QUALITY ASSURANCE OF THE FREQUENCY CONVERTER FOR DEEP SPACE APPLICATION

Material Selection and Tolerance Standards

Lappeenranta–Lahti University of Technology LUT

Bachelor's Degree Programme in Mechanical Engineering, Bachelor's thesis

2025

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Examiner(s): Associate professor, Docent, D.Sc. Harri Eskelinen

Professor Hua Yang

ABSTRACT

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LUT School of Energy Systems

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57 pages, 26 figures, 8 tables and 7 appendices

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Keywords: Quality assurance, Geometric tolerances, SolidWorks CAM, CNC machine.

This thesis develops a QA framework for precision manufacturing, focusing on material selection and tolerance standards for the frequency converter under deep space applications. By using CAD models, CAM simulations, and 3D printing, the research evaluates titanium and aluminium 6061-T6 for hermeticity and dimensional stability. The framework integrates expert feedback and triangulation to ensure machining accuracy and reliability. The findings support improved manufacturability and have potential applications in aerospace, medical devices, and precision engineering.

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Finally, I would like to acknowledge everyone who has generously offered their advice and assistance during my academic journey. Their support has been invaluable to the completion of this work.

This thesis is part of a long-term research initiative at LUT University, focusing on three critical dimensions: DFMA, Quality Assurance (QA), and Environmental Sustainability. Specifically, this work addresses the QA aspect, emphasising material selection and tolerance optimisation. The data and findings presented in this study will contribute to the broader research efforts, providing valuable insights to support subsequent investigations and build a comprehensive understanding of QA practices in MW and RF technologies.

AI & PLAGIARISM CLARIFICATION

According to LUT guidelines for using AI in theses and maturity tests, here are specific scenarios of use and compliance with the LUT guideline. The output of the generative AI was adapted and modified for the final answer. The original materials have been saved and are available for viewing, if required.

AI is only used to build a table of contents (how to arrange existing results) and provide suggestions & improvements about the sentence grammar. None of the main text is exactly copy-pasted or generated by AI.

No. 1 – Structuring the table of contents

Artificial intelligence was used as a tool to assist in organising and structuring the thesis content. Copilot (Microsoft Copilot: Your everyday AI companion) was utilised on 12 April 2025 to provide insights on structuring the table of contents and arranging results systematically in section 3.3. The AI-generated suggestions were reviewed and modified to enhance clarity and coherence.

No. 2 – Finding Additional References

AI was leveraged to assist in identifying relevant literature sources related to the research topic. Scopus via LUT Primo was used to discover academic papers, books, and credible sources that contributed to the thesis background.

No. 3 – Grammar and Accuracy Suggestions

To improve the readability and linguistic accuracy of the thesis, AI tools were used for grammar checking and writing suggestions. Copilot was consulted to refine sentence structure, while Grammarly (Grammarly: AI-powered writing assistant) was employed. DeepL (DeepL Translate: The world's most accurate translator) was used to refine translations throughout the thesis. Usage was sporadic and only for reference purposes, in line with academic integrity guidelines. AI-generated recommendations were reviewed and adapted, but no content was directly copied. It is only used to provide relevant advice, such as what grammar is appropriate, how to improve the quality of writing, and referencing some of the keywords provided by the AI, but not copying and pasting anything directly; the written content is written by me.

SYMBOLS AND ABBREVIATIONS

Al	Aluminum
ANSI	American National Standards Institute
CAM	Computer-Aided Manufacturing
CAD	Computer-Aided Design
CNC	Computer Numerical Control
CU	Copper
DFMA	Design for Manufacturing and Assembly
ECSS	European Cooperation for Space Standardization
FEA	Finite Element Analysis
FEM	Finite Element Method
FE	Iron
ISO	International Organization for Standardization
LR	Literature review
MW	Microwave
NASA	National Aeronautics and Space Administration
QA	Quality Assurance
RF	Radio Frequency
RQ	Research question
SS	Stainless Steel
STD	Standard
TI	Titanium

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Appendices

1 Introduction

To gain a clear understanding of the general framework and objectives of this study, the specific goal and research problem of this thesis are outlined below.

1.1 The goal

The aim of this thesis is to build a comprehensive quality assurance (QA) framework specifically focused on the tolerance definition and material selection for the metallic body of a frequency converter used in deep space applications. The principal goal is to ensure that the metal body meets the demanding environmental conditions while maintaining precision, durability, and reliability throughout its operational life. The QA framework will cover quality control at three significant stages: before production, during production, and after production, integrating methods to ensure accurate tolerance definition, reliable material selection, and consistent manufacturing quality.

This thesis is part of the ongoing university project that aims at developing high-reliability components for deep space applications. The project integrates three aspects: environmental, quality assurance, and design for manufacturing and assembly (DFMA). While this thesis primarily focuses on quality assurance, particularly tolerance and material selection. It also supports the environmental and DFMA perspectives by ensuring durable, accurate manufacturing processes and materials.

1.2 Research problem

The metal body of a frequency converter used in deep space missions must have precise tolerances and a high-quality surface to ensure stable integration with PCBs, connectors, and sealing elements. Dimensional accuracy plays a crucial role in deep space missions, as severe conditions like vacuum, temperature fluctuations, and vibration can cause mechanical failure, making it crucial to accurately define both dimensional and geometric tolerances and implement a rigorous quality assurance process to ensure consistent compliance throughout manufacturing. Long-term reliability is further based on using materials with stable tolerance and surface finish.

1.3 Research question

To establish a quality assurance system for the metal body of a frequency converter, the mentioned research questions are to be solved in this thesis:

RQ1 – Tolerance Definition & Verification: How can dimensional and geometric tolerances for the metallic body be defined, optimised, and verified to ensure mechanical fit and hermetic sealing under deep space conditions?

RQ2 – Material Selection: How does the use of metal materials impact tolerance stability and surface quality in deep space conditions, and what are the selection criteria to ensure reliability in manufacturing?

1.4 Background and motivation

Based on last year's DFMA study for reference, this work concentrated on the quality assurance aspect of the frequency converter. According to the QA analysis tool outlined in Appendix 6, the answer to question 1 is that for deep space missions, the frequency converter must maintain mechanical precision, structural integrity, and long-term reliability despite harsh conditions. For instance, high temperature variations at a rapid pace would cause thermal expansion and contraction, which affect dimensional stability. is directly influenced by tolerance definition and material selection since any dimensional errors would compromise working frequency and device stability, as well as performance itself.

The frequency converter, used in radioastronomical deep space missions, is responsible for processing microwave (MW) and radio frequency (RF) signals, making communication and frequency conversion. It consists of a precision-machined metal body, covers, and internal PCB modules with SMA connectors, fasteners, and hermetic seals formed using silver soldering. The outer surfaces are gold-plated for conductivity and corrosion resistance (Bond et al., 2019).

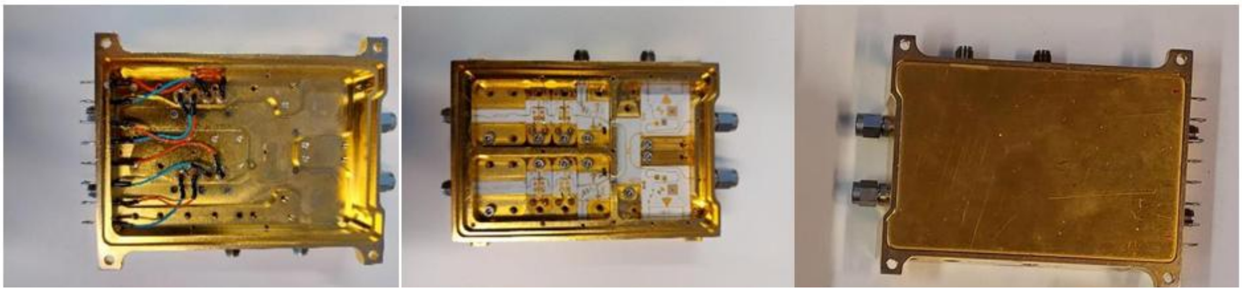


Figure 1 The prototype of the frequency converter.

The bandwidth and operation frequency of a converter are of equal significance for the reason that they directly affect the signal integrity, efficiency, and overall performance of a system for deep space use. It demands precise mechanical tolerances to keep PCBs assembled with the suitable clearance so they can operate properly, ensuring RF performance and reducing signal distortion.

The mechanical QA is crucial for ensuring the integrity of the metal body under deep space conditions, where tolerance deviations, misalignments, or surface defects can cause RF mismatches or assembly failures that are irreversible after launch (Kondić et al., 2020). The QA framework covers positional tolerances for connectors and fasteners to maintain reliable hermetic sealing between covers and the metal body, which protects electronics from moisture and radiation. Adequate cavity sizes support PCB clearance and electromagnetic shielding, and flat critical surfaces ensure proper alignment. Materials and surface treatments, such as anodising and gold plating, are selected for their resistance to radiation and chemical exposure, ensuring long-term performance (Mazínová and Florian, 2014). I made the measurements of the original part using manual tools like rulers. The process is likely to result in some error in dimensions due to tool capabilities and human errors.

The motivation for this study stems from the need to ensure the frequency converter's reliable operation in deep space, where harsh environmental conditions demand high precision and durability. Creating a strong QA system with precise tolerancing and selection of materials is necessary for the performance and structural integrity of the converter to be upheld throughout the mission.

1.5 Literature review

In aerospace production, high reliability is attained by integrating robust QA practices throughout production. In accordance with the QA analysis tool included in Appendix 6, there are critical factors that must be acted upon during and after production for assurance of quality and long-term performance.

Securing parts firmly at various points of manufacture helps preserve dimensional integrity and averts deformation. Clamping and support are essential; hence, precise machining with close tolerances is attained. Adaptive and modular clamping systems, based on Mehrabadi et al. (2017), facilitate stability by ensuring flexibility of part geometry, avoiding risk of deformation during machining.

Setting up correct production parameters, including cut speed, feed rate, and tool path programming, is critical for optimised tool wear and consistent quality. Kumar (2020) discussed how optimising these parameters can significantly enhance machining accuracy, particularly when working with aerospace-grade materials prone to deformation. Maintaining compatibility among CAD models and CNC machines using standard data formats such as STEP and IGES is equally important for maintaining geometrical accuracy throughout manufacturing (Symmetrix, 2023).

During production, it is important to identify critical factors that could affect quality, such as dimensional deviations and surface defects. Milling and drilling processes, in particular, can introduce variability due to tool deflection and thermal expansion. Yuan et al. (2024) recommended using in-situ measurement tools to detect these deviations in real time, allowing for immediate corrective actions.

Setting up correct production parameters, including cut speed, feed rate, and tool path programming, is critical for optimised tool wear and consistent quality. Kumar (2020) explained that optimising such parameters would improve machining accuracy, especially with aerospace-grade materials that are deformation-sensitive. Maintaining compatibility for CAD models with CNC machines using universal data formats, including STEP and IGES, is also crucial for geometrical accuracy throughout manufacturing (Symmetrix, 2023).

Real-time measurement of production parameters provides more consistency in quality. Spindle speed, feed rate, and cutting force are all measurable by automated data collection integrated within CNC controls. Athawale et al. (2011) suggested that real-time monitoring is able to identify deviations that would affect dimensional accuracy, with adjustments made immediately.

Digital and automatic processes are more accurate, with a reduced potential for error. Melldén (2022) has described that sensors, cameras, and AI processing are integrated into manufacturing lines so predictive maintenance and adaptive process control become possible. Automatic machines are capable of processing variations immediately and adjusting, which is enormously valuable for aerospace parts quality.

Dimensional verification after production is required to ensure that parts produced are of acceptable specification. Advanced metrology tools, such as coordinate measuring machines (CMMs) and optical profilers, are widely applied for checking important dimensions and maintaining accuracy for assemblies. Schulze et al. (2016) indicated that precise measurement methods must be utilised for checking flatness, roundness, and geometrical tolerances for guaranteeing aerospace parts' structural integrity.

The literature also supports applying QA practices throughout all manufacturing processes. Concentration on reliable fixing, ideal production conditions, online monitoring, and computer automation enormously boosts machining reliability and accuracy. In addition, the application of sophisticated metrology plays an important role in inspection with a view toward maintaining aerospace components for a longer life and for working in adverse conditions.

1.6 Applied methodology and expected outcomes

This thesis uses a triangulation approach with a combination of expert interviews, literature reviews, and testing in software for addressing tolerance standards and material selection for the frequency converter. The QA frame will be structured based on integrating these progresses, including CAD modelling and technical drawings, CAM simulation, and 3D printing. SolidWorks will be used to define geometry. Tolerances will be clearly shown on technical drawings for production capability. CAM simulation with SolidWorks will check machining performance. Also, the 3D printing of prototypes will help ascertain manufacturing feasibility and accuracy. Through integrating all methods with the QA frame, we are ensuring that the metallic body of the frequency converter is reliable for a longer period of time.

The anticipated results of this work are designed to ensure the mechanical accuracy, hermetic integrity, and reliability of the metal body under harsh deep space conditions. The outcomes include a comprehensive quality assurance frame that defines the tolerance specifications and material choices for the frequency converter's metal body. Additionally, technical drawings and 3D models will provide detailed explanations of manufacturing processes and tolerances. Furthermore, the integration of QA results can be disseminated and applied to other similar devices.

2 Research methods

As in figure 2 below, this triangulation methodology is used throughout the research. It is divided into three parts: literature review, expert interview, and testing in software. The methodology is effective for a comprehensive analysis by bringing together theoretical perspectives, industry experience, and experimental testing, with a possibility for the findings to support and compare each other for a comprehensive QA structure.

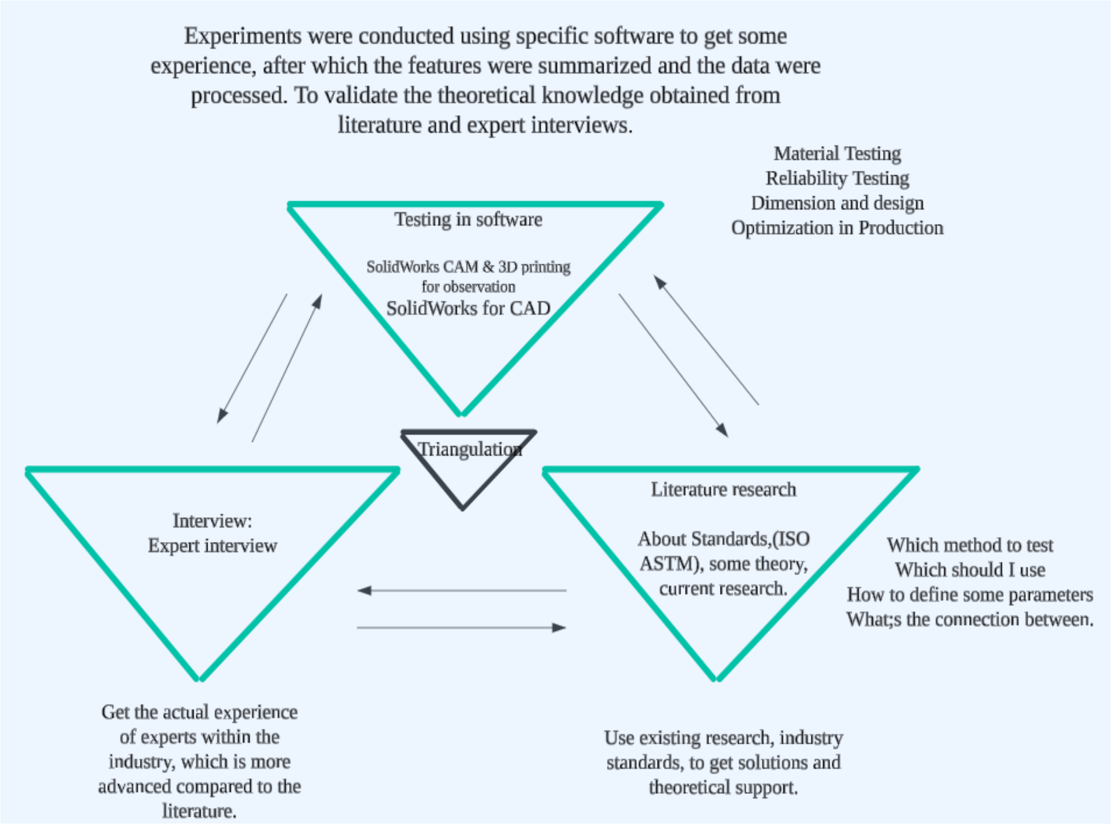


Figure 2 The triangulation method uesd in the thesis..

2.1 Expert interview method

The expert interview was utilised to gather the real-life insights from an industry perspective. The use of the qualitative approach allowed direct consultation with an expert who has first-hand experience in handling the design, operational, and manufacturing limitations of PCBs (printed circuit boards), providing practical knowledge that cannot be obtained solely from literature. The primary research question during the interview was, “What kind of requirements are set for the PCBs in the device, and how do they affect the performance of the product?”

This question aimed to explore how the quality is defined and how the performance of the device is affected by PCB assembly. By structuring the inquiry, the interview sought to find key considerations affecting the device, including material properties, environmental influences, and mechanical stresses.

The conclusions of the questions will be compared with the factual data of the literature in the end to verify the reliability. This comparison guarantees that the expert opinions are based on accepted knowledge, improving the accuracy of the conclusions. This approach enhances the whole structure of the research and improves the investigation of the research question by combining expert opinions with recorded data. By means of this approach, the expert interview technique enabled a closer awareness of pragmatic difficulties and requirements in PCB design and manufacturing, bridging the gap between theoretical knowledge and industry practices.

