact force simulations. This helps understands which joint preparation is accomplishable under the different variation scenarios.
- **Geometry assurance:** RD&T is also used to simulate geometrical variations between parts to be welded, ensuring that the fixtures can accommodate these variations and maintain the necessary tolerances for high-quality welds.
- **Force and stress analysis:** RD&T combined with FEA software like ANSYS helps in analyzing the forces required to clamp parts to their nominal shapes and the resultant stress distributions. This ensures that the chosen joint preparation method does not introduce undue stress that could compromise the material's integrity.
- **Digital twin technology:** The creation of digital twins through 3D scanning allows for more accurate simulations. These digital twins replicate the real-world variations and behaviors of manufactured parts, providing a reliable basis for decision-making regarding joint preparation.

Based on the findings from this thesis, it can be concluded that the research questions have been effectively answered. The factors influencing the choice of joint preparation have been comprehensively identified and validated through both theoretical and practical approaches. Additionally, the role of simulation software in aiding these decisions has been thoroughly demonstrated, showing its significant impact on improving geometric quality in welding through predictive analysis and enhanced process control.

## 6.2 Sources of error

In this thesis a single part was scanned to generate a digital twin and therefor introducing a possible error. Relying on a single part can result in an incomplete understanding of the variability and behavior of different parts under similar conditions. To achieve a more accurate simulation multiple part should be used to understand how different part behaves when exposed to forces. By using multiple parts, it would be possible to observe and account for variations in manufacturing deviations and differences in geometry that can impact how parts behave when exposed to clamping forces. This approach would provide more data and allowing for better identifications of patterns and trends, leading to a more robust conclusion.

To validate the simulations conducted a physical test on a similar part could be performed. However, this has not been accomplished due to time constraints and a lack of experience with such tests. Conducting these physical tests in the future would significantly enhance the project by providing a deeper understanding of how different geometries and support material affect the required forces. This hands-on approach would complement the simulations and ensuring a more comprehensive analysis and potentially lead to a more accurate and reliable results.

## 6.3 Conclusion

This thesis has thoroughly explored the optimization of fixturing for improved geometric quality in welding, particularly focusing on the factors influencing weld joint preparation and the role of simulations aiding these decisions.

The thesis identified factors such as material properties, component geometry, accessibility for milling, production efficiency and economic considerations. As stated in previous section these factors are intertwined and must be balanced to determine the optimal decision for which joint preparation to utilize. The findings underline the possibility of integrating simulations tools in the design and manufacturing processes to enhance quality and efficiency and carry over engineering expertise to the next generation of engineers.

RD&T has the possibility to simulate manufacturing and assembly conditions providing a predictive analysis to ensure geometric quality. Using digital twins enhances the reliability of simulations, enabling precise replication of real-world conditions and providing more reliable results for the decision-making process. The integration of force and stress analysis using RD&T and FEA tools like ANSYS ensures that the used force for fixturing do not introduce harmful stresses that could compromise the materials integrity. By predicting potential issues early manufacturers can reduce waste, avoid costly rework and gives better opportunity for high product quality.

However, the thesis was limited to simulations without completing full welding simulations due to time constraints and the complexity of these simulations. This leaves a gap that could be explored in future research. Furthermore, the use of a single scanned part for generating a digital twin may not fully capture the variability and behavior of different parts. Future studies should include multiple samples to ensure a comprehensive understanding.

In conclusion, this thesis has demonstrated the role of simulation software in optimizing fixturing and improving geometric quality in welding. By understanding and addressing intricate factors influencing weld joint preparation, manufacturers can achieve higher precision and efficiency in their processes. Future research should these findings to further refine the decision-making process of weld joint preparation to enhance the manufacturing quality of fabricated structures.

## 6.4 Directions for further research

The plan outset of the project was to perform welding simulations using RD&T. The primary goal was to gain a deeper understanding of the welding process and to save time through advanced simulations. Due to the complexity of welding simulations and time constraints, these simulations could not be completed. This unfinished task presents an opportunity for further exploration in a future thesis project, where more time be used to implement these simulations.

As the thesis progressed into its later stages the idea of utilizing scan data to analyze the forces involved during fixturing. This idea led to the scanning and analysis of a single part using RD&T. The late introduction of this approach meant that there was only time to scan and analyze one component. Multiple parts could have been scanned and analyzed if this strategy been adopted earlier in the project, thereby providing a more accurate set of results.

