QUICK CHANGER OF MULTI PURPOSE END EFFECTOR FOR FUSION APPLICATION

Lappeenranta–Lahti University of Technology LUT

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

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Examiners: University Lecturer Changyang Li

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ABSTRACT

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Quick changer of multi purpose end effector for fusion application

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Since the theory of using tokamak to achieve controllable nuclear fusion was proposed in the 1950s, tokamak devices have been highly anticipated as the most likely device to achieve controllable nuclear fusion. In recent years, countries around the world have increased research on tokamak devices. There are more than 200 tokamak test devices around the world, including JET in Europe, EAST and CFETR in China, and ITER, which is being built by countries around the global. However, the core components of the tokamak are in a harsh environment, and the remote maintenance process of the fusion reactor is very complex and time-consuming. The aim of this thesis is to design a quick changer that can work in the harsh environment inside a tokamak device to meet the maintenance needs inside the device. The quick changer allows the maintenance manipulator to change many different tools and end-effectors more efficiently. Using SolidWorks for design and modelling, the manufacturing process of the quick changer was analysed using SolidWorks CAM. Addition of a protective film of titanium diboride to the quick changer using magnetron sputtering. ANSYS was used for static analysis and safety factor to verify the feasibility of the quick change structure.

SYMBOLS AND ABBREVIATIONS

Roman characters

A	area	[mm2, m2]
F	force	[N]

Greek characters

τ	shear stress	[Pa, MPa]

Constants

g	gravitational acceleration	9,81 m/s

Abbreviations

CFETR	China Fusion Engineering Test Reactor
CMOR	CFETR Multi-purpose Overload Robot
SAM	Snake Arm Maintainer
CAD	Computer Aided Design
CAM	Computer-Aided Manufacturing
ISO	International Standardization Organization
FEA	Finite Element Analysis
CNC	Computerized Numerical Control
AMCs	Aluminium Matrix Composites

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1 Introduction

The importance of tokamak devices will be shown in this section and how to perform maintenance on tokamak devices will be explained. Afterwards, the research objectives and research questions are presented.

1.1 Research background

As global energy demands continuously grow, nuclear fusion energy has garnered widespread attention as a clean, efficient, and virtually limitless energy solution. At present, the mainstream nuclear fusion in the world is achieved by tokamak devices (Figure 1). Compared to traditional nuclear fission reactions, nuclear fusion offers a safer method of energy generation with less production of radioactive waste.

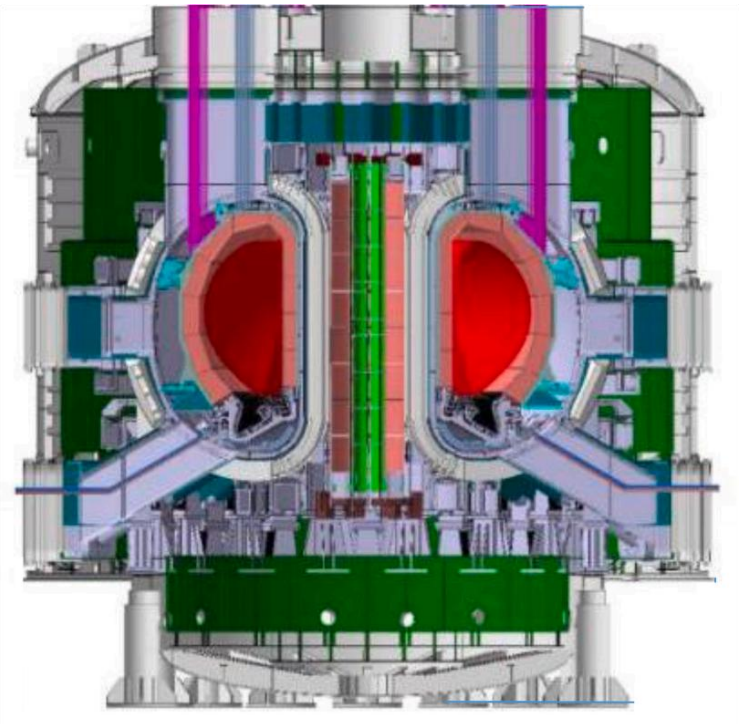

Figure 1. Cross section of the tokamak device (Song et al., 2022).

Achieving and sustaining a controlled nuclear fusion reaction requires extreme environmental conditions, such as high temperatures and intense radiation. This results in the reactor chamber needing to withstand extreme conditions, and maintenance of the reactor becomes significantly frequent, presenting major challenges to maintenance operations. Traditional Maintenance methods are not only inefficient but also may expose maintenance personnel to high-risk environments. Therefore, developing robotic systems capable of operating in such high-risk environments has become crucial.

In recent years, robotic technology has been increasingly used in the maintenance and overhaul of nuclear facilities. For example, the Multipurpose Overload Robot (CMOR) used in CFETR (Figure 2). This is a heavy-duty multi-joint manipulator with a terminal payload of 2 tons that allows maintenance personnel to control it remotely (Song et al., 2022). When the base of the CMOR is fixed, the manipulator has 8 degrees of freedom (Figure 3). This allows it to move flexibly in the space within the reactor and transport the end effector to any maintenance location within the reactor (Qin et al., 2022).

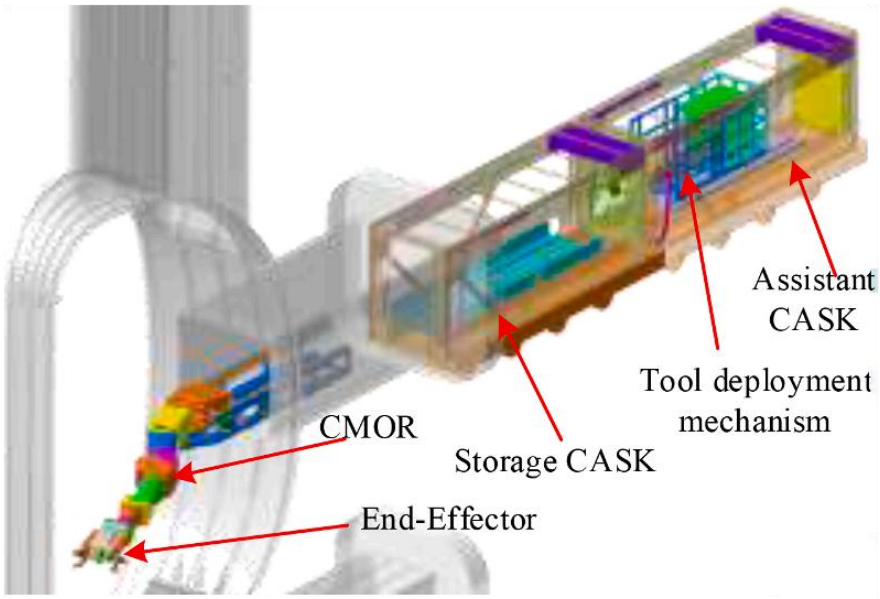

Figure 2. Composition CFETR remote maintenance system (Qin et al., 2022).