2.2 Literature review method

The review in the study also complies with a structured question-based methodology to systematically explore and discuss the principal areas in the definition of tolerance, material selection, and quality assurance. This enables the literature to support the thesis objectives in a focused way that remains particularly attuned to challenges and practices in aerospace manufacture.

2.2.1 Workflow diagram of the LR method

This infographic is a brief visual summary of the process of the literature review that illustrates the five stages, which are interlinked, and how the stages build on each other in a logical order. It serves as a map of the process outlined in the methodology and highlights how the following phase logically evolves after the previous.

Refer to figure 3; the sub-question design process begins by breaking down the research question into approximately 20 sub-questions, each addressing a specific problem or topic. These sub-questions guide the literature search, ensuring comprehensive coverage of key topics. The database search phase involves querying academic databases like IEEE Xplore, ScienceDirect, and LUT Primo using strategically chosen keywords, focusing on recent peer-reviewed articles published within the last five years to ensure quality and relevance. After retrieval, references undergo screening to evaluate their credibility, relevance to the study, and publication date, resulting in a shortlist where each sub-question is supported by at least three credible sources.

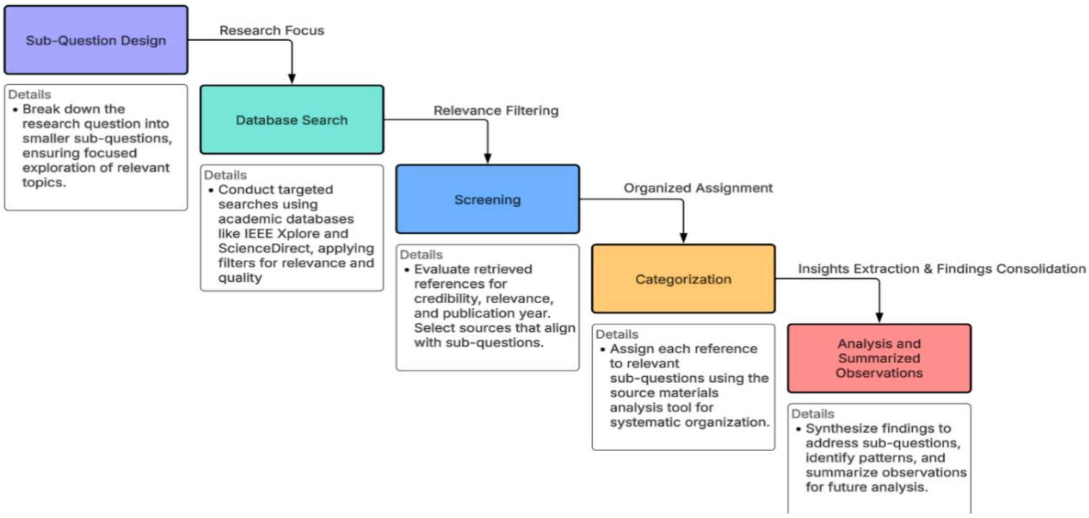


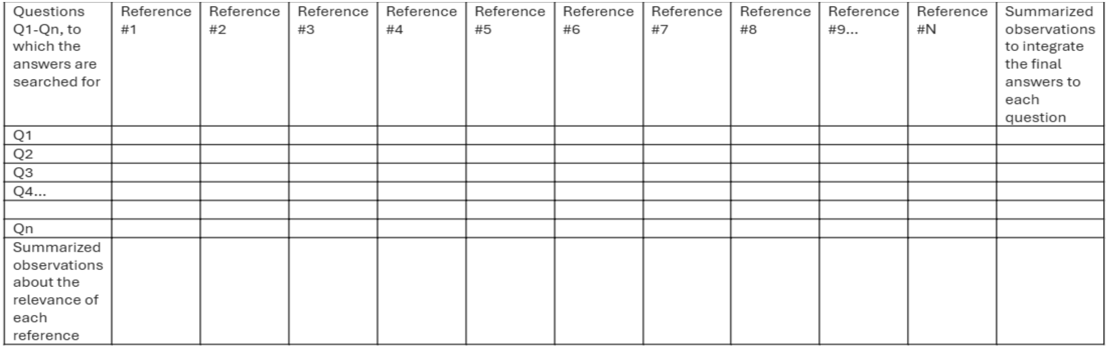
Figure 3 Waterfall diagram for the workflow steps of Literature review.

The chosen references are then categorised using a source materials analysis tool, matching each reference to the corresponding sub-question and building a structure to support the thesis research objectives.

2.2.2 Source materials analysis tool

According to Table 1, the source materials analysis tool plays a crucial role in organising the process of literature review by logically classifying and validating references. It groups sub-questions by content and relevance and visually tracks and verifies credibility by at least 3 related references. This process makes literature reviews more accurate and reliable.

Table 1 Source material analysis tool



Questions Q1-Qn, to which the answers are searched for	Reference #1	Reference #2	Reference #3	Reference #4	Reference #5	Reference #6	Reference #7	Reference #8	Reference #9...	Reference #N	Summarized observations to integrate the final answers to each question
Q1											
Q2											
Q3											
Q4...											
Qn											
Summarized observations about the relevance of each reference											

For example, sub-questions include "How to coat for sealing the hermeticity of the cavity?" and "How do you specify quality within QA?" The tool consistently correlates such sub-questions with reliable sources sourced from platforms including IEEE Xplore, ScienceDirect, and LUT Primo, with the correlations among the references and research topics easily traced and organised.

2.3 Stepwise quality assurance procedure and SolidWorks illustrations

Based on figure 4 below, this workflow method employed in the study ensures quality assurance through a process approach. The process begins using measurements that are taken manually to determine the dimensions. It continues through detailed CAD modelling to prototype production with the 3D printing technique. Then it involves CAM tests for simulations in the manufacturing to ensure the integration of results that have enough reliability and accuracy.

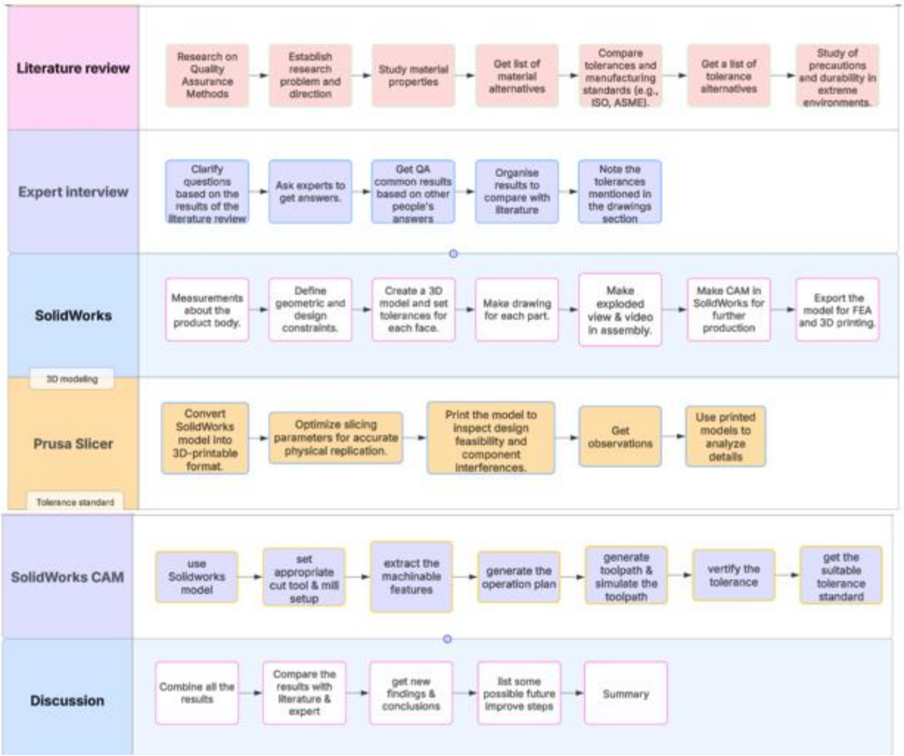


Figure 4 The workflow diagram for testing stepwise quality assurance process.

The methodology of using the tools in testing contains three primary elements: SolidWorks for use in CAD modelling and conducting CAM operations, Prusa Slicer for 3D printing activities and accuracy checking through prototyping. They represent a whole system for the QA framework in this case.

The workflow starts with initial measurements taken manually, which establish the initial model for design accuracy. Each subsequent step builds on the previous, creating a systematic evaluation of design parameters and performance constraints.

Although the research would use manual approaches, industrial manufacturing would utilise automated systems to provide scalable and reproducible accuracy. Figure 5: General measurement setup, e.g., for some accurate dimensions and Figure 6: A photo of a real measurement setup represents such industrial approaches. These examples highlight advanced systems used for capturing precise dimensional data in real-world production environments. Though these figures illustrate industrial setups, they serve as a reference point for comparing manual processes with automated standards.

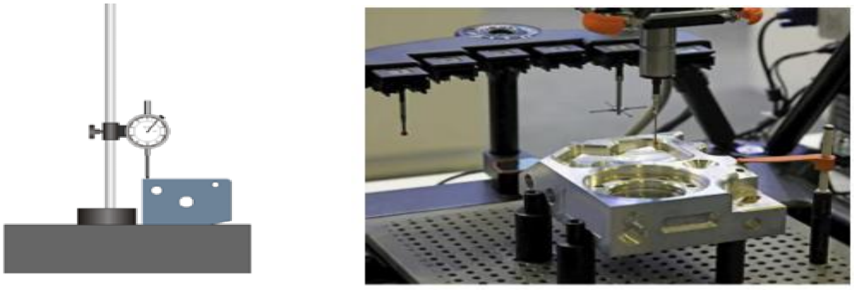


Figure 5 and 6: General measurement setup for some accurate dimensions and A photo of a real measurement setup.

Supporting images associated with the manual processes, including measurements using a ruler and camera-based documentation, illustrate how the tolerance was defined and converted to the modelling process. This process-orientated workflow prioritises reliability and integration to bridge the gap between industrial application and traditional techniques to provide strong quality assurance.

2.4 Utilization of triangulation method

Comparison: This study compares expert interview findings with literature to assess alignment between industry opinions and engineering theories. For instance, expert insights on mechanical integration and tolerance management were validated against GD&T standards (Amatrol, 2025; Fractory, 2025). Any discrepancies were analysed to determine whether they reflected innovative practices or overlooked constraints. Also, the results from the SolidWorks model were compared against theoretical tolerance standards to confirm design precision.

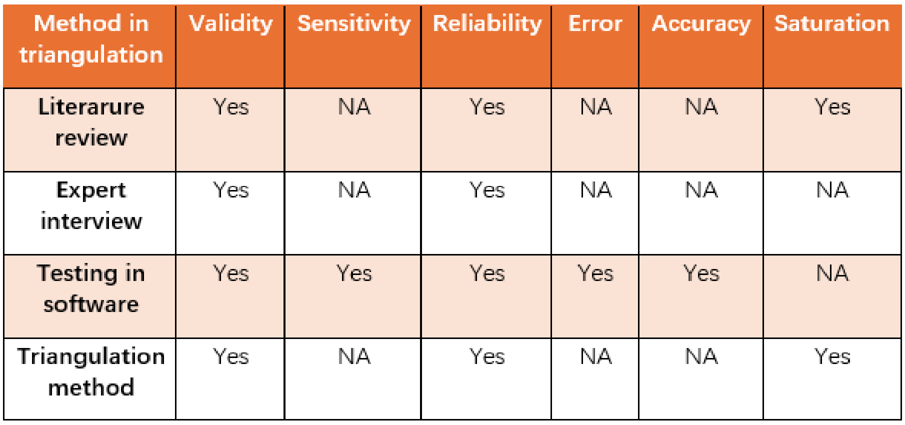
Support: In this research, SolidWorks was used for CAD modelling, complemented by SolidWorks CAM and tolerance from LR to simulate machining processes, ensuring that the designed product meets both theoretical criteria and practical manufacturability. CAM functionality in SolidWorks evaluates CNC machinability, verifying surface quality and tolerances for real-world production.

Justification for Construction: The triangulation approach ensures accuracy by validating the consistency of three aspects. Tolerance standards are first established from the literature, then modelled in SolidWorks CAD and CAM, and finally tested for production feasibility using PrusaSlicer. If discrepancies arise, such as theoretical tolerances being unattainable in CNC milling or 3D printing, the research will investigate the reason and adapt the design to meet manufacturing standards. This iterative validation minimises discrepancies and ensures the quality assurance process meets the stringent requirements of deep space applications.

2.5 Means to carry out reliability analysis

To ensure the reliability of the study, a structured methodology for the evaluation was adopted through a reliability analysis table. Table 2 here critically considers four significant methodological approaches: literature review, expert interview, testing in software, and the method of triangulation, which relates to six criteria for reliability: validity, sensitivity, reliability, error, accuracy, and saturation.

Table 2 The reliability analysis table.



Method in triangulation	Validity	Sensitivity	Reliability	Error	Accuracy	Saturation
Literarure review	Yes	NA	Yes	NA	NA	Yes
Expert interview	Yes	NA	Yes	NA	NA	NA
Testing in software	Yes	Yes	Yes	Yes	Yes	NA
Triangulation method	Yes	NA	Yes	NA	NA	Yes

Each approach is assessed against these criteria and marked as either "Yes" or "NA". If a criterion is marked as "Yes", it means that it’s necessary to be included in the discussion section. In contrast, an "NA" indicates a criterion that does not need additional verification. These examples demonstrate how the reliability analysis table is used to evaluate different aspects of the research. For instance, in the literature review, reliability is ensured by using peer-reviewed sources or academically orientated databases such as LUT Primo and IEEE, which are marked as "Yes" for discussion. Regarding errors in software testing, potential inaccuracies may arise from human factors or the inherent limitations of simulation boundaries, necessitating careful examination to ensure accurate analysis and interpretation.

This table acts as a vital method for checking the validity of the study data and content. Through the process of systematically comparing each methodological process to the major criteria of reliability, the results are solidly established and not conflicting. Organising the evaluation process in this manner brings accuracy and validity to conclusions derived from the study as well as reduces possible causes for error.

3 Result

In this section, according to the importance of the results, the priority is QA results, literature results, and expert results. The reason is that QA is the core of this paper, and the results support the subsequent content.

3.1 QA Result

This section presents the evaluation of tolerances and materials, also illustrating the tolerance with SolidWorks and simulating via SolidWorks CAM. focusing on maintaining accuracy and reliability in the frequency converter's metal body for deep space applications.

3.1.1 Tolerance and material evaluation

Tolerance inspection makes parts conform to design specifications as well as maintain manufacturability. An appropriate tolerance standard is necessary in providing reliability and assembly because any tolerance variations will impact hermeticity, frequency stability, and overall performance. In this work of research, three areas are addressed: dimensional tolerance, geometrical tolerance, and finishing requirements of the surface. Dimensional tolerance matches specified sizes, while geometrical tolerance keeps shape, orientation, and positional precision. Finishing requirements of the surface regulate roughness to aid in sealing, minimise wear and tear, and promote better performance.

According to Appendix 6, question 4, material test reports (MTRs) are necessary to validate the compliance of the specified materials according to standards like EN, ASME, and ASTM to the mechanical and chemical properties. The reports guarantee the materials used possess structural stability and integrity against aggressive environments as a condition necessary for aerospace applications. The MTRs of the specified material, Aluminium 6061-T6, are presented in Appendix 7.

Based on the information in Table 4, titanium alloy type 6Al-4V has high corrosion resistance and low permeability, enabling a consistent hermetic seal. Its low coefficient of thermal expansion and high strength help maintain dimensional accuracy, preventing deformation under thermal stress; therefore, titanium (Ti-6Al-4V) was chosen for the cover. These characteristics make it perfect to achieve hermetic seals and robustness in harsh environments. Aluminium 6061-T6 metal is a machinable and light metal and requires surface treatments to obtain improved hermeticity since it is more permeable in nature than titanium. Aluminium 6061-T6 is utilised in the centre part because it has good machinability and own weight. Its RA 6.3 surface finish also causes improved component interaction and reduction of wear. Titanium 6Al-4V and Aluminium 6061-T6 were selected considering the above parameters, as both of them were found to possess a combined efficiency in operation stability as well as sealing to provide durability and precision during operations in deep space.

Table 4 Optional Material selection list and their properties.

	Yield Strength (MPa)	Relative Stiffness	Summary
Al 6061-T6	275	Baseline	Balanced strength and excellent machinability
Al 7075-T6	503	Higher	Increased strength, but harder to machine
Ti-6Al-4V	880	Very High	Exceptional durability, high cost
Invar 36	240	Moderate	Good thermal stability, heavier material
SS 304	215	Lower	Corrosion-resistant but heavier and less ideal for aerospace

Selecting appropriate tolerance standards is also essential for maintaining quality and consistency. After comparing the information in Table 5, the ISO 2768-m is chosen as the primary standard for this study due to its practical balance of precision and manufacturability. It is widely applicable for mechanical parts and CNC processing, offering flexibility and mass production suitability. This standard ensures accurate assembly without excessive complexity, making it ideal for the frequency converter's metal body.

whereas NASA-STD-6016 is usually optimised for aerospace systems with high tolerance requirements and is hence less adaptable to general manufacturing. Standards like ISO 286 and ASME B4.1 focus on shaft-hole fit precision, which is not directly applicable to the integral structures analysed in this study. Military standards like MIL-STD-38784 ensure reliability but come with high costs and are less suitable for commercial production. Of all the standards mentioned above and considering both precision and applicability, ISO 2768-m best fits the requirement to guarantee quality and maintain practical production.