To improve the understanding of various machining processes further investigation is necessary in RD&T when using a broader array of digital twins. This approach has potential to provide a more detailed insight into the behavior of actual parts during fixture clamping. In present thesis a single scanned part served as a digital twin and therefore introducing possible source error. Using multiple digital twins and determine the clamping sequence can accomplish a more accurate simulation. These simulations enable the creation of a virtual model of the fixturing process.

For such a virtual model to functional the heat generated during welding must be considered. While this aspect was a secondary focus in this thesis and was not explored due to the time limitation, it is possible in the new test version in RD&T. This signifies RD&T capacity to handle simulation about geometrical variation, force variation and the impact of welding. Doing these simulations within a single software platform saves valuable time.

Future research needs investigate how the machining decision impacts aerodynamics. According to the interviews with engineers from GKN Aerospace this is an aspect that is not considered. Surface roughness after the welding process varies depending on one-sided or three-sided machining is used. This research will enhance the understanding of the relationship between machining process and aerodynamics.

Certain functions in RD&T could need further testing and exploration. This thesis utilized ANSYS to analyze the stresses associated with fixturing. If more research is conducted into RD&T's stress analysis capability, ANSYS could potentially be excluded. Currently, RD&T effectively analyzes stress using a shell mesh, further investigation could include stress analysis for a solid mesh.

Another function requiring further testing is the effect of group tolerancing to achieve more reliable result before a digital twin is created. This could provide insights of how a manufactured part appears and behaves when clamped in a fixture.

Summarized list for recommendations for further research is find below:

- **Comprehensive Welding Simulations**: Future work should focus on completing welding simulations within RD&T to gain deeper insights into the welding process and its effects on joint preparation.
- **Expanded Digital Twin Utilization**: Utilizing multiple parts for generating digital twins would provide a more robust dataset, enhancing the reliability of simulation results.
- **Real-World Validation**: Conducting physical tests to validate simulation results would provide additional confidence in the findings and could uncover practical nuances not captured in simulations.
- **Extended Economic Analysis**: A more detailed analysis of the long-term economic impacts of different joint preparation methods could offer further insights into cost-effectiveness and strategic decision-making.
- **Utilize Extensive Scan Data at Earlier Stages**: Implementing scan data earlier in the process would improve the accuracy and reliability of simulations.
- **Incorporate Aerodynamics and Structural Integrity Considerations**: Including these factors would ensure that joint preparations meet both aerodynamic performance and structural requirements.
- **Optimize the Sequencing of Fixturing Processes**: Enhancing the sequencing can improve overall efficiency and effectiveness of the fixturing process.
- **Further Explore the Stress Analysis Functions in RD&T**: This would expedite analysis and provide more detailed insights into stress distributions.
- **Investigate the Impact of Grouped Tolerances for More Reliable Pre-Digital Twin Results**: Understanding the effects of grouped tolerances would lead to more accurate and reliable simulation outcomes before generating digital twins.

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# Appendix

***Table A1.*** *Specifies about the interviewees.*

| **Gender** | **Role** | **Actor** |
|---|---|---|
| Male | Principal Manufacturing Engineer - production | GKN Aerospace |
| Male | Principal Engineer - Design | GKN Aerospace |
| Male | Principal Manufacturing Engineer - Tooling | GKN Aerospace |
| Male | Consulting within Production | GKN Aerospace |
| Male | Principal Engineer - Product Support | GKN Aerospace |
| Male | Senior Research Engineer | GKN Aerospace |

***Table A2.*** *Table of interview questions*

| |
|---|
| What does the workflow look like for developing fixtures today? |
| Which factors influence the choice of joint preparation, one-sided, or three-sided? |
| Advantages and disadvantages of three-sided joint preparation? |
| Advantages and disadvantages of one-sided joint preparation? |
| Why do we want to switch from three-sided joint preparation to one-sided joint preparation? |
| What are the limits for material deformation, such as sheet metal, related to structural requirements? |
| If the process is designed for three-sided joint preparation, how much effort is required to switch to one-sided joint preparation? |
| When is it not possible to use three-sided joint preparation?<br>When is it not possible to use one-sided joint preparation?<br>What are the exceptions?<br>What could be the consequences of the choice? |
| Where and when is the decision made regarding which method of joint preparation to use (three-sided or one-sided)? |
| What are the requirements for gap and flush before and after welding? |
| What is the maximum force that the fixtures currently in use can withstand? |

| |
|---|
| How is the force required for fixturing measured in the case of one-sided joint preparation? |
| Is it possible to adjust fixtures directly on-site during assembly? Is that possibility available? |
| Are there any thoughts on how to optimize fixture concepts for the future that we can consider? |