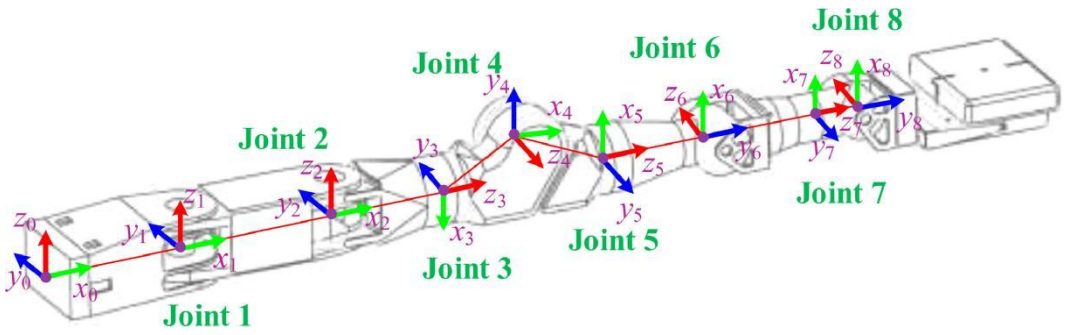

Figure 3. CMOR coordinate system of each link (Qin et al., 2022).

In addition, the manipulator used in the reactor is the Snake Arm Maintainer (SAM). SAM is an important subsystem of the CFETR remote operation and maintenance system (Figure 4).

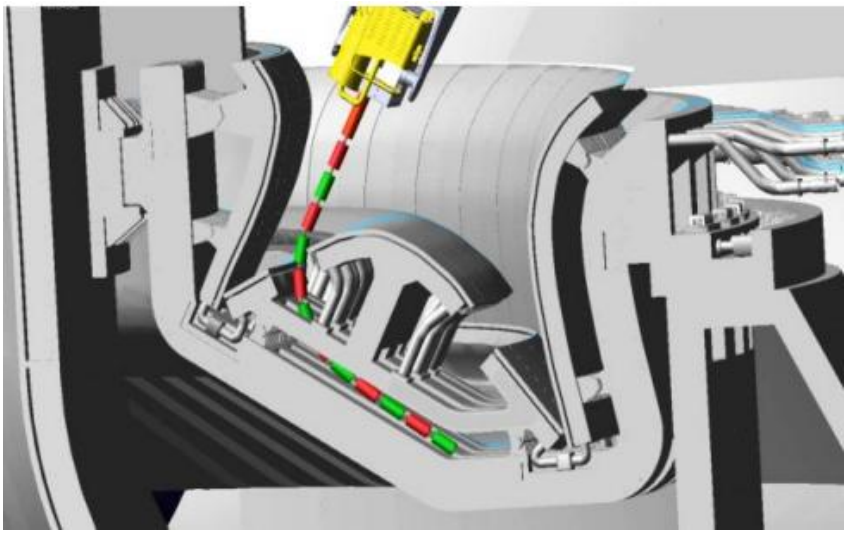

Figure 4. Snake Arm Maintainer (Wang, 2023).

When in use, the SAM can be connected to the quick changer on the end of the CFETR Multi-purpose Overload Robot (CMOR). This allows SAM to perform maintenance operations in the complex, limited space of the vacuum vessel (Qin et al., 2022; Wang, 2023).

1.2 Research objectives

The complexity of nuclear fusion reactors and the diversity of maintenance tasks require robotic systems to be highly flexible and adaptable. Therefore, the design of the quick-change device is particularly critical, because it directly affects the robot's ability to perform different maintenance tasks, including inspection, cleaning, component replacement, etc. During maintenance, two heavy-duty manipulators can enter the vacuum vessel at the same time. One manipulator is responsible for transporting toolboxes and various end effectors, and the other manipulator can use the quick-change device to perform various maintenance work in the vacuum vessel (Figure 5, Figure 6). For example, the ends of CMOR and SAM are equipped with standardized quick-change devices to facilitate the automatic switching of different end effectors or tools (Song et al., 2022; Qin et al., 2022).

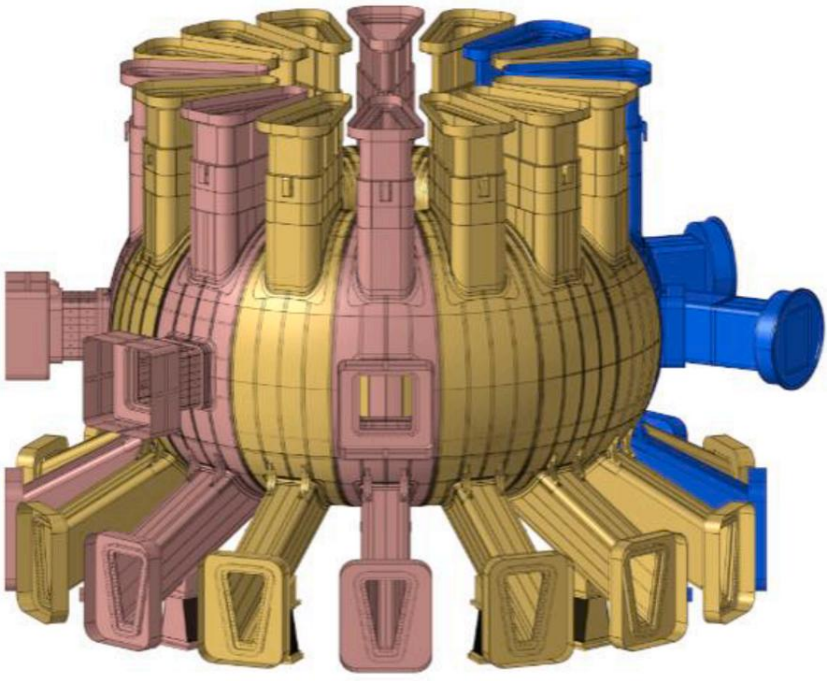

Figure 5. The vacuum vessel structure of the tokamak device (Song et al., 2022).