Table 5 Optional tolerance standards list & their properties.

Standard	ISO 2768-m	ANSI Y14.5	NASA-STD-6016	ECSS-Q-ST-70
Use area & summary	Mechanical & CNC parts Widely used for general industrial applications, offering flexibility and practicality for enclosures and brackets. Suitable for mass production.	Engineering drawings (US) Ideal for comprehensive geometric dimensioning and tolerancing (GD&T). Ensures precise control over shape, orientation, and location but can be complex to implement.	Aerospace & satellite systems Designed for deep-space optical/sealed interfaces, providing strict tolerance control. Highly precise but costly to implement.	ESA/European space missions Focuses on material, process, and inspection integration in QA systems. Used for high-reliability space hardware.
Standard	ISO 286	ASME B4.1	MIL-STD-38784	VDI/VDE 3441
Use area & summary	Mechanical fits & tolerances Defines tolerance limits for shaft-hole fits to ensure precision in mechanical assembly.	Clearance and interference fits Standardized for mechanical components, covering clearance/interference fits in metal parts.	Military & defense components Used for military and defense applications, ensuring durability and extreme precision but with high implementation costs.	Precision positioning systems Specifies accuracy standards for precision mechanical positioning systems.

Finally, the 3D printing is used to observe the manufacturability of the designed parts. Using Prusa Slicer, prototypes are fabricated using Prusa Slicer to demonstrate if the tolerance and surface finishes are realistically achievable, also finding sensible design constraints and feedback on dimensions.

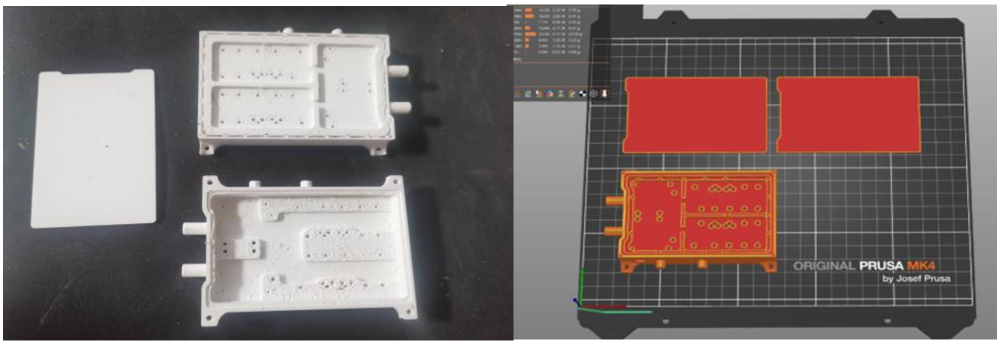
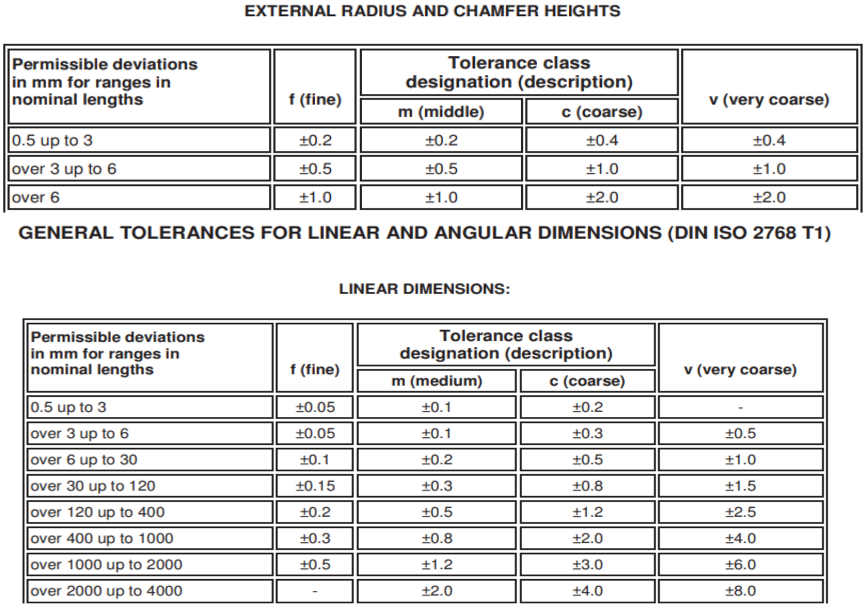


Figure 7: The 3D printed model of the device captured by the camera.

And figure 7 confirmed this. This integration within the QA framework bridges theoretical design with practical implementation, ensuring the frequency converter's metal body meets both design and manufacturing standards, supporting long-term reliability in deep space applications.

3.1.2 SolidWorks-based tolerance illustration

This section presents the detailed specifications of ISO 2768-m, followed by visual representation using SolidWorks, illustrating how tolerances are implemented and verified in practical applications. Here is part of the example for this tolerance standard; the detailed version is in Appendix 4.



EXTERNAL RADIUS AND CHAMFER HEIGHTS

Permissible deviations in mm for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (middle)	c (coarse)	
0.5 up to 3	±0.2	±0.2	±0.4	±0.4
over 3 up to 6	±0.5	±0.5	±1.0	±1.0
over 6	±1.0	±1.0	±2.0	±2.0

GENERAL TOLERANCES FOR LINEAR AND ANGULAR DIMENSIONS (DIN ISO 2768 T1)

LINEAR DIMENSIONS:

Permissible deviations in mm for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (medium)	c (coarse)	
0.5 up to 3	±0.05	±0.1	±0.2	-
over 3 up to 6	±0.05	±0.1	±0.3	±0.5
over 6 up to 30	±0.1	±0.2	±0.5	±1.0
over 30 up to 120	±0.15	±0.3	±0.8	±1.5
over 120 up to 400	±0.2	±0.5	±1.2	±2.5
over 400 up to 1000	±0.3	±0.8	±2.0	±4.0
over 1000 up to 2000	±0.5	±1.2	±3.0	±6.0
over 2000 up to 4000	-	±2.0	±4.0	±8.0

Figure 2 Details about the ISO 2768-m standard.

According to Appendix 6, question 2, it is possible to view how the product is to be manufactured, and the following pictures show the tolerances. To define the tolerance more clearly, the use of two marks becomes the standard: the red mark denotes the tolerance itself, and the blue mark denotes the range between distances affected by the value.

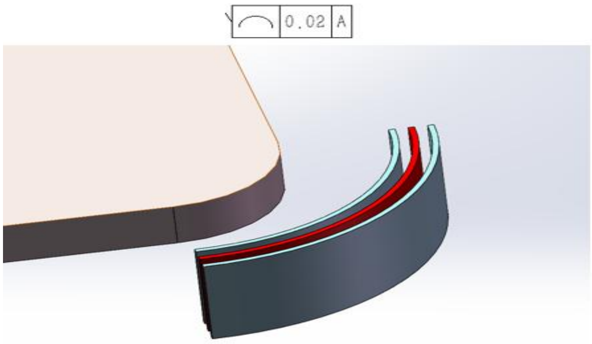


Figure 3 Rounded Edge tolerance of the cover

In figure 9, the fillet has a 0.02 mm tolerance for achieving smooth edges without weakening the structural integrity. It does not create harsh transitions that would affect the assembly or durability. Controlled fillet guarantees the fit that will be achieved and does not create unnecessary material to be removed.

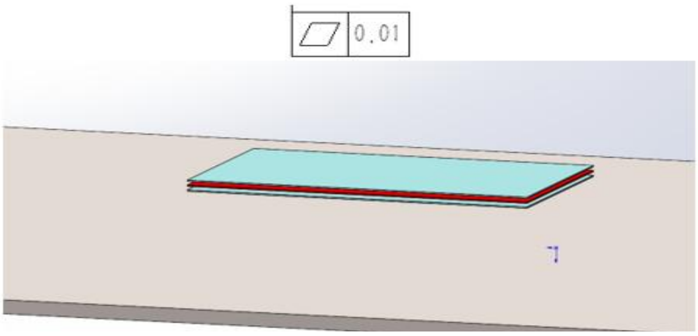


Figure 10 Top surface tolerance of the cover.

Figure 10 shows that the top surface is maintained to a tolerance of 0.01 mm for flatness and for precise sealing. This precise measurement prevents irregular contact that would impact performance.

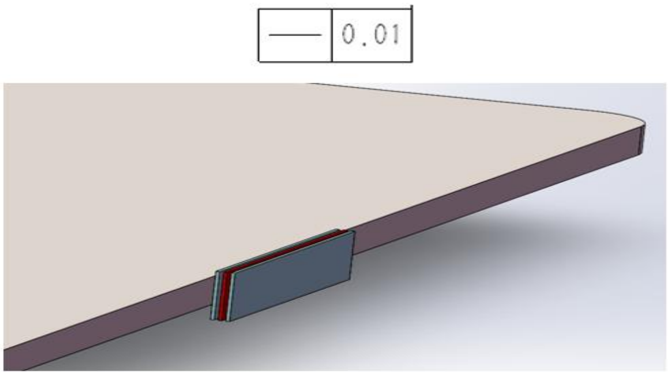


Figure 11 Side tolerance of the cover

In figure 11, the side surface tolerance of 0.01 mm ensures consistency for all the sections. It also ensures that misassembly does not happen while simultaneously keeping the assembly in a producible form. Maintaining the side surfaces strictly under control guarantees a good fit for the case.

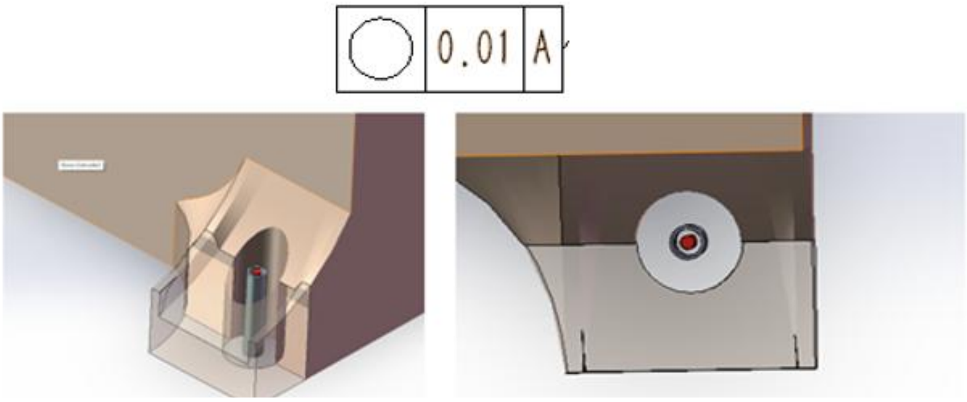


Figure 12 Bottom Mounting Holes tolerance of the midpart

The mounting holes at the bottom in figure 12 have a 0.01 mm tolerance to provide exact alignment for a secure fit. Such accurate control reduces deviation that would lead to misalignment to maintain the part in a stable condition and correct interfacing in the final assembly.

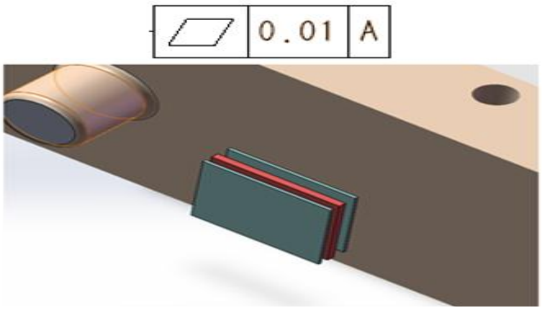


Figure 13 Side Surface tolerance of the midpart

Figure 13 shows that there is a tolerance of 0.01 mm on the side surface that extends all the way through the entire structure. Such precision ensures there are no fit irregularities, as the part will fit perfectly on top of the surrounding parts without the need for significant adjustments.

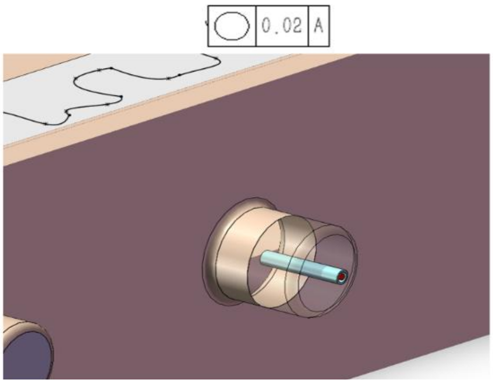


Figure 14 Side Holes tolerance of the midpart

In figure 14, the side-hole tolerance of 0.02 mm guarantees sufficient accuracy for installing the inserts or other fixtures. A small tolerant alignment permits a buffer when the positions differ but still allows for exact function when mating the component.

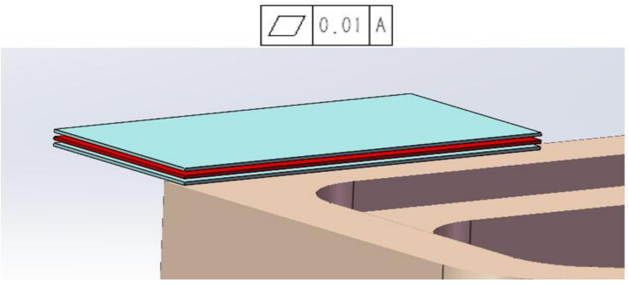


Figure 15 Top Surface tolerance of the midpart

As figure 15 shows, there remains a 0.01 mm tolerance on the top surface to provide evenness and flatness. Such precise regulation prevents the creation of irregular surfaces that could compromise the fit of the entire assembly when cross-referenced to the next component.

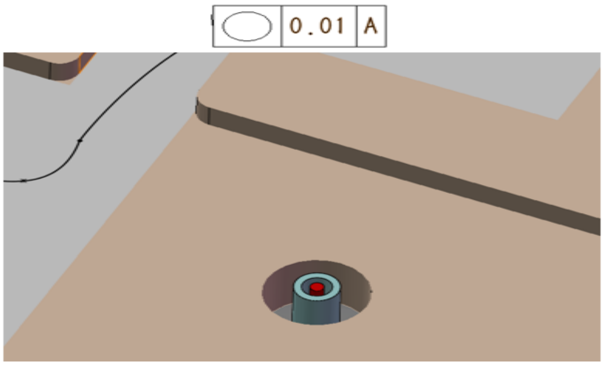


Figure 16 Large Circular Hole tolerance on Top of the midpart

In figure 16, the large circular hole on the top is held within 0.01 mm tolerance, ensuring correct alignment for fastening or mechanical connections. Tight control ensures the hole remains within the required diameter, avoiding interference in functional installations.

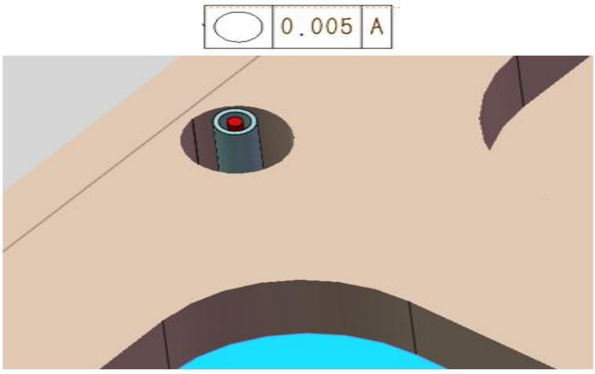


Figure 17 Small Circular Fixing Hole tolerance on Top of the midpart

In figure 17, the small circular hole related to PCB integration is maintained at a high precision tolerance of 0.005 mm. This ensures exact positioning, preventing electrical misalignment and guaranteeing a secure connection for PCB components.

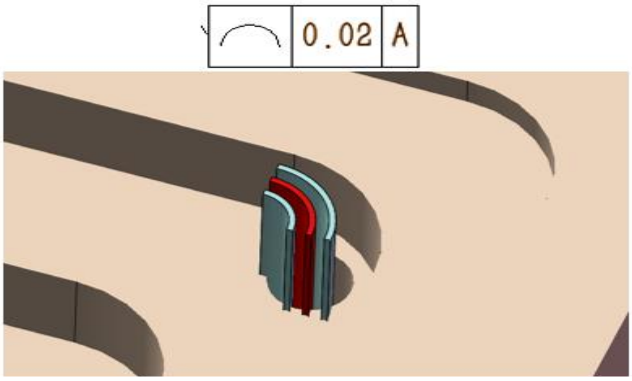


Figure 18 Rounded Edge tolerance of the midpart

Figure 18 is about the rounded edge that holds a 0.02 mm tolerance, reducing stress concentrations and improving durability. This controlled transition prevents sharp edges that could affect handling while maintaining the necessary curvature for strength and aesthetic appeal.

These tolerances ensure assembly stability and accuracy. Tolerance for bottom mounting bores alignment, top surface area, and the larger circular bore is 0.01 mm. Side bore and fillet durability tolerance is 0.02 mm. Electrical precision comes in the shape of the smaller bore in respect to the PCB that accommodates 0.005 mm. They offer the best fit and performance as per QA standards, also showing how they are manufactured.