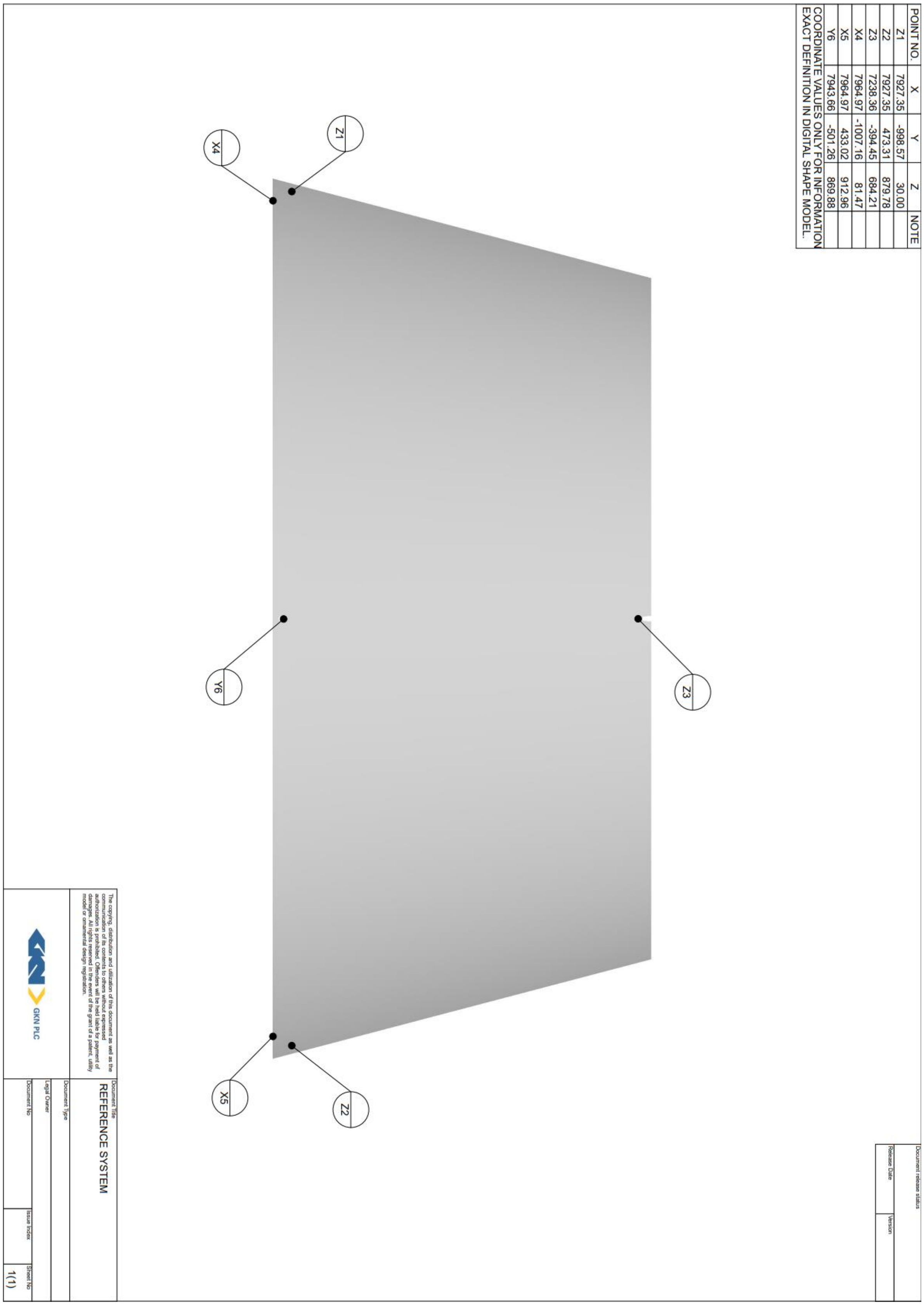


***Figure A3.*** *6-direction locating scheme*

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