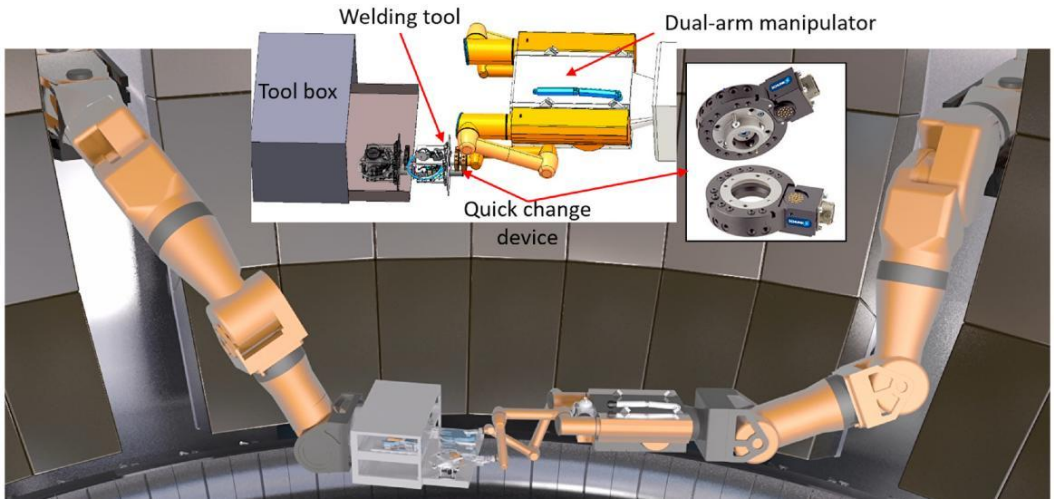

Figure 6. Heavy-duty manipulator into the vacuum vessel (Zhao et al., 2022).

Despite some progress in the application of robotic technology in the nuclear fusion field, designing a robot end quick-change device that can adapt to the extreme environment inside a nuclear fusion reactor and efficiently change different tools and equipment remains a technical challenge. Currently, maintenance manipulators for small nuclear reactors use pneumatically actuated quick changers, which allow the use of different maintenance tools (Leaño et al., 2021). There are also some manipulators that are equipped with gripper at the end for changing different tools (Iqbal et al., 2012). In addition, there are quick-change devices that use a new structure, such as a retaining pin, and there are glovebox that work together (Blake et al., 2022).

However, the existing solutions are usually faced with complex design, limited adaptability, and the replacement efficiency is still not ideal. And in order to ensure high dexterity of the manipulator, the payload of the manipulator is increased, and unnecessary accessories are to be avoided. Consequently, it is best not to use common industrial quick changer interfaces. For example, electromagnetic or pneumatic quick changers, because they take up a large part of the available payload (Blake et al., 2022; Zhao et al., 2022).

Therefore, this study aims to explore and develop a new type of robot end quick-change device to meet the unique requirements of nuclear fusion reactor maintenance, supporting the realization of safe and efficient nuclear fusion energy production. The design involves creating a quick-change device that can adapt to high radiation and magnetic field

environments. The design needs to consider modularity and universality to accommodate a variety of maintenance tasks and tool requirements.

By optimizing the design and selecting appropriate materials, the aim is to minimize the weight and size of the quick changer while ensuring its structural strength and durability. Additionally, enhancing the efficiency and precision of the end effector changing capabilities will reduce the robot system's end effector changing time, thereby increasing the overall efficiency of maintenance operations.

The performance of the quick changer in extreme conditions will be evaluated to ensure its long-term stable operation is unaffected by radiation. The quick changer's performance and reliability will be tested and verified in a simulated nuclear fusion reactor environment. The performance of the robot end quick-change device, including its changing efficiency, maintenance cycles, and lifespan, will be analysed and assessed.

1.3 Research questions

The most important thing for the quick changer is to ensure high dexterity of the manipulator without compromising the payload of the manipulator. So, in this thesis, several research questions were proposed. Firstly, what are the special maintenance needs of nuclear fusion reactors, and what specific requirements do they have for the design of robot end quick-change devices? Secondly, how to optimise the design of end quick change device to ensure the durability and reliability of the device?

Through these questions, the research will explore the design and material selection of the installation. And how design parameters affect the overall performance of the device, including the efficiency, accuracy, and durability of the quick-change mechanism. To ensure that the device can effectively meet the challenges of fusion reactor maintenance.

2 Methods

In the methods section, an explanation of how to model the designed quick-change device using SolidWorks software is shown. It also describes how to perform a finite element analysis of the model using ANSYS software. The boundary conditions, material properties and load conditions set are given to ensure that the simulation conditions are as close as possible to the actual operating environment.

2.1 CAD modeling in SolidWorks

SolidWorks is a 3D CAD design software. It is used in many fields for 3D design and engineering modelling. Provides a series of design, analysis, product data management and other tools. I first used SolidWorks to 3D model multiple parts. 3D modelling of 4 parts using SolidWorks and using standard screws from the toolbox. Enable exhaustive inspection and testing of designs, checking complex parts and assembly from multiple angles and levels of detail. And accurately simulate and modify the designed quick changer.

Use the Rounded Corners function on 3D models that have been built. Used to create smooth transitions on the edges or vertices of a 3D model. Not only do rounded corners improve the look and feel of the part, but they also help to enhance the durability of the structure, as sharp corners tend to be areas of stress concentration, which can easily lead to material fatigue or fracture.

Use the scaling function for parts that do not match the size of the model. Select the origin scaling of the model to control how and where the model is scaled. Enter the scale according to the final size of the model. This allows the model of the part to be resized. All dimensions of a model can be increased or decreased by a specific ratio relative to the original dimensions of the model.

Use the Select Material feature to specify a material for my model. In SolidWorks, the software provides an extensive library of materials, including a variety of metals, plastics, composites, and many more. I chose aluminium alloy 7075-T6, which is the most advanced high-strength, high-toughness aluminium alloy available. This alloy consists mainly of aluminium, zinc, magnesium, and copper. Where T6 refers to a specific heat

treatment process used to enhance the properties of the metal material. This includes solution heat treatment, quenching and artificial ageing. This alloy is lightweight than many other alloys, but is extremely high strength and has high hardness and wear resistance.

Use SolidWorks to assemble parts together to form a quick changer. Use fit functions to define and control the geometric relationships and interactions between parts in an assembly. This ensures proper positioning of the parts and helps simulate actual mechanical motion to verify the feasibility and functionality of the design. Once the fit is complete, use the exploded view feature to display the parts in a decentralized manner, clearly revealing where they are located and how they are connected to each other. This provides a visual way to show the inner workings of the quick changer.

Create 2D drawings from 3D CAD models, including front, side and top views. Describe the design and dimensions of the quick changer in detail on the engineering drawings. Add tolerances for the quick changer on the engineering drawing, including dimensional tolerances, geometric tolerances, and surface roughness marks. Create engineering drawings for assemblies, including exploded view, isometric view, and bills of materials.

By using precise tolerances, it is ensured that the assembled parts fit together correctly. It also reduces manufacturing costs by avoiding over-machining and material wastage. Use the suitable surface roughness to ensure good adhesion, which aids in the subsequent coating coverage of the parts. In addition, reducing stress concentration and slowing down the expansion of fatigue cracks on the surface of the parts.