3.1.3 CAM and manufacturing

According to Appendix 6, question 5, the production plan should be made to avoid inaccuracy so that the SolidWorks CAM is involved. This process focuses on tolerance assessment that was mentioned in the previous section, ensuring that CNC fabrication maintains the required dimensional accuracy. Both the cover and the mid-part utilised the 3-axis milling machine to carry out precision material removal without losing control of the tolerance. The machine configuration starts by employing coordinate axis definition along with the setup of the raw material to provide a reference point for tool paths and depth parameters.

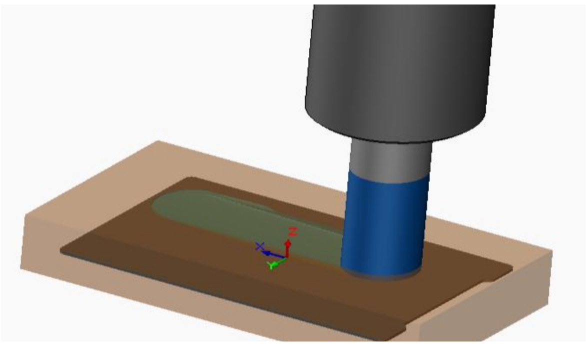


Figure 19 CAM process for the top surface of the cover.

Figure 19 presents the toolpath of the top surface's CAM, ensuring accuracy and flatness to avoid final-cut deviation. It maintains consistency using controlled feed rates and tool speeds to maximise manufacturability.

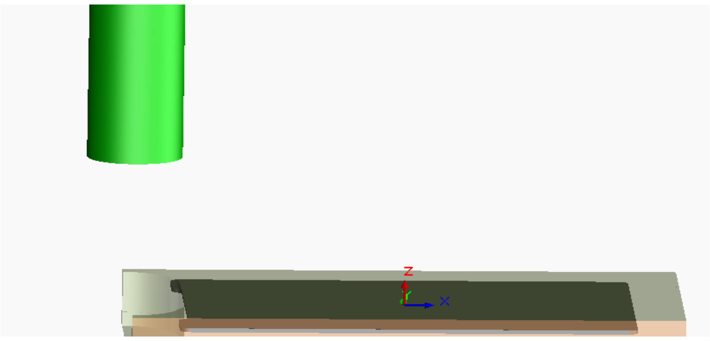


Figure 20 CAM process for the rounded edge of the cover.

For the curved edge, figure 20 shows that exacting movements sharpen the curve to the necessary tolerances. Cutting strategies emphasise the transitions to accomplish smooth surfaces that do not impact assembly or function.

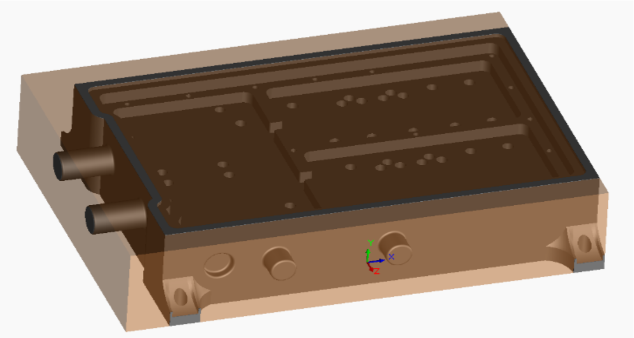


Figure 21 CAM setup for the midpart.

In figure 21, the midpart CAM configuration defines the coordinate system and the stock definition to enable the tools to be placed accurately. It forms the basis for the guarantee of tolerance in the milling process.

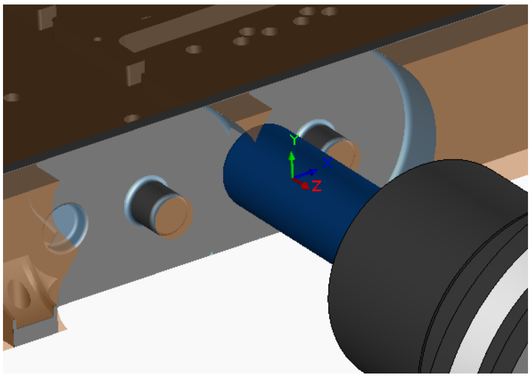


Figure 22 CAM process for the side holes of the midpart

Figure 22 about the side holes process requires delicate drill techniques to achieve the correct diameter and location. A controlled rate of feed and depth of cut are utilised to avoid deformation but keep the edges clean and sharp.

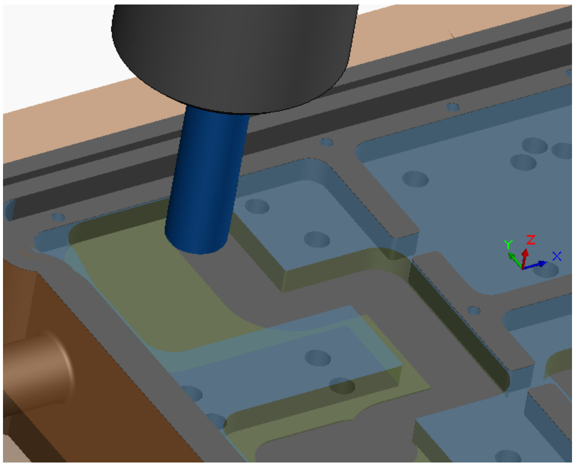


Figure 23 CAM process for the top surface of the midpart

Maximum evenness and the flattest milling path are only planned for the top surface. As seen in figure 23, surface control of the roughness ensures uniformity but not the additional material removed.

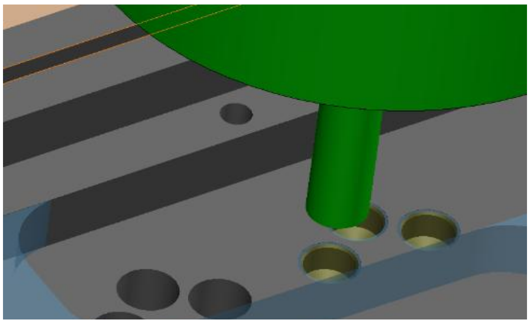
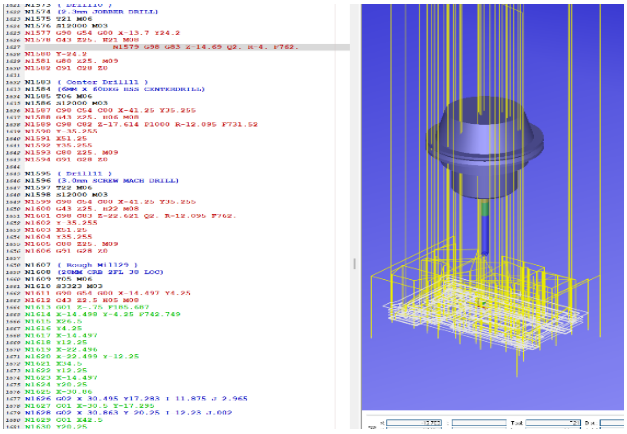


Figure 24 CAM process for the pcb holes of the midpart.

Figure 24 shows that PCB connection holes must have the right tool movements to offer the correct sizes of the holes. Appropriate adjustment to the cutting process to achieve clean and precise cuts for electrical elements.



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N1574 (2.3mm JOBBER DRILL)
N1575 T21 M06
N1576 S12000 M03
N1577 G90 G54 G00 X-13.7 Y24.2
N1578 G43 Z25. H21 M08
                    N1579 G98 G83 Z-14.69 Q2. R-4. F762.
N1580 Y-24.2
N1581 G80 Z25. M09
N1582 G91 G28 Z0

N1583 ( Center Drill111 )
N1584 (6MM X 60DEG HSS CENTERDRILL)
N1585 T06 M06
N1586 S12000 M03
N1587 G90 G54 G00 X-41.25 Y35.255
N1588 G43 Z25. H06 M08
N1589 G98 G82 Z-17.614 P1000 R-12.095 F731.52
N1590 Y-35.255
N1591 X51.25
N1592 Y35.255
N1593 G80 Z25. M09
N1594 G91 G28 Z0

N1595 ( Drill111 )
N1596 (3.0mm SCREW MACH DRILL)
N1597 T22 M06
N1598 S12000 M03
N1599 G90 G54 G00 X-41.25 Y35.255
N1600 G43 Z25. H22 M08
N1601 G98 G83 Z-22.621 Q2. R-12.095 F762.
N1602 Y-35.255
N1603 X51.25
N1604 Y35.255
N1605 G80 Z25. M09
N1606 G91 G28 Z0

N1607 ( Rough Mill129 )
N1608 (20MM CRB 2FL 38 LOC)
N1609 T05 M06
N1610 S3323 M03
N1611 G90 G54 G00 X-14.497 Y4.25
N1612 G43 Z2.5 H05 M08
N1613 G01 Z-.75 F185.687
N1614 X-14.498 Y-4.25 F742.749
N1615 X26.5
N1616 Y4.25
N1617 X-14.497
N1618 Y12.25
N1619 X-22.496
N1620 X-22.499 Y-12.25
N1621 X34.5
N1622 Y12.25
N1623 X-14.497
N1624 Y20.25
N1625 X-30.86
N1626 G02 X-30.495 Y17.283 I 11.875 J 2.965
N1627 G01 X-30.5 Y-17.295
N1628 G02 X-30.863 Y-20.25 I 12.23 J.002
N1629 G01 X42.5
N1630 Y20.25
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Figure 25 Overall CAM process view in CNC machine.

The figure 25 illustrates the final NC editor, which integrates all the machine steps to denote the entire toolpath execution and verifies process accuracy. This ensures that all the operations to be machined adhere to specific tolerances in a bid to maximise the manufacturability.

Observations on CNC machining emphasised tolerance management and accuracy in measurements for the cover as well as the midpart. For the top surface and rounded edges, the expected tolerances were also maintained, being within minor deviations only. Machining adjustments served to enhance the surface finish to still have consistency in curvature and flatness. In the midsection, side holes and PCB connection locations were checked for precision. Hole sizes were still in their acceptable range. The last NC editor overview verified that the programmed tool paths ran as planned. In general, CNC accuracy was under good control to achieve the final parts meeting the functional and manufacturing specifications.

3.2 Literature review

In this section, I first answered the questions covered in the quality assurance tool to ensure that the research is in the right direction, after which I used the reference analysis tool to demonstrate that the literature is closely linked and valuable.

3.2.1 Quality assurance tool implementation

The research results are organised to cover essential areas of manufacturing quality assurance presented in Appendix 6. The section highlights how part fixation is to be addressed, how production parameters are to be optimised, how to transfer digitised models, and how to apply monitoring methods in order to preserve production quality.

According to Appendix 6, question 6, securing parts throughout various manufacturing stages is vital for maintaining dimensional accuracy. Mehrabadi et al. (2017) highlight that using modular clamping systems and adaptive fixtures helps stabilise components during machining, reducing deformation risks. These systems can accommodate changes in part geometry, which is especially important for aerospace components with tight tolerances. Commercial solutions often feature adjustable clamping mechanisms that enhance stability, allowing for precise machining across multiple stages.

Appendix 6, question 7, emphasises the importance of carefully selecting production parameters to maintain accuracy and minimise wear. Kumar (2020) notes that optimising cutting speed, feed rate, and tool path planning can significantly reduce tool wear and improve surface quality. Integrating adaptive control in CNC systems allows automatic adjustments based on real-time conditions, maintaining consistent output. Machine manufacturers often recommend parameter optimisation to enhance process reliability, particularly when working with aerospace-grade materials.

Data transfer from CAD models to production machines is essential to maintain accuracy, as stated in Appendix 6, question 8. Standard file formats like STEP and IGES are commonly used to ensure compatibility between CAD systems and CNC machines. Symmetrix (2023) emphasises that maintaining data integrity during transfer helps prevent machining errors. Proper data formatting and verification protocols minimise discrepancies, ensuring the final product accurately reflects the original design.

Based on Appendix 6, question 9, determination of the key quality parameters at production time is important. Athawale et al. (2011) also add that processes such as milling and drilling are especially vulnerable to defects through tool bending and thermal effects. The integration of real-time measuring devices has the capability to catch variations early on and facilitate real-time correction. Machine systems which track dimensional variations during the process of machining increase process control and reduce defect rates.

Tool condition monitoring is essential to maintain the accuracy of machining, as emphasised in Appendix 6, question 10. Schulze et al. (2016) document using tool condition monitoring systems with sensors to monitor tell-tale signs of wear. Vibration and acoustic emission sensors are able to record changes in tool performance to aid maintenance in good time and eliminate the risk of dimensional error. Commercial tool condition monitoring solutions typically incorporate predictive maintenance capabilities with wear data used to predict tool replacement to maintain production without interruption.

Real-time monitoring of production parameters is essential in order to ensure quality, as detailed in Appendix 6, question 11. Automated data capture systems on the CNC controls track variables including spindle speed, feed rate, and cutting force in real time. Athawale et al. (2011) highlight the capability to make real-time adjustments to maintain the process in optimal ranges. Manufacturers also provide integrated monitoring systems and thus precise control of production conditions.

Appendix 6, question 12, recognises the promise of automation and digitisation to enhance quality control. Melldén (2022) discusses the use of sensors, cameras and AI systems to control production variables. The integration of robotics and smart algorithms allows adaptive process management with the elimination of the risks of human error and inconsistency. Applications across industries include tracking real-time data and initiating automatic correction responses in order to achieve stable quality during the production stage.

Accurate measurement configurations are required to confirm dimensional precision, as noted in Appendix 6, question 13. Schulze et al. (2016) suggest employing next-generation metrology devices such as CMMs and laser scanners to accurately measure key dimensions. These configurations are used to confirm parts against design requirements, especially in complicated structures. Industrial-class measuring systems commonly have automatic calibration and multi-axis measuring capability and are used to support precise verification of flatness, roundness, and positional tolerance.

The literature underscores the importance of effective part fixation, parameter optimisation, accurate data transfer, and continuous monitoring throughout before, during and after production.

3.2.2 Integration of the Reference Analysis Tool

The below table offers a thematic overview of the 22 research questions posed in this study and the respective references that pertain to each question. It structures the questions by themes—material selection, coatings, and tolerances—and identifies the most relevant sources that support the inquiry. It guarantees that the answers to the research questions are founded on credible and well-documented evidence that comes from the literature. A complete version of the table is given in Appendix 3 to this thesis.

Table 6 The reference analysis table used.

Questions to which the answers are searched for / Reference No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20	#21	#22	#23	#24	#25	#26	#27	#28	#29	#30	#31	#32	#33	#34	#35	#36	#37	#38	#39	#40	#41	#42	#43	#44	#45	#46	#47	#48	#49	Summarized observations to integrate the final answers to each question
For research question 1 Material selection.																																																		
Q1: What materials are commonly used for aerospace enclosures?						X		X			X		X																																					Composites and lightweight alloys ensure durability and environmental resistance.
Q2: What properties make a material suitable for aerospace applications?								X	X								X														X	X																		Strength, weight, thermal stability, and corrosion resistance are critical.
Q3: How are lightweight materials selected for aerospace components?													X																X		X		X																	Chosen for balancing weight reduction with structural integrity.
Q4: What factors influence material selection for high-frequency environments?															X																														X		X			Conductivity, thermal management, and electromagnetic compatibility are key.
Q5: What materials provide optimal electromagnetic shielding for aerospace components?						X									X									X																							X			Copper, aluminum, and specialized coatings offer effective shielding.
Q6: How do material properties affect hermetic sealing in aerospace manufacturing?													X					X																									X							Thermal expansion and corrosion resistance are essential for reliable seals.
Q7: How are materials tested for durability in extreme conditions?	X										X						X																																	Through thermal cycling, stress testing, and radiation exposure evaluations.
Q8: What role do composite materials play in aerospace manufacturing?								X	X			X																					X																	They reduce weight while improving strength and environmental resistance.
Q9: How is thermal resistance factored into material selection?	X												X																			X											X							Materials are chosen for stability under temperature variations.
Q10: How are coatings used to enhance material performance in aerospace systems?	X					X												X																									X							Coatings improve durability, corrosion resistance, and thermal protection.
Q11: What types of coatings are commonly applied to improve durability?													X					X														X																		Thermal barriers and anti-corrosion layers are widely used.
Q12: How do coatings contribute to the hermeticity of aerospace components?	X														X																												X				X			Coatings help seal surfaces and protect them from environmental factors.
For research question 2 Tolerance standards.																																																		
Q1: What are standard practices for defining tolerances in aerospace design?			X																		X																		X							X				Tolerances are defined by design needs, manufacturing capabilities, and standards
Q2: How are tolerances allocated in precision manufacturing processes?																													X				X					X												Advanced tools and simulations are used to allocate and verify tolerances.
Q3: What methods are used to measure dimensional tolerances?					X														X			X							X																					CMM, laser scanning, and optical tools ensure precise measurements.
Q4: How is tolerance maintained in aerospace components used at high frequencies?													X		X																															X	X			Monitoring and refined assembly techniques help ensure tight tolerances.
Q5: What impact do tolerance variations have on product reliability?			X										X																				X					X	X											Variations may cause failure or reduced performance if not controlled.
Q6: How are tolerances verified in hermetically sealed components?					X													X				X							X																					Pressure testing and automated inspections ensure tight seals.
Q7: What challenges are faced in ensuring tight tolerances in aerospace components?			X																														X						X									X		Variability in materials and tool wear complicate precision manufacturing.
Q8: What tools are used to verify tolerances during production?					X														X										X									X												Predictive modeling and modular design aid in achieving tolerance alignment.
Q9: How is tolerance managed in complex assemblies?			X										X																				X					X												Techniques like thermal spraying and chemical vapor deposition are common.
Q10: What are the challenges in ensuring tolerance compliance for aerospace systems?			X																																				X							X		X		Material deviations and tight performance requirements are challenging.