SolidWorks CAM functions are utilized to identify manufacturing features and generate machining strategies. Create, edit, and manage CAM toolpaths directly within the SolidWorks interface to check for potential problems before actual machining. Additionally, this allows manufacturing capabilities and limitations to be considered earlier in the design process, which reduces rework and increases manufacturing efficiency.

2.2 Finite element analysis in ANSYS

Using ANSYS to perform mechanical analysis on the designed quick-change device can accurately simulate and analyse the deformation and performance of the structure after stress. And the analysis of ANSYS is used to modify and optimize the design and verify

that the quick-change device meets the safety requirements under load conditions. This can ensure the safety and reliability of the quick-change device design. In addition, using the post-processing function of ANSYS, I can visualize the analysis results, including stress distribution, deformation, and so on, so that it is easier to find potential problem areas.

2.2.1 ANSYS simulation setup

The quick changer is made of 7075-T6 aluminium alloy. This is the strongest aluminium alloy available, not only lightweight, but also extremely strong and commonly used in highly advanced equipment in aerospace and other fields. The following table shows the basic properties of this aluminium alloy (Table 1).

Table 1. Base material properties of 7075-T6 aluminium alloy.

Poisson's ratio	0.33	
Mass density	2810	[kg/m2]
Elastic modulus	7.20e+10	[N/m2]
Shear modulus	2.69e+10	[N/m2]
Tensile strength	5.70e+08	[N/m2]
Yield strength	5.05e+08	[N/m2]
Thermal expansion coefficient	2.36e-05	[/K]
Specific heat	960	[J/(kg*K)]
Thermal conductivity	130	[W/(m*K)]

Meshing the model before analysis allows complex geometric shapes to be broken down into smaller, simpler shapes such as triangles and quadrilaterals. These smaller shapes are called " elements " and the vertices of the elements are called " nodes ". I set the mesh size to 8mm. When analysing with software, the finer the mesh, the more accurate the results will usually be, because a finer mesh allows for better resolution of geometric details and

more precise calculations. To increase the speed of analysis, smaller meshes can be used in areas where greater accuracy is needed, while larger meshes can be used in other areas.

For the analysis of assembly, I also need to define the interactions and constraints between the different parts in the model. This is called "contact" in the ANSYS software. Contact is a key feature in FEA that allows the simulation of contact behavior between components, including Bonded, No Separation, Frictionless, Rough, and Frictional. By accurately defining the type of contact, it allows ANSYS to accurately simulate physical properties. It also allows for more accurate prediction of the stress distribution and deformation of assembly when subjected to external forces.

2.2.2 Static analysis of the quick-change device

A variety of stresses are analysed for quick changers, including von Mises stress, shear stress, and strength stress. Von Mises stress, also known as equivalent stress, is a calculation method that represents the equivalent internal stresses within a material in a complex stress state. Such stresses are derived from the von Mises stress criterion, which is one of the most commonly used criteria for evaluating the yielding of materials. The von Mises criterion is a comprehensive concept that is based on the theory of energy failure and considers the first, second and third principal stresses. The von Mises stresses are particularly suitable for yield analysis of most metallic materials because these materials do not usually show volume changes until they reach their yield strength. The use of von Mises stress guidelines in engineering design and analysis can help engineers ensure that structural components do not yield under expected loading conditions.

Shear stress is the stress that occurs when an external force acting on a material causes adjacent layers within the material to slide in parallel directions. Shear stress is usually denoted by the symbol τ and is defined as the distribution of the shear force F along the surface of the material acting on the area A, i.e. $\tau = F/A$. When a material is subjected to shear stress, it may deform but the volume usually remains constant. Analysing shear stresses ensures the strength and stability of a structure to prevent damage or excessive deformation under shear.

Total Deformation is the change in the overall shape of an object experienced by an external force. This deformation involves the sum of the displacements of the points of the

object in the x, y, and z directions. It reflects the overall change in a quick-change structure when it is subjected to forces, pressures, stresses, and so on. This simulates the performance of the quick-change structure under actual operating conditions and verifies that the quick-change device will not lose functionality or integrity due to excessive deformation.

3 Results

This section shows the designed end quick change device in detail, including the 3D model, exploded views and engineering drawings of each part. The working principle of the quick-change device is also explained in detail. In addition, the results of the finite element analysis using ANSYS are shown, including the von Mills stresses, shear stresses, and total deformations of the quick-change device, as well as specific mesh distribution diagrams. Finally, the manufacturing process of the various parts of the quick change device is explained, and the analysis of magnetron sputtering on the surface of 7075 aluminum alloy is presented.

3.1 Design of CAD model

This is the end quick-change device I designed for maintaining tokamak devices (Figure 7). The quick-change device consists of four parts. The left part is connected to the end-effector or other service tool by ten ISO 4762 M12 x 35 hexagon socket head cap screws. The right part is connected to the manipulator by ten ISO 4762 M12 x 35 hexagon socket head cap screws.

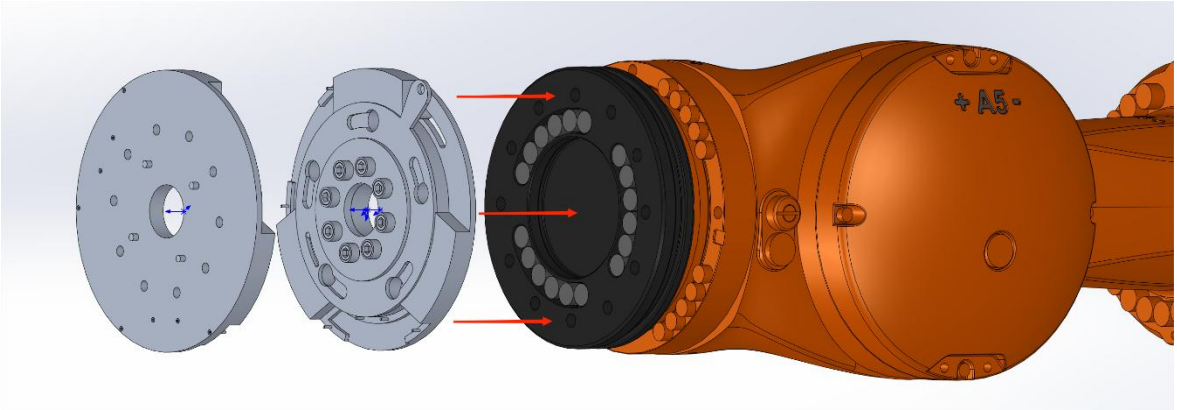

Figure 7. The quick changer I designed.

By exploding the quick-change device in a straight line, you can clearly see the four parts that make up the device (Figure 8). Part 1 connects to the end-effector or maintenance

equipment and part 4 connects to the manipulator. Parts 2, 3 and 4 are fastened together by means of eight ISO 4762 M12 x 30 hexagon socket head cap screws. The manipulator is connected to the mechanism 2 by means of an ISO 4762 M8 x 30 hexagon socket head cap screw. This allows the manipulator to control the part 3 through mechanism 2. Part 3 can be turned clockwise or counterclockwise and the rotation is limited by mechanism 1 and 2.

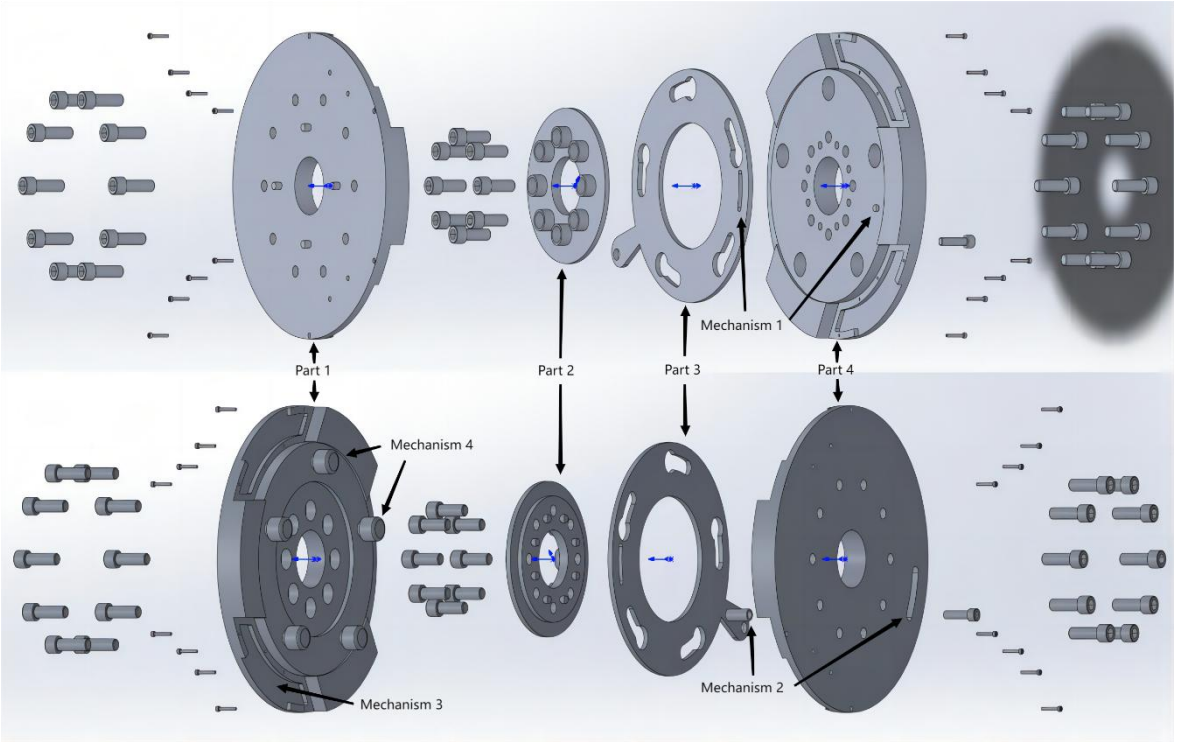

Figure 8. Exploded view of the quick changer.

Mechanism 3 has a total of 4 places on Part 1 and Part 4, which are used to connect the electrical module and the servo module (Figure 8). Each place is secured by four ISO 4762 M3 x 20 hexagon socket head cap screws. When the quick changer is locked, the electrical and servo modules on both sides are also connected at the same time. In addition, due to the versatility of the mechanism 3, the modules can be installed in any position and can be easily removed and interchanged (Figure 9).

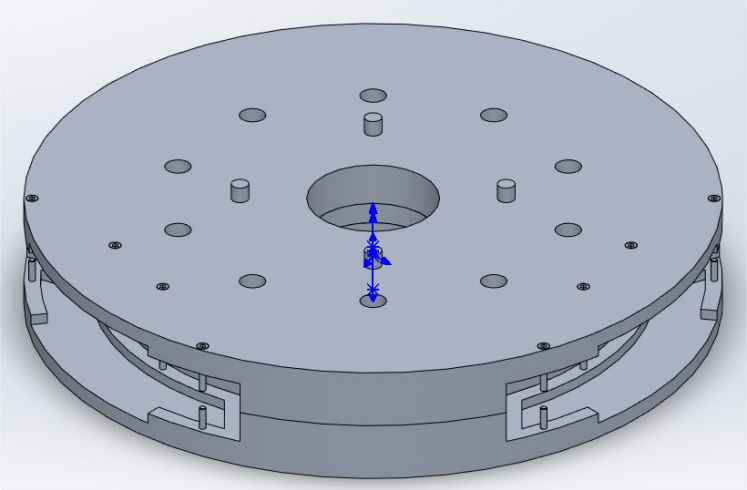

Figure 9. The locking state of the quick changer.

The control module of the end-effector and maintenance equipment can be connected to the manipulator through an orifice in the center of the quick-change device. Additionally, when the manipulator malfunctions, the operator can manually manipulate the protruding portion of the mechanism 2 to rotate the part 3 to disengage the quick-change device (Figure 8).

When the quick-change device is assembled, it is in state 1 (Figure 10). At this time, the mechanism 4 can pass through the part 3, making the part 1 and the part 4 close together (Figure 8). After that, the manipulator turns the part 3 clockwise through the mechanism 2 to state 2 (Figure 10), and the mechanism 4 will be stuck by the part 3, making the quick-change device successfully locked. When you want to release the lock, you can rotate the part 3 counterclockwise to return to state 1 (Figure 10), after which the part 1 can be successfully detached.

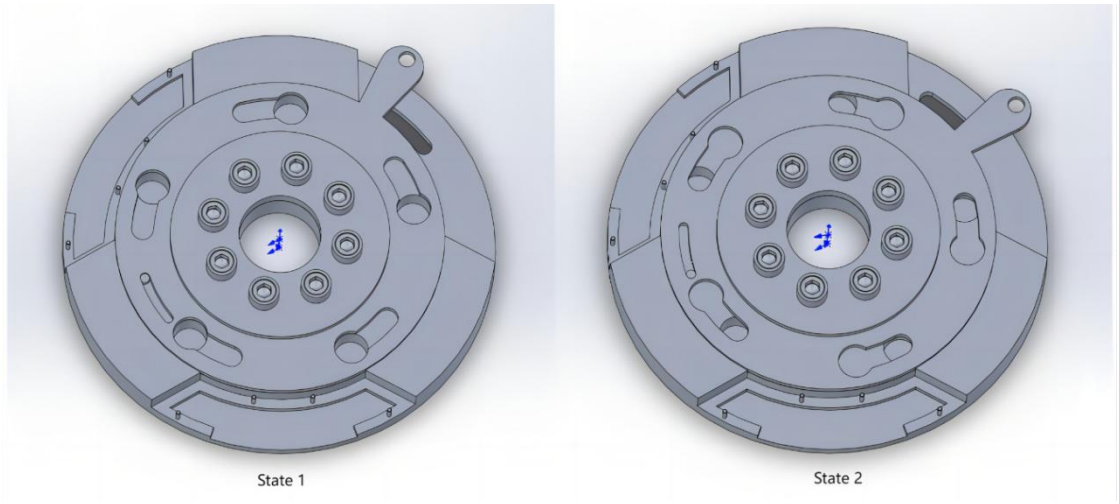

Figure 10. Locking principle of the quick-change device.