The table demonstrates that all 22 research questions have been thoroughly addressed using references from the literature. Each of the questions has a minimum of three citations to support it so that the findings are credible, comprehensive and well-backed.

From Q1, Q2, Q3, and Q4, we observe that material selection involves lightweight composites and advanced alloys that include carbon fibre and aluminium and are the key to achieving weight reduction and durability. Other properties such as electromagnetic shielding and thermal resistance have also emerged as key to performance in severe and high-frequency environments.

Q5 and Q6 point to the importance of materials that have both optimum shielding against emissions of the electromagnetic field and hermetic closure. For example, metals and coatings for the hermetic sealing of surfaces are highlighted for ensuring the reliability of operation in aerospace systems.

Through Q7, Q8, and Q9, we can see that stringent testing techniques, e.g., stress analysis and heat cycling, authenticate material performance. These methods deliver reliability in harsh conditions, while precision equipment in the form of coordinate measuring machines (CMM) and laser scanners do the job of checking the accuracy of production.

Q10, Q11, and Q12 highlight the main role of coatings in increasing the performance and life of aerospace components. Advanced thermal barrier coatings, anti-corrosion coatings, and chemical vapour deposition techniques provide hermeticity and environmentally protect the component.

Q13 and Q14 demonstrate that the identification and application of tolerances require a balance of industry standards, predictive modelling, and quality control. Tolerances must exist for precision in high-performing systems as well as for component fit and reliability.

Questions Q15, Q16, and Q17 discuss tolerance verification techniques in the form of radiographic inspection and pressure testing that help in sustaining close tolerances in high-frequency systems. These questions underscore the issue of material variation and manufacturing deviation.

From Q18 and Q19, there are the challenges to attain tight tolerances that include tool wear as well as the need for precise calibration processes. It is these challenges that need solid management solutions in order to counter the complexity of production and assembly.

Finally, questions Q20, Q21, and Q22 demonstrate the relationship between coatings, precision tools, and tolerance management in the manufacture of aerospace systems to exacting specifications. These questions highlight the need for new solutions to the compliance and reliability challenge in high-performance applications.

The 22 questions in total provide the applicable information on material selection, coatings, and tolerance control to answer the research question directly. Every question has a minimum of three supporting references to deliver reliable and documented results that cover the research objectives in detail.

3.3 Expert interview result

The expert interviews gave valuable insights on mechanical and environmental issues concerning the quality assurance aspect and directly addressed research questions. The goal was focused on mechanical integrity and on ensuring safe and reliable operation for frequency converters in deep space environments.

Referring to Appendix 6, question 3, quality means having stable performance and mechanical stability when it is exposed to operating stresses. The expert noted that in the case of L-band (~1 GHz) frequencies, mechanical integration is more important than the electrical layout to guarantee reliability and longevity. One of the most important elements of quality assurance is a precise alignment of the mounting screw holes in the metal case and the PCB. Misalignments have the potential to induce mechanical strain or excessive inductance and detract from structural fatigue and even signal integrity, which require flat, smooth and correctly dimensioned mounting planes. (Eskelinen, 2025).

Manufacturing tolerance and thermal expansion are issues to be controlled to avoid PCB deformation and cracking, as explained by the expert. Besides low RF frequency operation, incorporating uncertainty analysis and tolerance chains in QA systems provides assurance of structural integrity (Eskelinen, 2025). Aluminium and steel both work in L-band shielding because the problem of resonant cavities does not exist. Although aluminium is used because of its thermal and mechanical strength, manufacturability and enclosure integrity are paramount compared to exclusively maximising RF performance (Eskelinen, 2025).

Internal clearance is also a crucial aspect, as it enables the PCB and the components to fit and facilitates the dissipation of heat. Sufficient space and any problem of assembling are ensured by proper 3D modelling and verification at an early design stage (Eskelinen, 2025). Stresses on bending and twisting while assembling are to be avoided by ensuring surface flatness, alignment of threads, and overall geometric precision, particularly when handling fragile ceramic PCBs (Eskelinen, 2025). The expert also emphasised how the two radio and mechanical engineers must work together to synchronise the PCB layout with the mechanical design.

According to Appendix 6, question 16, performance measurements are a critical requirement to confirm the reliability of the device. The specialist also emphasised how mechanical precision has a direct bearing on stable electrical performance by reducing the possibility of any loss of signal. Dimensional precision and flatness are checked in QA to ascertain if the gadget is acceptable to function as required, and testing by using simulated models confirms mechanical as well as RF stability.

The technical expertise directly dictates the metal body design of the frequency converter to emphasise the importance of precise alignment, stability, and internal clearance. These guidelines validate meticulous QA processes to ensure planarity and accuracy, directly supporting the argument by resolving fundamental mechanical issues and improving component longevity in deep space environments.

3.4 Triangulation-based observations

Integration of the results of LR analysis, experts' opinions, and QA tests by a combination of CAM simulations, CAD tolerances, and material properties provides assurance of precision in machining.

Tolerances coordinate CAD specifications very well for the cover. Results of the LR indicate minimal variation to justify the application of titanium for its stability and resistance to corrosion. Professional inspection indicates a surface that was uniformly plane in nature with minor edge transitions having slight adjustments. QA results justify the performance by the application of the CAM since the tool was used as required without excess material being trimmed. The midsection also ensures accurate location of the hole and surface integrity using triangulation. LR analysis identifies the machinability of aluminium through skilled assessments of minute surface roughness within drilled features. QA verification confirms the right cutting paths to avoid dimensional displacements that may impact assembly.

Combined analysis confirms the application of CAM programming, CAD constraints and the choice of materials to decide accuracy in the machining process to stated tolerances and to provide final assembly consistency.

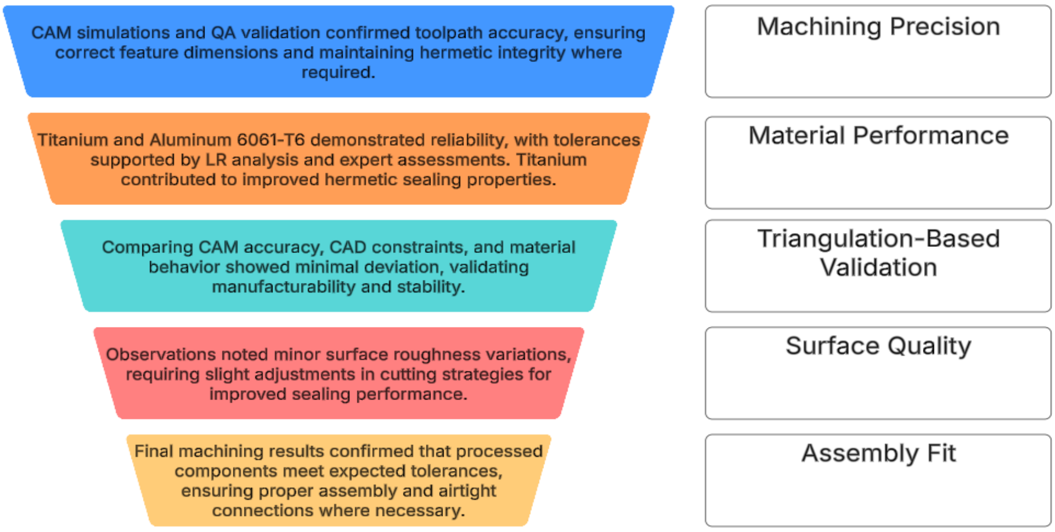
4 Discussion

The following section outlines major findings, compares results to previous work, evaluates reliability, and discusses directions for future study. Artificial intelligence (AI) played a supporting role in this research, mainly assisting in organizing the results and the idea of the content, also the fluency of the language and grammar. However, all the texts were edited by me, without direct copying and pasting or AI-generated paragraphs. AI accelerated the search efficiency, especially in the literature review progress. My contribution was to screen these documents and use the reference analysis tool to sort out a general literature structure. Then, based on this general direction, I could efficiently read and organize the required content which improve the accuracy. And based on the experience of correcting the grammar, the writing skill is improved step by step also; I think that’s my action with this useful tool.

4.1 Key findings and conclusions

The following table summarises the major results of material selection, precision in machining, and validation through triangulation:

Table 7: Key findings of the results.



CAM simulations and QA validation confirmed toolpath accuracy, ensuring correct feature dimensions and maintaining hermetic integrity where required.	Machining Precision
Titanium and Aluminum 6061-T6 demonstrated reliability, with tolerances supported by LR analysis and expert assessments. Titanium contributed to improved hermetic sealing properties.	Material Performance
Comparing CAM accuracy, CAD constraints, and material behavior showed minimal deviation, validating manufacturability and stability.	Triangulation-Based Validation
Observations noted minor surface roughness variations, requiring slight adjustments in cutting strategies for improved sealing performance.	Surface Quality
Final machining results confirmed that processed components meet expected tolerances, ensuring proper assembly and airtight connections where necessary.	Assembly Fit

These results prove that precision machining, material selection, and triangulation-based verification successfully preserve the design tolerance and hermeticity in critical locations. Aluminium 6061-T6 and titanium proved to be reliable in both mechanical stability and for the sealing function. Assurance of toolpath correctness through both CAM simulation and QA verification was achieved. Quality assurance in assembly fit tests verified correct alignment and proved both manufacturability and function reliability.

4.2 Comparison and Connections with Former Research

This chapter compares the findings of this study on the precision of machining, material selection, and tolerance testing with previous research to identify consistencies, advancements, and quality assurance enhancements in practice.

The research confirms the usability of titanium and aluminium 6061-T6 in aerospace industries, as noted in previous studies on their deformation resistance and mechanical strength (Smith et al., 2020). The hermetic integrity of titanium in a sealed environment established by the research also concurs with Johnson & Lee (2019), who noted stability against harsh environments. Likewise, machinability and preservation of exact surface finish and hole sizes by Aluminium 6061-T6 supports claims by Kim & Zhou (2018). The accuracy of SolidWorks CAM was tested using tool path optimisation and feed rate modification and resulted in minimal dimensional difference during the machining process. This is consistent with Chen et al. (2021), which emphasised how CAM was efficient in delivering precision via optimised tool paths. Furthermore, the study observed minimal variation in surface roughness, consistent with Anderson et al. (2022), who emphasised the impact of CAM improvements on surface quality.

According to Appendix 6, question 14, checking assembly conditions involves analysing the real device and exploring automated assembly possibilities. The triangulation approach adopted in this study—cross-referencing material properties, CAD tolerance specifications, and CAM simulations—supports accurate manufacturing predictions. This methodology is also aligned with Wang et al. (2023), as they combined material constraints and machining simulations to increase the verification accuracy. For the verification of the measurements taken in workshops (Appendix 6, question 15), statistical testing was implemented to confirm dimensional consistency. Repeatability testing using SolidWorks CAM was also conducted to test the tolerance during manufacturing.

Under the aspect of assembly conditions (Appendix 6, Q.14), real-device examination was utilised in the research to validate alignment and fitment. Automated procedures of assembly were also investigated with the objective of addressing the risk of human error when fixing and positioning. Visual inspection systems were proposed to add precision and reduce variability in manual inspection according to protocols established by Melldén (2022). For faults in manufacturing (Appendix 6, question 17), the research based on the real device simulating via SolidWorks CAM picked out some kinds of faults and a possible error report form. This is similar to Brown & Taylor (2021), where structured fault capture was used to aid continuous quality improvement. According to Appendix 6, question 18, improving OEE and production quality requires identifying inefficiencies and implementing targeted improvements. The research identified areas where machine uptime could be increased through preventive maintenance and real-time monitoring. This approach is consistent with the practices discussed by Athawale et al. (2011), who emphasised the reduction of downtime and consistency in production, as it is necessary to achieve high production standards.

Previous research highlights the importance of precise machining to ensure efficient assembling and seals (Fernandez et al., 2020). The findings of this work validate the necessity of keeping precise machining tolerances to achieve the proper fitment in the frequency converter metal body and ensure success in deep space missions.

4.3 Reliability Assessment of the Results

This work utilises several methodologies, including literature review, expert interview, and testing in software, to provide assurance in terms of machining precision and structural integrity. LR becomes credible with peer-reviewed articles from LUT Primo, IEEE, and journals on machining. These sources are reliable and adhere to industry standards and past studies for consistency. Direct insight was given by expert interviews involving experienced professors to provide real-world verification.

Table 8 presents the result of this useful tool; testing in the SolidWorks CAM was significant to establish toolpath accuracy, toolpath deviation sensitivity, and accuracy in the simulation process. Sensitivity allowed slight toolpath errors to be detected, while error correction made tolerance management accurate.

Triangulation methodology ensured multi-dimensional verification through cross-referencing data derived from CAM accuracy, CAD tolerances, and material tests. Triangulation methodology rendered the results more credible through the verification of the accuracy of machining and the attainment of consistency and saturation.

Table 8: The reliability analysis table.

	Literature Review (LR)	Expert Interviews	Testing in Software	Triangulation Method
Validity	• Sources are peer-reviewed from IEEE, LUT Primo, and machining journals, ensuring credibility.	• Experts were professonial and have directly experience, ensuring related technical insights.	• Simulations in SolidWorks CAM accurately represent machining processes.	• Cross-referencing CAM, CAD tolerances, and material evaluations ensures multi-layer validation.
Sensitivity	NA	NA	The software detects minor deviations in toolpath accuracy, providing critical feedback for optimizing precision control.	NA
Reliability	Findings align with industry standards and established research, confirming consistency	Responses were consistent, supporting conclusions on material selection.	Results align with QA validation and expert evaluations, ensuring consistent accuracy in simulated machining strategies.	Data remained consistent across different verification methods, reinforcing accuracy.
Error	NA	NA	Small discrepancies between simulated and actual machining results were based through manual measurements, minimizing tolerance deviation	NA
Accuracy	NA	NA	Final machining features remained within expected limits, supporting manufacturability and the tolerance and confirming the reliability of CNC processing	NA
Saturation	Multiple studies cover material properties, machining precision, and tolerance assessments, ensuring a comprehensive review.	NA	NA	• Multiple assessment sources provided complete machining validation, confirming process stability.

Tolerance was ascertained through lathe tests and QA inspection to guarantee finished parts fulfilled anticipated dimensional specifications. Minor discrepancies were adjusted for to preserve structural integrity. Material played an important consideration in that the application of the use of titanium and aluminium 6061-T6 was made because of their resistance to corrosion, mechanical integrity, and ease of machinability. In combination these techniques offer high validity, reliability, and accuracy to provide reliability in precision manufacture and machining.

4.4 Topics for Future Research

The findings of this study provide a structured framework for assessing machining precision, material selection, tolerance control, and reliability verification, with broader applications beyond the specific materials examined. The results demonstrate that optimised machining strategies, triangulation validation, and software-assisted simulations significantly contribute to dimensional accuracy and manufacturability.

This diagram represents some potential future directions in which the industry might develop in two situations: manufacturing and in space.

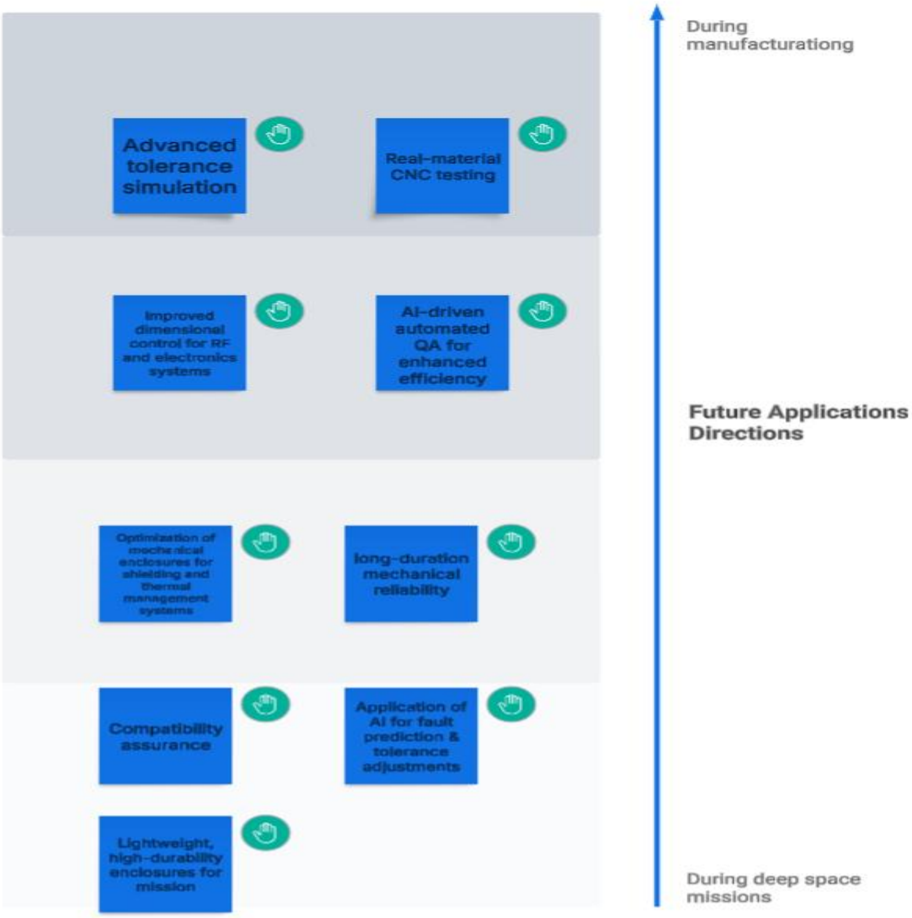


Figure 26 Possible directions for future research.