Figure 11, Figure 12, Figure 13, and Figure 14 are engineering drawings of the parts, the size of the engineering drawing paper is A3. Each engineering drawing is marked in detail with the specific dimensions of the part. Each part shows a top view, a bottom view, a side view, and an oblique view. Parts 1, 3 and 4 are at a scale of 1:3, and part 2 is at a scale of 1:1.5. Figure 15 shows the bill of Materials for the quick changer as a complete assembly at a scale of 1:4.5.

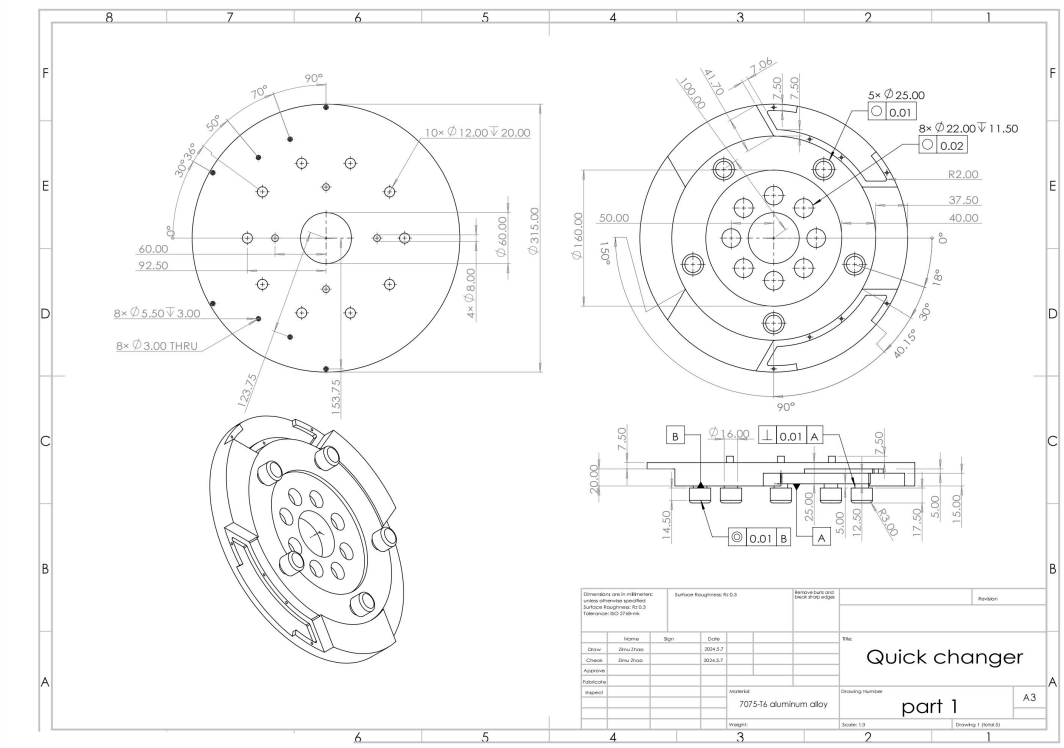

Figure 11. Engineering drawing of part 1.

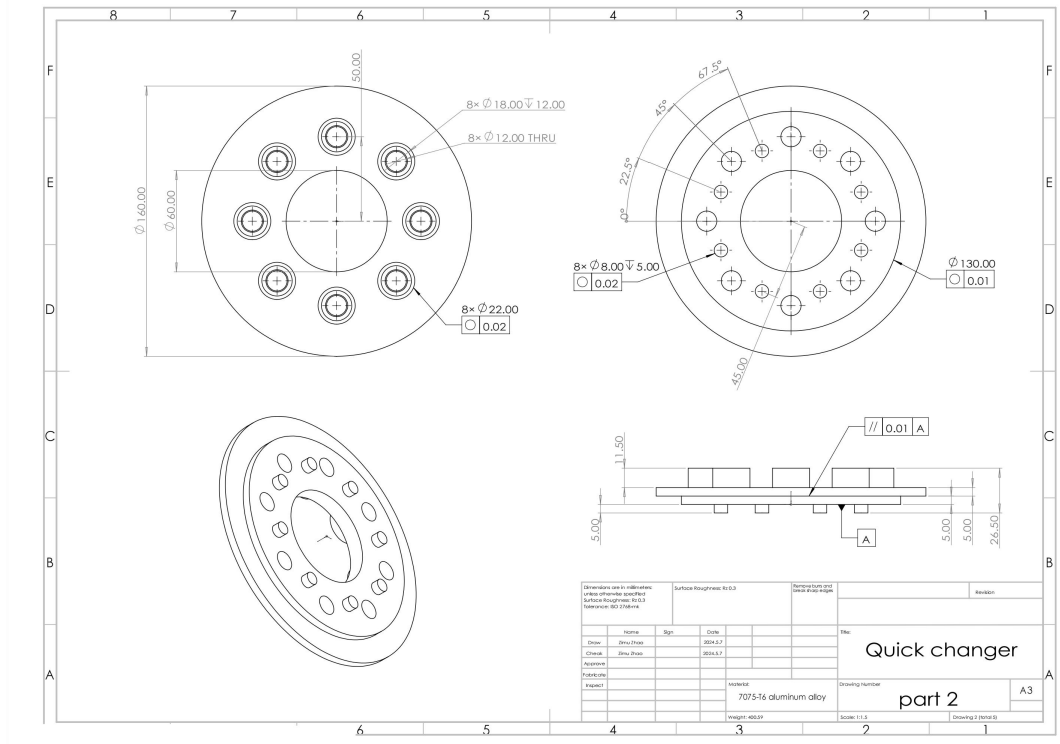

Figure 12. Engineering drawing of part 2.

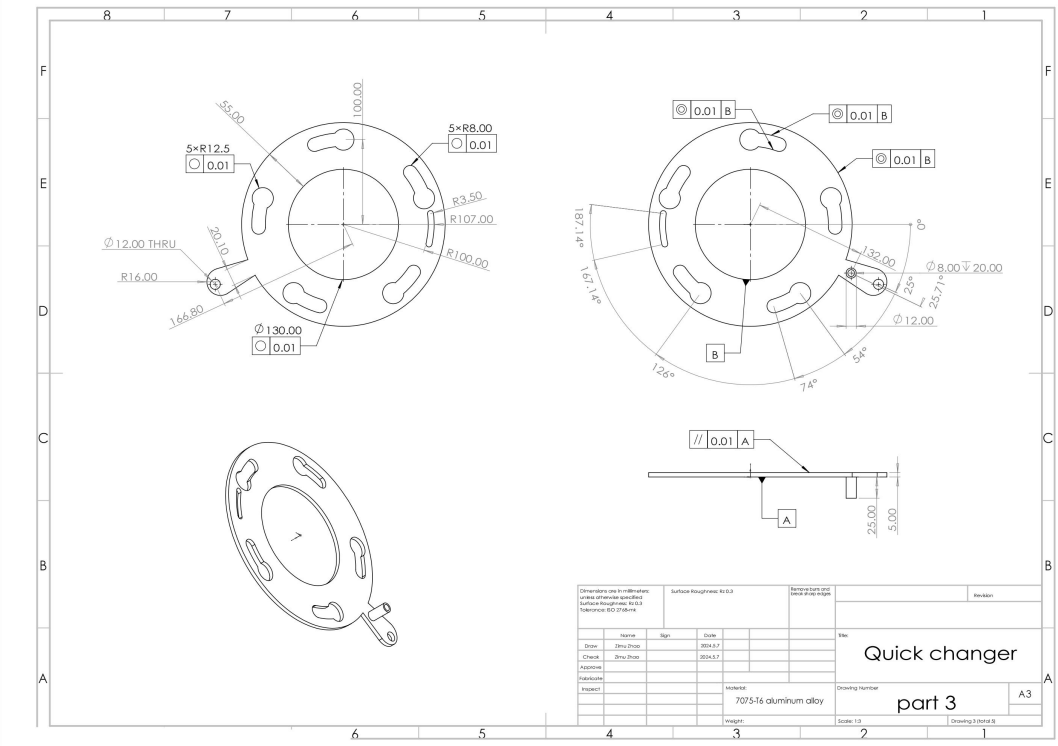

Figure 13. Engineering drawing of part 3.

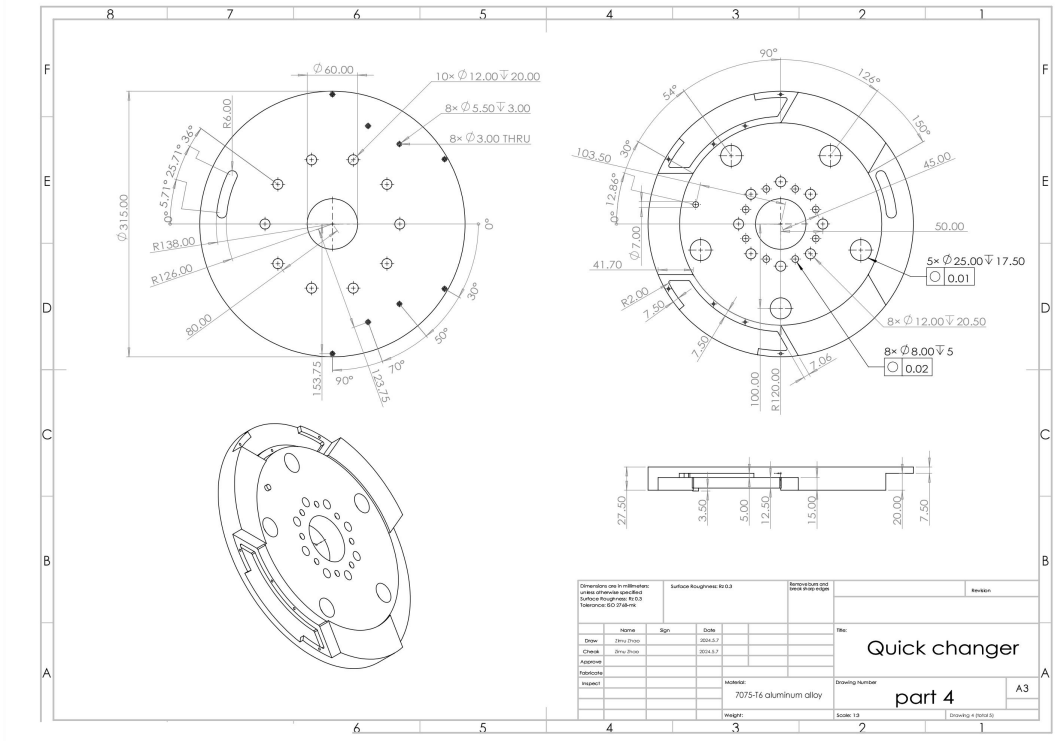

Figure 14. Engineering drawing of part 4.