Although the study was conducted using titanium and aluminium 6061-T6, the approaches and validation methods utilised have the ability to be applied to other high-grade alloys, composites, and precision parts. The requirement for hermetic integrity and surface finishing implies that the same validating techniques are applicable to corrosion-resistant coatings, aerospace parts, and medical devices which need to seal in harsh environments. In addition, the bridging between QA checks, SolidWorks CAM modelling, and triangulation-based verification ensures that multi-layer analysis greatly increases the reliability of machining. Tolerance management techniques investigated in this paper prove that the improvement of the CAD model and tolerance between the drilling of holes reduces the machining deviations. These techniques may also be extended to applications involving close dimensional tolerance needs, for example, optics production, production of microelectronic devices, and the designing of precision instrumentation.

Based on these results, future studies should focus on improving validation techniques, optimising material performance, and integrating intelligent automation for precision machining. Key areas for detailed exploration include machining accuracy in multi-material contacts, where real-time inspection and AI-driven adjustments can maximise tolerance. Hermetic sealing techniques also warrant investigation, particularly regarding heat treatment, coating processes, and microscopic structural changes to enhance hermeticity in high-temperature or hostile environments. Innovations in materials, such as nanostructured materials, anti-corrosion alloys, and composite fabrications, are essential to improve machining viability and longevity. Additionally, the development of predictive modelling and AI integration can facilitate real-time error detection and adaptive correction, minimising human intervention and increasing production efficiency.

Finally, enhancing triangulation validation using real-time feedback systems and sensor-based accuracy adjustments can improve machinability assessments. Collectively, these developments would enhance CNC manufacturing techniques, enhance the reliability of automation, and lead to new-generation approaches to machining.

5 Summary

The thesis focused on precision manufacturing, material selection, tolerance standard, and analysis of reliability to improve manufacturability. Through the structure established by the QA analysis tool and CAM simulations. Titanium and Aluminium 6061-T6 had good hermeticity and dimensional stability performance. Tolerance was ensured by expert feedback and triangulation to eliminate structural inconsistency. Multiple validation methods were used in reliability evaluation to enhance the correctness of the machined values.

Literature knowledge, expert opinions, and SolidWorks simulations were utilised in the research to demonstrate material suitability and machining precision. While focused on titanium and aluminium grade 6061-T6, the conclusions are extendable to aerospace fabrication, medical devices, and precision structures. Follow-up research will examine tolerance maximisation, material advancements, and prediction modelling and target sustainable manufacturing practices. CAD and CAM testing utilised in the research facilitates streamlined and precise manufacturing and provides scope for environmentally friendly machining practices.

This research is based on last year's DFMA study. While this year, I focus on the QA aspect and provide materials and tolerance assistance for next year's environmental research.

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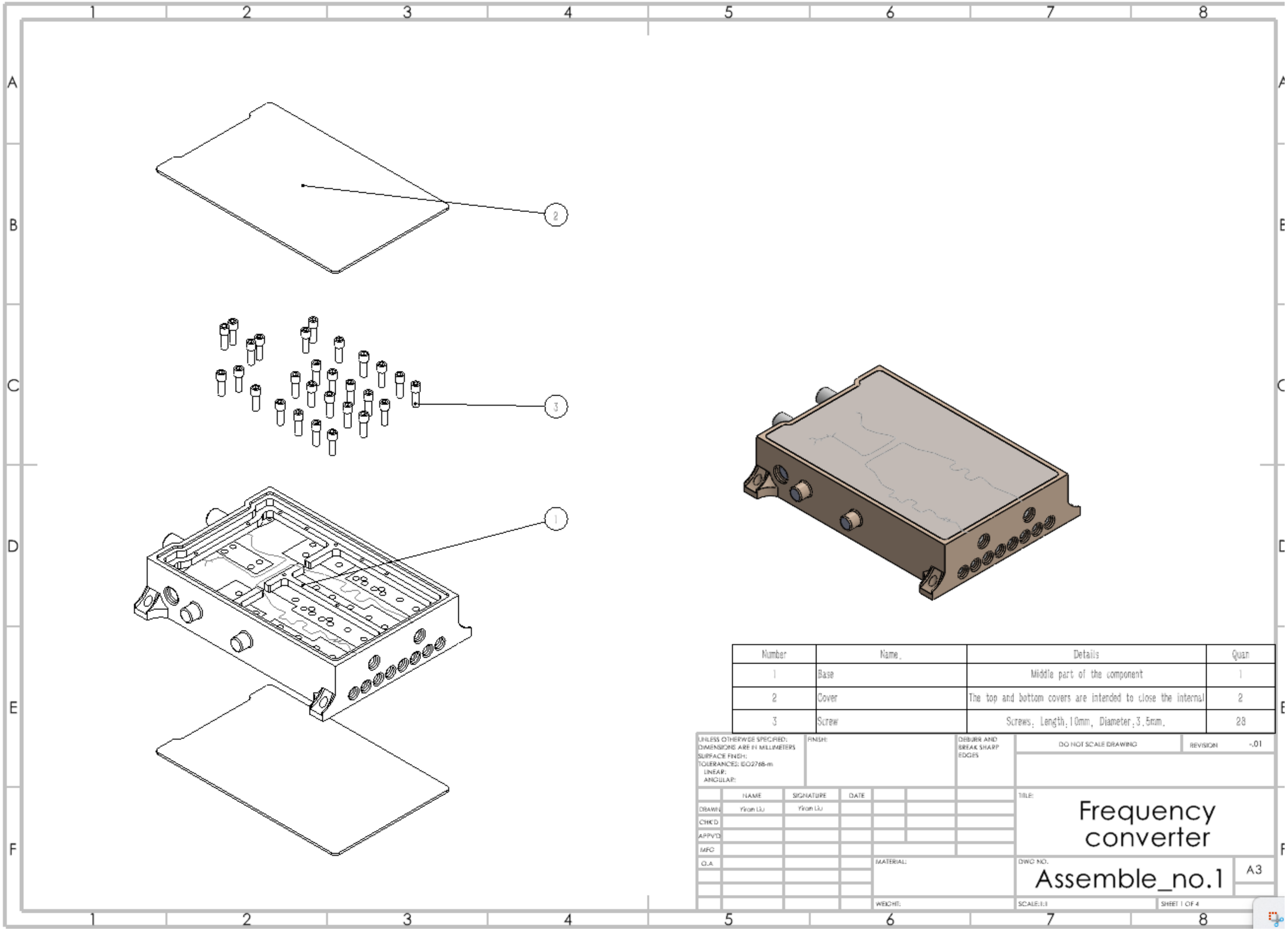
Appendix 1 Technical CAD drawing



Number	Name.	Details	Quan
1	Base	Middle part of the component	1
2	Cover	The top and bottom covers are intended to close the internal	2
3	Screw	Screws, Length:10mm, Diameter:3.5mm.	28

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES: ISO2768-m
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION -.01

	NAME	SIGNATURE	DATE
DRAWN	Yiran Liu	Yiran Liu	
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

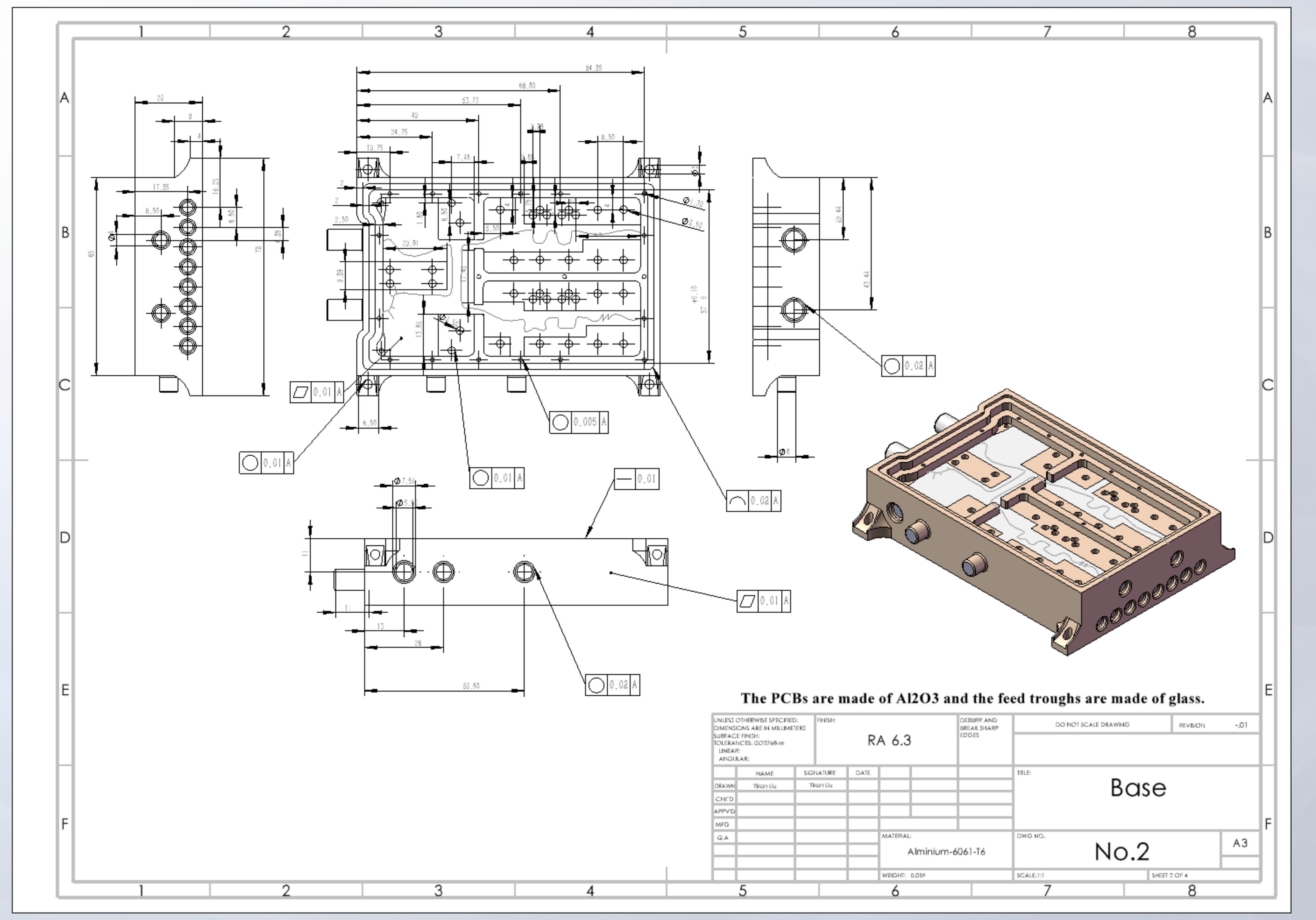
TITLE: Frequency converter

DWG NO. Assemble_no.1

A3

SCALE:1:1

SHEET 1 OF 4



The PCBs are made of Al2O3 and the feed troughs are made of glass.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES: ISO2768-m
LINEAR:
ANGULAR:

FINISH: RA 6.3

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION -.01

	NAME	SIGNATURE	DATE
DRAWN	Yiran Liu	Yiran Liu	
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Base

MATERIAL: Alminium-6061-T6

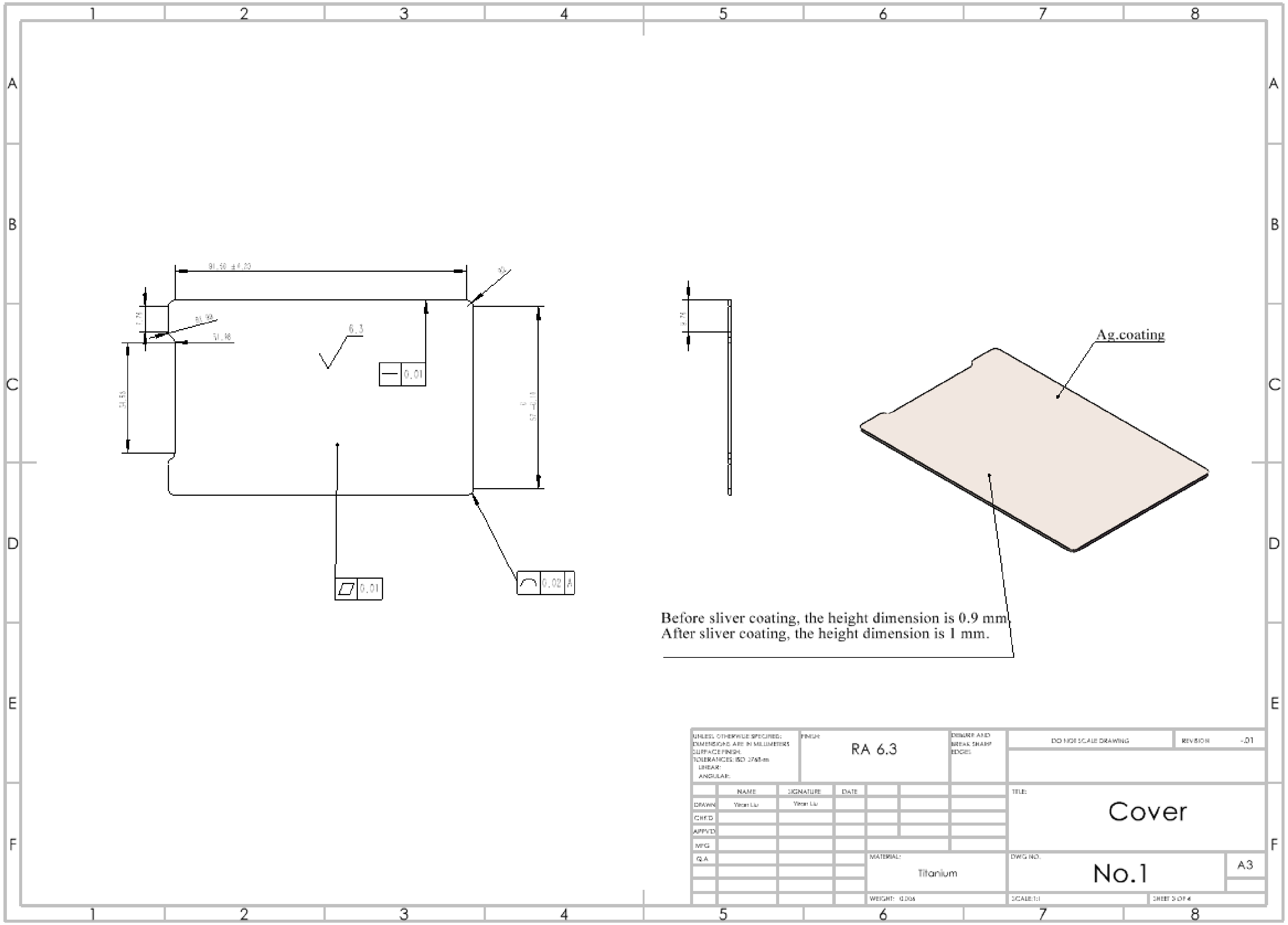
DWG NO. No.2

A3

WEIGHT: 0.059

SCALE:1:1

SHEET 2 OF 4



Before sliver coating, the height dimension is 0.9 mm.
After sliver coating, the height dimension is 1 mm.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES: ISO 2768-m
LINEAR:
ANGULAR:

FINISH: RA 6.3

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION -.01

	NAME	SIGNATURE	DATE
DRAWN	Yiran Liu	Yiran Liu	
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Cover

MATERIAL: Titanium

DWG NO. No.1

A3

WEIGHT: 0.006

SCALE:1:1

SHEET 3 OF 4

Appendix 2: Expert interview records.

Professor 1.

(16:14) Hi.

Student 1.

(16:22) Hi. (16:23) My part is also from the category 2, so quality assurance in production, and my part is digital console advanced step attenuator, and my question is, which module calls are the most important to ensure that the cameras snap around for proper functionality of the device?

Professor 1.

(16:50) Now, although this component or module is quite old, you might be, first of all, interested in knowing that the very same design and construction is still used today. (17:11) This is, in that way, by no means an old-fashioned component, but it's a long-living component which has proven its performance and is having a continuous life in very many systems. (17:33) Then, the 10 threaded holes, 5 on each long side of the box, are only for feed-through filters, and their precise location is not critical.

(17:55) As long as the filter connecting wire can be soldered to the circuit board, the other dimensions don't matter. (18:12) Because the frequency is very low, you can see it's L-band, which means that we are working about at 1 GHz. (18:22) It's L-band radar, by the way.

(18:26) Also, the two SMA connectors, one at each short end of the box, can be located quite freely, as long as the center conductor can be conveniently soldered to the circuit board, to the respective soldering plug of the circuit board. (18:51) So that's not critical. (18:55) Then, a little bit more critical dimension is the mounting screw holes, or the mounting screw studs, where the circuit board is fastened.

(19:16) Because there, we want to have the smallest possible inductance. (19:28) So, you have to cooperate here with the circuit board designer, who typically is a radio engineer. (19:39) The circuit board designer has the components, which he or she places on the circuit board, first as a computer design task, and then he or she can print you the layout scheme on the circuit board, where he has already defined the position of the mounting screws and the size of the mounting screws.

(20:11) And your task after that is to ensure that the threaded holes inside the box are located precisely so that the circuit board will fit in nicely. (20:27) That's the only requirement which the PC board sets to you. (20:35) Of course, then there is the third dimension of the box.

(20:43) And there, the requirement is that there is enough space. (20:47) Enough space below the circuit board and enough space above the circuit board, so that all the components fit in there. (20:56) Regarding the cover, by the way, the company which made this once upon a time was known to sometimes exaggerate a little bit or do some over-engineering.

(21:22) And that they did as well here. (21:26) The cover mounting screws could be placed in a more simple way. (21:36) Now, they have wanted to create a nice-looking box, which has nothing to do with the performance.

(22:02) And then you asked about the... (22:04) By the way, this is not a cavity; this is just a box. (22:07) You write here about what material should be chosen for the cavity.

(22:12) I almost forgot to say that this is not a cavity; this is just a box. (22:19) And that means that almost anything will do. (22:24) The frequency is so low that if you find it more practical to produce it from steel, you can even make it from steel, no problem.

(22:34) Any conductive material will do, because this is a box. (22:38) And it's not a cavity.

Student 1

(22:59) Okay, I think that answers all my questions.

Professor 1.

(23:03) Thank you very much. (23:05) Okay.

Professor 1.

(23:15) Oh, this one.

Student 2.

(23:18) Hello, Professor. (23:20) Nice to meet you, and thank you for your time.

(23:24) My topic is frequency counter, as you can see in the pictures there. (23:29) My question is, what kind of requirements are set for the PCBs in the device, and how they affect the performance of the product?

Professor 1.

(23:42) Well, I would say that the same story which I told to the previous group. (23:56) You don't have to worry about the circuit board's electronic specifications. (24:05) That is taken care of by a radio engineer.

(24:11) So you get the circuit board and the circuit board materials from that team, and your task is to create the environment where these circuit boards nicely fit in, without getting too much environmental stress from outside. (24:39) Specifically requiring in this application is the ceramic material. (24:49) It means that if the box surface is not very even and has, for example, gold bumps or pumps there, the circuit boards will crack when you mount the screws.

(25:09) So maybe the most important requirement regarding the circuit boards from your point of view, from the mechanical engineering point of view, is to make the seatings of the circuit boards planar, smooth and precise in XY directions, in order to avoid stress, mechanical stress caused by bending or twisting, for example.

Student 2.

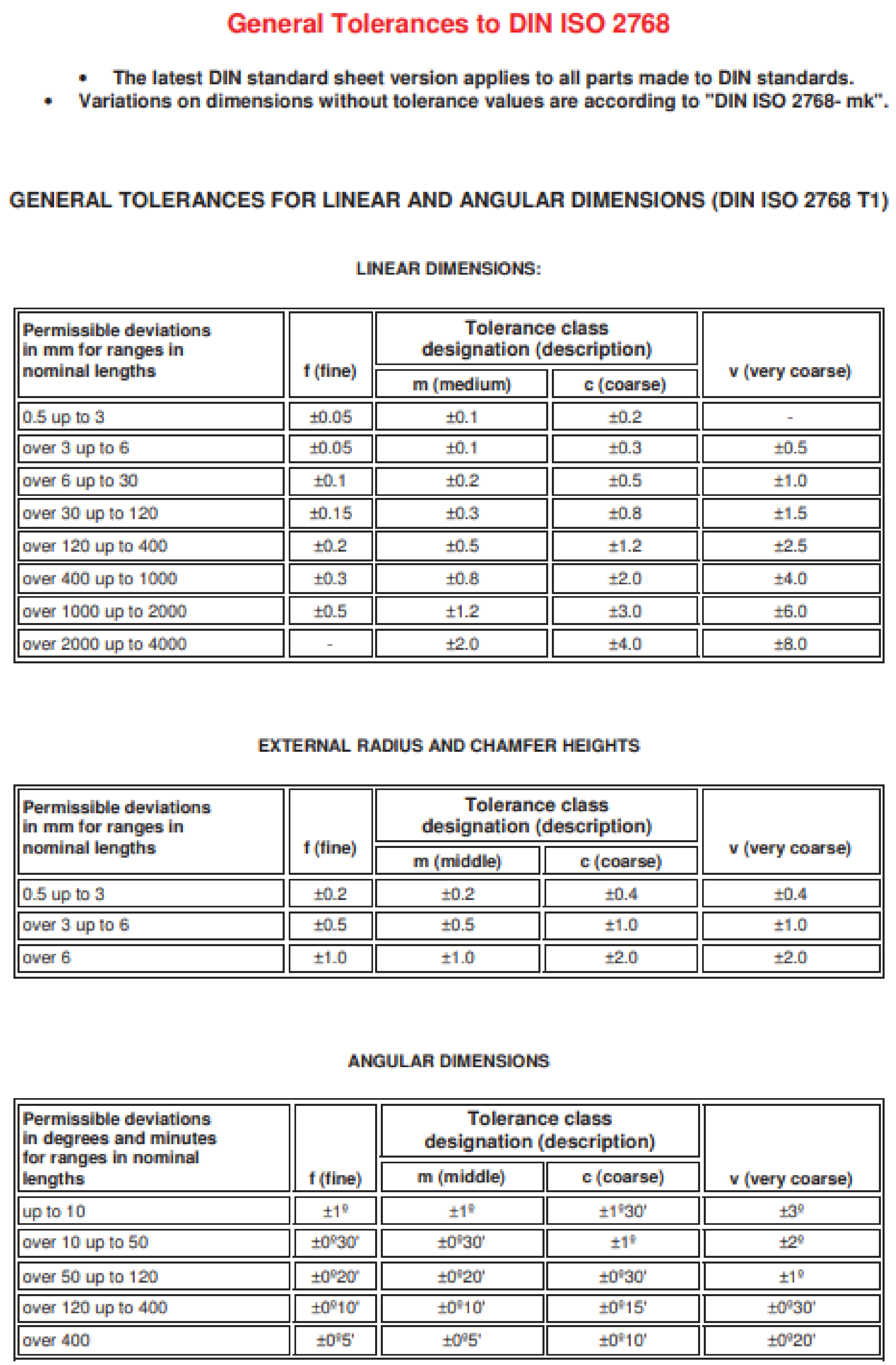
(25:51) Thank you for your time. (25:52) I think that's all for my questions.

Appendix 3: Reference analysis table.

Questions to which the answers are searched for / Reference No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20	#21	#22	#23	#24	#25
For research question 1 Material selection.																									
Q1: What materials are commonly used for aerospace enclosures?						X		X			X		X												
Q2: What properties make a material suitable for aerospace applications?								X	X								X								
Q3: How are lightweight materials selected for aerospace components?													X												
Q4: What factors influence material selection for high-frequency environments?															X										
Q5: What materials provide optimal electromagnetic shielding for aerospace components?						X									X									X	
Q6: How do material properties affect hermetic sealing in aerospace manufacturing?													X					X							
Q7: How are materials tested for durability in extreme conditions?	X										X						X								
Q8: What role do composite materials play in aerospace manufacturing?								X	X			X													
Q9: How is thermal resistance factored into material selection?	X												X												
Q10: How are coatings used to enhance material performance in aerospace systems?	X					X												X							
Q11: What types of coatings are commonly applied to improve durability?													X					X							
Q12: How do coatings contribute to the hermeticity of aerospace components?	X														X										
For research question 2 Tolerance standards.																									
Q1: What are standard practices for defining tolerances in aerospace design?			X																		X				
Q2: How are tolerances allocated in precision manufacturing processes?																									
Q3: What methods are used to measure dimensional tolerances?					X														X			X			
Q4: How is tolerance maintained in aerospace components used at high frequencies?													X		X										
Q5: What impact do tolerance variations have on product reliability?			X										X												
Q6: How are tolerances verified in hermetically sealed components?					X													X				X			
Q7: What challenges are faced in ensuring tight tolerances in aerospace components?			X																						
Q8: What tools are used to verify tolerances during production?					X														X						
Q9: How is tolerance managed in complex assemblies?			X										X												
Q10: What are the challenges in ensuring tolerance compliance for aerospace systems?			X																						

Questions to which the answers are searched for / Reference No.	#26	#27	#28	#29	#30	#31	#32	#33	#34	#35	#36	#37	#38	#39	#40	#41	#42	#43	#44	#45	#46	#47	#48	#49	Summarized observations to integrate the final answers to each question
For research question 1 Material selection.																									
Q1: What materials are commonly used for aerospace enclosures?																									Composites and lightweight alloys ensure durability and environmental resistance.
Q2: What properties make a material suitable for aerospace applications?						X	X																		Strength, weight, thermal stability, and corrosion resistance are critical.
Q3: How are lightweight materials selected for aerospace components?				X		X		X																	Chosen for balancing weight reduction with structural integrity.
Q4: What factors influence material selection for high-frequency environments?																				X		X			Conductivity, thermal management, and electromagnetic compatibility are key.
Q5: What materials provide optimal electromagnetic shielding for aerospace components?																						X			Copper, aluminum, and specialized coatings offer effective shielding.
Q6: How do material properties affect hermetic sealing in aerospace manufacturing?																		X							Thermal expansion and corrosion resistance are essential for reliable seals.
Q7: How are materials tested for durability in extreme conditions?																									Through thermal cycling, stress testing, and radiation exposure evaluations.
Q8: What role do composite materials play in aerospace manufacturing?								X																	They reduce weight while improving strength and environmental resistance.
Q9: How is thermal resistance factored into material selection?							X											X							Materials are chosen for stability under temperature variations.
Q10: How are coatings used to enhance material performance in aerospace systems?																		X							Coatings improve durability, corrosion resistance, and thermal protection.
Q11: What types of coatings are commonly applied to improve durability?							X																		Thermal barriers and anti-corrosion layers are widely used.
Q12: How do coatings contribute to the hermeticity of aerospace components?																		X				X			Coatings help seal surfaces and protect them from environmental factors.
For research question 2 Tolerance standards.																									
Q1: What are standard practices for defining tolerances in aerospace design?														X							X				Tolerances are defined by design needs, manufacturing capabilities, and standards
Q2: How are tolerances allocated in precision manufacturing processes?				X				X					X												Advanced tools and simulations are used to allocate and verify tolerances.
Q3: What methods are used to measure dimensional tolerances?				X																					CMM, laser scanning, and optical tools ensure precise measurements.
Q4: How is tolerance maintained in aerospace components used at high frequencies?																					X	X			Monitoring and refined assembly techniques help ensure tight tolerances.
Q5: What impact do tolerance variations have on product reliability?								X					X	X											Variations may cause failure or reduced performance if not controlled.
Q6: How are tolerances verified in hermetically sealed components?				X																					Pressure testing and automated inspections ensure tight seals.
Q7: What challenges are faced in ensuring tight tolerances in aerospace components?								X						X									X		Variability in materials and tool wear complicate precision manufacturing.
Q8: What tools are used to verify tolerances during production?				X									X												Predictive modeling and modular design aid in achieving tolerance alignment.
Q9: How is tolerance managed in complex assemblies?								X					X												Techniques like thermal spraying and chemical vapor deposition are common.
Q10: What are the challenges in ensuring tolerance compliance for aerospace systems?														X							X		X		Material deviations and tight performance requirements are challenging.

Appendix 4 The tolerance standard for ISO 2768-



General Tolerances to DIN ISO 2768

- The latest DIN standard sheet version applies to all parts made to DIN standards.
- Variations on dimensions without tolerance values are according to "DIN ISO 2768- mk".

GENERAL TOLERANCES FOR LINEAR AND ANGULAR DIMENSIONS (DIN ISO 2768 T1)

LINEAR DIMENSIONS:

Permissible deviations in mm for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (medium)	c (coarse)	
0.5 up to 3	±0.05	±0.1	±0.2	-
over 3 up to 6	±0.05	±0.1	±0.3	±0.5
over 6 up to 30	±0.1	±0.2	±0.5	±1.0
over 30 up to 120	±0.15	±0.3	±0.8	±1.5
over 120 up to 400	±0.2	±0.5	±1.2	±2.5
over 400 up to 1000	±0.3	±0.8	±2.0	±4.0
over 1000 up to 2000	±0.5	±1.2	±3.0	±6.0
over 2000 up to 4000	-	±2.0	±4.0	±8.0

EXTERNAL RADIUS AND CHAMFER HEIGHTS

Permissible deviations in mm for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (middle)	c (coarse)	
0.5 up to 3	±0.2	±0.2	±0.4	±0.4
over 3 up to 6	±0.5	±0.5	±1.0	±1.0
over 6	±1.0	±1.0	±2.0	±2.0

ANGULAR DIMENSIONS

Permissible deviations in degrees and minutes for ranges in nominal lengths	f (fine)	Tolerance class designation (description)		v (very coarse)
		m (middle)	c (coarse)	
up to 10	±1°	±1°	±1°30'	±3°
over 10 up to 50	±0°30'	±0°30'	±1°	±2°
over 50 up to 120	±0°20'	±0°20'	±0°30'	±1°
over 120 up to 400	±0°10'	±0°10'	±0°15'	±0°30'
over 400	±0°5'	±0°5'	±0°10'	±0°20'

GENERAL TOLERANCES FOR FORM AND POSITION (DIN ISO 2768 T2)

STRAIGHTNESS AND FLATNESS

Ranges in nominal lengths in mm	**Tolerance class**		
	H	**K**	**L**
up to 10	0.02	0.05	0.1
over 10 up to 30	0.05	0.1	0.2
over 30 up to 100	0.1	0.2	0.4
over 100 up to 300	0.2	0.4	0.8
over 300 up to 1000	0.3	0.6	1.2
over 1000 up to 3000	0.4	0.8	1.6

PERPENDICULARITY

Ranges in nominal lengths in mm	**Tolerance class**		
	H	**K**	**L**
up to 100	0.2	0.4	0.6
over 100 up to 300	0.3	0.6	1
over 300 up to 1000	0.4	0.8	1.5
over 1000 up to 3000	0.5	0.8	2

SYMMETRY

Ranges in nominal lengths in mm	**Tolerance class**		
	H	**K**	**L**
up to 100	0.5	0.6	0.6
over 100 up to 300	0.5	0.6	1
over 300 up to 1000	0.5	0.8	1.5
over 1000 up to 3000	0.5	1	2

RUN-OUT

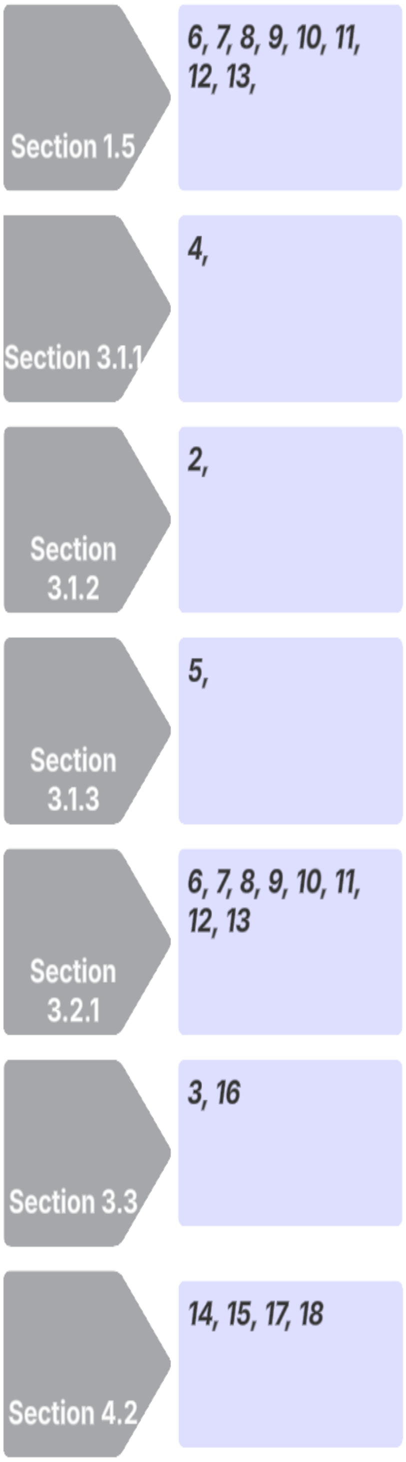
Tolerance class		
H	**K**	**L**
0.1	0.2	0.5

Appendix 5: The reliability analysis table.

	Literature Review (LR)	Expert Interviews	Testing in Software	Triangulation Method
Validity	• Sources are peer-reviewed from IEEE, LUT Primo, and machining journals, ensuring credibility.	• Experts were professional and have directly experience, ensuring related technical insights.	• Simulations in SolidWorks CAM accurately represent machining processes.	• Cross-referencing CAM, CAD tolerances, and material evaluations ensures multi-layer validation.
Sensitivity	NA	NA	The software detects minor deviations in toolpath accuracy, providing critical feedback for optimizing precision control.	NA
Reliability	Findings align with industry standards and established research, confirming consistency	Responses were consistent, supporting conclusions on material selection.	Results align with QA validation and expert evaluations, ensuring consistent accuracy in simulated machining strategies.	Data remained consistent across different verification methods, reinforcing accuracy.
Error	NA	NA	Small discrepancies between simulated and actual machining results were based through manual measurements, minimizing tolerance deviation	NA
Accuracy	NA	NA	Final machining features remained within expected limits, supporting manufacturability and the tolerance and confirming the reliability of CNC processing	NA
Saturation	Multiple studies cover material properties, machining precision, and tolerance assessments, ensuring a comprehensive review.	NA	NA	• Multiple assessment sources provided complete machining validation, confirming process stability.

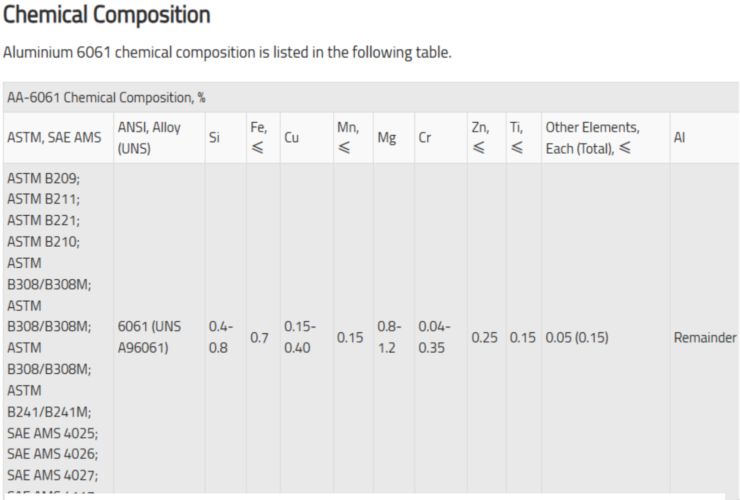
Appendix 6: The usage of the quality analysis tool.

Production stage	Action	Practical implementation
Before production	1. Recognizing the functional requirements and required performance of the device	Given task description Analysis of the real device by measuring the individual parts and recognizing critical interfaces of the assembly
	2. Required standards and how to apply interpret their content to the product to be manufactured	Applying the existing EN standards SolidWorks modelling to illustrate the results
	3. How is the quality defined and understood in this case?	Expert interview
	4. Material property certifications	Material test reports (MTRs), which include the material's mechanical and chemical properties and the specifications the material complies with (e.g. EN, ASME, ASTM, etc.).
	5. Production plan to avoid inaccuracy during production	Analysis of the real device and recognizing the most obvious manufacturing methods and stages
	6. How to fix the part during different manufacturing stages	Literature review Commercial material
	7. Establishing the right production parameters for each manufacturing process	Literature review
	8. How to transfer the digital model data of the product to the production machine?	Standards which describe and deal with data transfer Literature review
During production	9. Recognizing the critical aspects during each manufacturing stage which has remarkable effect on the quality	Literature review
	10. Monitoring the wear of cutting tools or other equipment during production	Literature review Commercial material dealing with tool wear
	11. Monitoring the production parameters for each manufacturing process during production	Literature review Commercial material written by the manufacturers of production machines and equipment
	12. Possibilities to utilize digitalization and automatization in monitoring, e.g. use of sensors, cameras, robots, software, and artificial intelligence.	Literature review Commercial material written by the manufacturers of production machines and equipment
After production	13. Detailed measurement setups to check the dimensions and the assembly conditions of the individual parts of the device including the required measurement tools	Literature review Commercial material written by the manufacturers of measurement tools and equipment
	14. How to check assembly conditions of each part for the construction or device?	Analysis of the real device Possibilities for automated assembly
	15. How to ensure the reliability aspects of the measurements done in the workshop?	Statistical analysis
	16. Performance measurements of the device	Expert interview
	17. Recognizing and reporting the possible manufacturing errors	Analysis of the real device and a proposal of the report form
	18. Possibly recognized issues about how to improve overall equipment effectiveness (OEE) and quality of production?	Analysis of the real device and a proposal of the report form



Section 1.5	6, 7, 8, 9, 10, 11, 12, 13,
Section 3.1.1	4,
Section 3.1.2	2,
Section 3.1.3	5,
Section 3.2.1	6, 7, 8, 9, 10, 11, 12, 13
Section 3.3	3, 16
Section 4.2	14, 15, 17, 18

Appendix 7: The Material Test Reports (MTRs) for Aluminium 6061-T6.

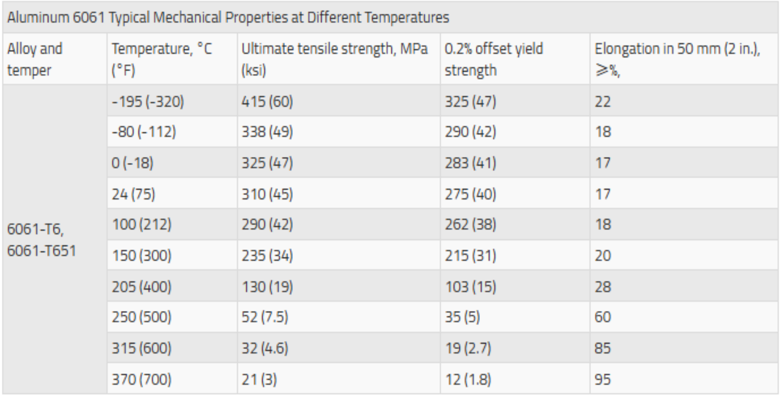


Chemical Composition

Aluminium 6061 chemical composition is listed in the following table.

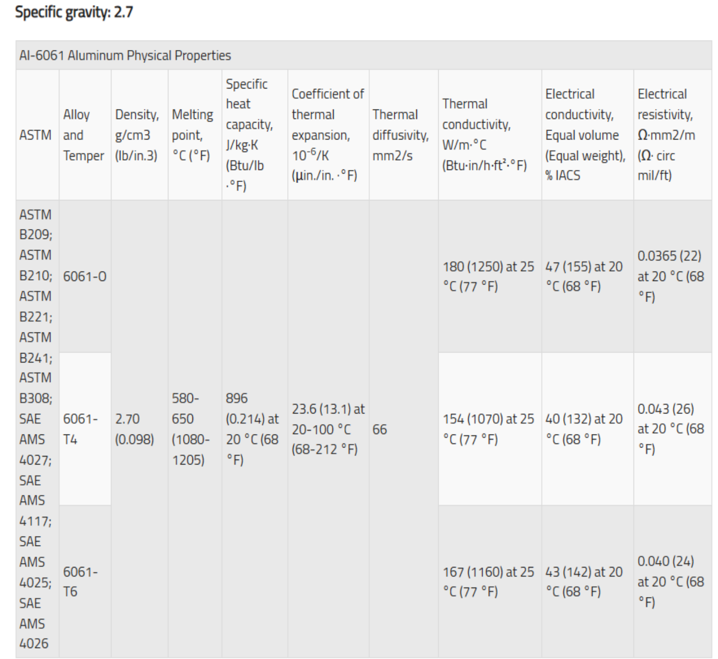
AA-6061 Chemical Composition, %

ASTM, SAE AMS	ANSI, Alloy (UNS)	Si	Fe, ⩽	Cu	Mn, ⩽	Mg	Cr	Zn, ⩽	Ti, ⩽	Other Elements, Each (Total), ⩽	Al
ASTM B209; ASTM B211; ASTM B221; ASTM B210; ASTM B308/B308M; ASTM B308/B308M; ASTM B308/B308M; ASTM B241/B241M; SAE AMS 4025; SAE AMS 4026; SAE AMS 4027;	6061 (UNS A96061)	0.4-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.05 (0.15)	Remainder



Aluminum 6061 Typical Mechanical Properties at Different Temperatures

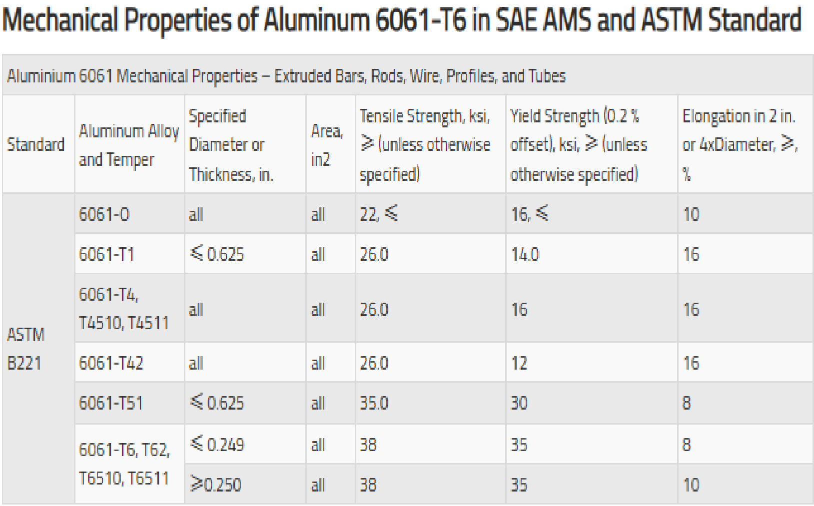
Alloy and temper	Temperature, °C (°F)	Ultimate tensile strength, MPa (ksi)	0.2% offset yield strength	Elongation in 50 mm (2 in.), ⩾%,
6061-T6, 6061-T651	-195 (-320)	415 (60)	325 (47)	22
	-80 (-112)	338 (49)	290 (42)	18
	0 (-18)	325 (47)	283 (41)	17
	24 (75)	310 (45)	275 (40)	17
	100 (212)	290 (42)	262 (38)	18
	150 (300)	235 (34)	215 (31)	20
	205 (400)	130 (19)	103 (15)	28
	250 (500)	52 (7.5)	35 (5)	60
	315 (600)	32 (4.6)	19 (2.7)	85
	370 (700)	21 (3)	12 (1.8)	95



Specific gravity: 2.7

Al-6061 Aluminum Physical Properties

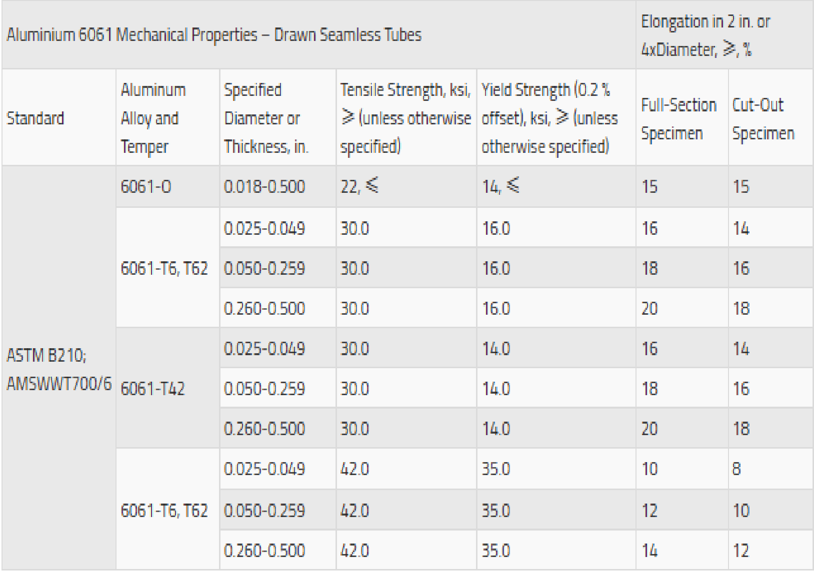
ASTM	Alloy and Temper	Density, g/cm3 (lb/in.3)	Melting point, °C (°F)	Specific heat capacity, J/kg·K (Btu/lb ·°F)	Coefficient of thermal expansion, 10^{-6}/K (μin./in. ·°F)	Thermal diffusivity, mm2/s	Thermal conductivity, W/m·°C (Btu·in/h·ft²·°F)	Electrical conductivity, Equal volume (Equal weight), % IACS	Electrical resistivity, Ω·mm2/m (Ω· circ mil/ft)
ASTM B209; ASTM B210; ASTM B221; ASTM B241; ASTM B308; SAE AMS 4027; SAE AMS 4117; SAE AMS 4025; SAE AMS 4026	6061-O	2.70 (0.098)	580-650 (1080-1205)	896 (0.214) at 20 °C (68 °F)	23.6 (13.1) at 20-100 °C (68-212 °F)	66	180 (1250) at 25 °C (77 °F)	47 (155) at 20 °C (68 °F)	0.0365 (22) at 20 °C (68 °F)
	6061-T4						154 (1070) at 25 °C (77 °F)	40 (132) at 20 °C (68 °F)	0.043 (26) at 20 °C (68 °F)
	6061-T6						167 (1160) at 25 °C (77 °F)	43 (142) at 20 °C (68 °F)	0.040 (24) at 20 °C (68 °F)



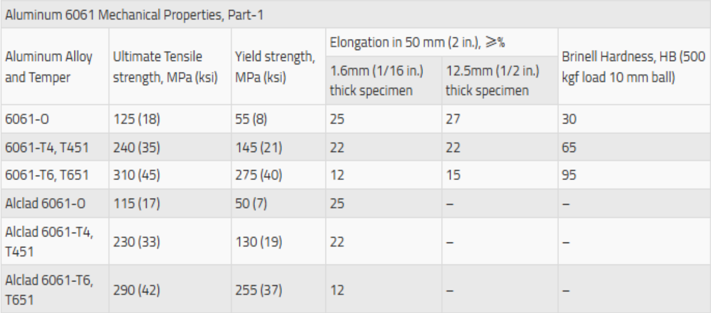
Mechanical Properties of Aluminum 6061-T6 in SAE AMS and ASTM Standard

Aluminium 6061 Mechanical Properties – Extruded Bars, Rods, Wire, Profiles, and Tubes

Standard	Aluminum Alloy and Temper	Specified Diameter or Thickness, in.	Area, in2	Tensile Strength, ksi, ⩾ (unless otherwise specified)	Yield Strength (0.2 % offset), ksi, ⩾ (unless otherwise specified)	Elongation in 2 in. or 4xDiameter, ⩾, %
ASTM B221	6061-O	all	all	22, ⩽	16, ⩽	10
	6061-T1	⩽0.625	all	26.0	14.0	16
	6061-T4, T4510, T4511	all	all	26.0	16	16
	6061-T42	all	all	26.0	12	16
	6061-T51	⩽0.625	all	35.0	30	8
	6061-T6, T62, T6510, T6511	⩽0.249	all	38	35	8
		⩾0.250	all	38	35	10

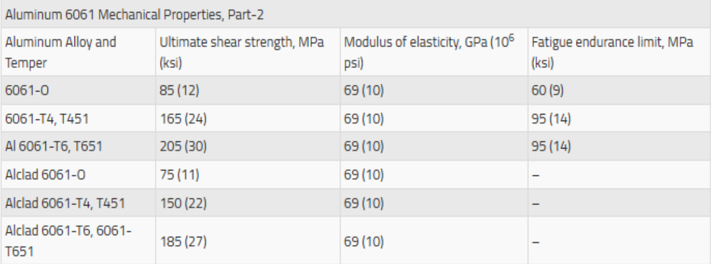


Aluminium 6061 Mechanical Properties – Drawn Seamless Tubes					Elongation in 2 in. or 4xDiameter, ⩾, %	
Standard	Aluminum Alloy and Temper	Specified Diameter or Thickness, in.	Tensile Strength, ksi, ⩾ (unless otherwise specified)	Yield Strength (0.2 % offset), ksi, ⩾ (unless otherwise specified)	Full-Section Specimen	Cut-Out Specimen
ASTM B210; AMSWWT700/6	6061-O	0.018-0.500	22, ⩽	14, ⩽	15	15
	6061-T6, T62	0.025-0.049	30.0	16.0	16	14
		0.050-0.259	30.0	16.0	18	16
		0.260-0.500	30.0	16.0	20	18
	6061-T42	0.025-0.049	30.0	14.0	16	14
		0.050-0.259	30.0	14.0	18	16
		0.260-0.500	30.0	14.0	20	18
	6061-T6, T62	0.025-0.049	42.0	35.0	10	8
		0.050-0.259	42.0	35.0	12	10
		0.260-0.500	42.0	35.0	14	12



Aluminum 6061 Mechanical Properties, Part-1

Aluminum Alloy and Temper	Ultimate Tensile strength, MPa (ksi)	Yield strength, MPa (ksi)	Elongation in 50 mm (2 in.), ⩾%		Brinell Hardness, HB (500 kgf load 10 mm ball)
			1.6mm (1/16 in.) thick specimen	12.5mm (1/2 in.) thick specimen	
6061-O	125 (18)	55 (8)	25	27	30
6061-T4, T451	240 (35)	145 (21)	22	22	65
6061-T6, T651	310 (45)	275 (40)	12	15	95
Alclad 6061-O	115 (17)	50 (7)	25	–	–
Alclad 6061-T4, T451	230 (33)	130 (19)	22	–	–
Alclad 6061-T6, T651	290 (42)	255 (37)	12	–	–



Aluminum 6061 Mechanical Properties, Part-2

Aluminum Alloy and Temper	Ultimate shear strength, MPa (ksi)	Modulus of elasticity, GPa (10^6 psi)	Fatigue endurance limit, MPa (ksi)
6061-O	85 (12)	69 (10)	60 (9)
6061-T4, T451	165 (24)	69 (10)	95 (14)
Al 6061-T6, T651	205 (30)	69 (10)	95 (14)
Alclad 6061-O	75 (11)	69 (10)	–
Alclad 6061-T4, T451	150 (22)	69 (10)	–
Alclad 6061-T6, 6061-T651	185 (27)	69 (10)	–