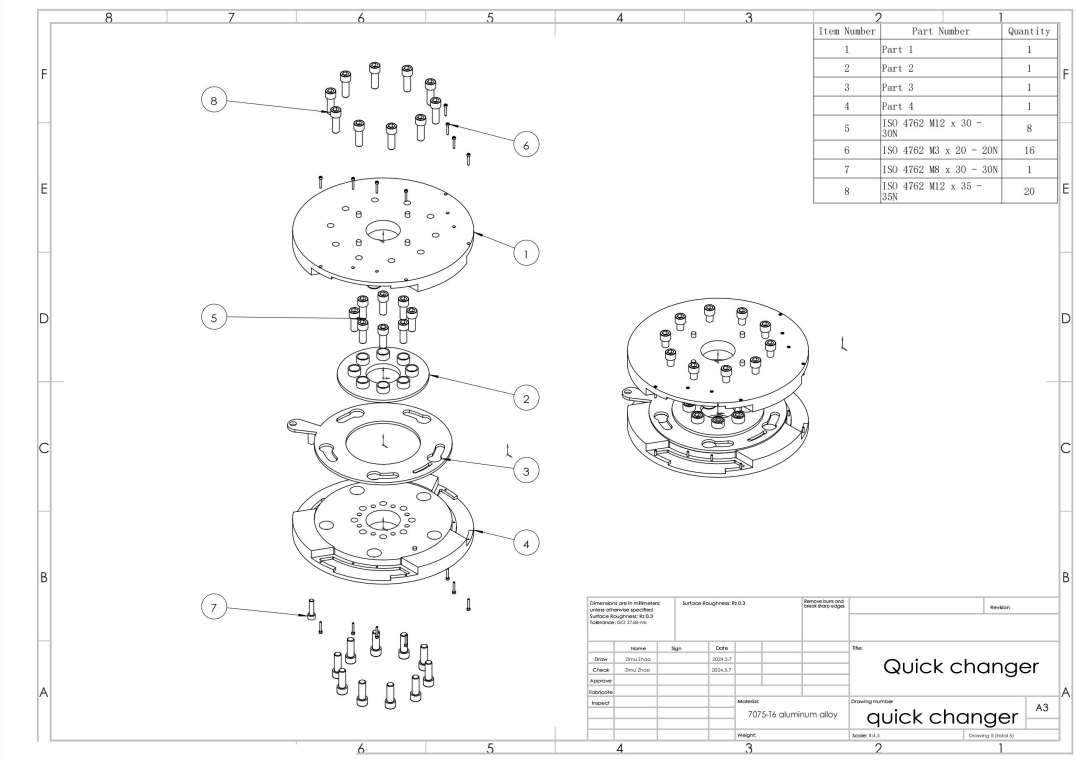

Figure 15. Bill of Materials.

The diameter of the quick changer is 315mm, including parts 1, 2, 3, and 4, eight ISO 4762 M12 x 30 hexagon socket head cap screws, sixteen ISO 4762 M3 x 20 hexagon socket head cap screws, one ISO 4762 M8 x 30 hexagon socket head cap screws, and 20 ISO 4762 M12 x 35 hexagon socket head cap screws.

3.2 Finite element analysis results

Save the assembly of the quick-change device in step format, and use ANSYS software for finite element analysis. One end of the quick-change device is fixed, and the other end is subjected to a load of 25,000 N, and the gravitational constant g is considered.

The distribution of the von Mises stresses, shear stresses, and total deformation for the overall quick changer is shown in the figure below (Figure 16). It can be seen that the maximum von Mises stress on the quick changer is 186.79MPa, the minimum is 0.011MPa, and the average von Mises stress on the whole is 20.35MPa. The maximum shear stress experienced by the quick changer is 82.756MPa, and the minimum is -94.814MPa. The

maximum deformation of the quick changer is 0.311mm, the minimum is 0mm, and the overall average deformation is 0.0085mm.

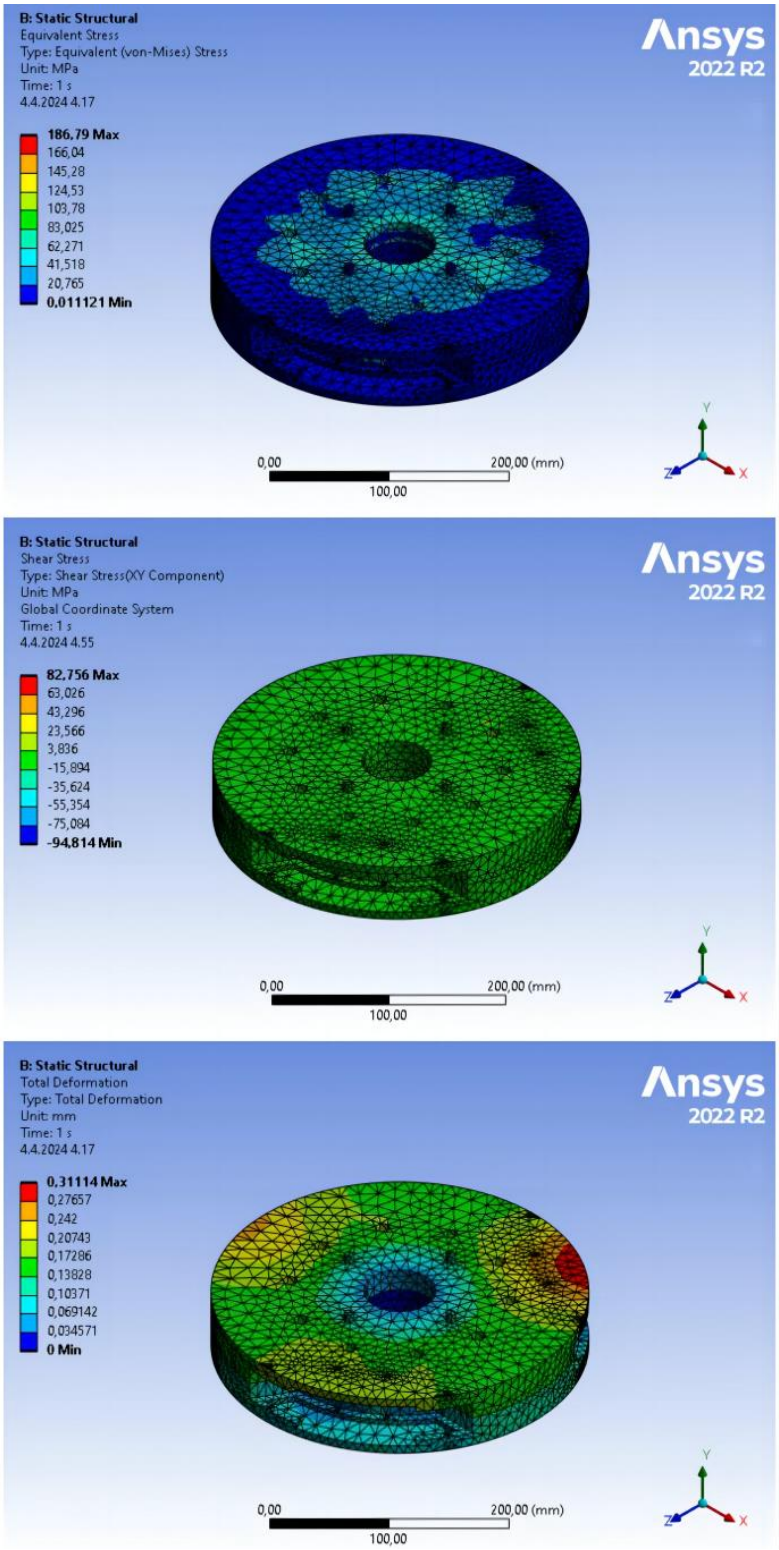

Figure 16. Analytical mesh diagram of the quick changer overall.

When the whole quick changer is disassembled, the stress distribution of each part can be seen separately (Figure 17, Figure 18, Figure 19, Figure 20). The maximum von Mises stress of part 1 is 186.79MPa, the minimum is 0.049MPa, and the average is 20.928MPa. The maximum von Mises stress of part 2 is 143.59MPa, the minimum is 0.224MPa, and the average is 31.25MPa. The maximum von Mises stress of part 3 is 117.31MPa, the minimum is 0.011MPa, and the average is 30.054MPa. The maximum von Mises stress of part 4 is 155.23MPa, the minimum is 0.106MPa, and the average is 16.662MPa.

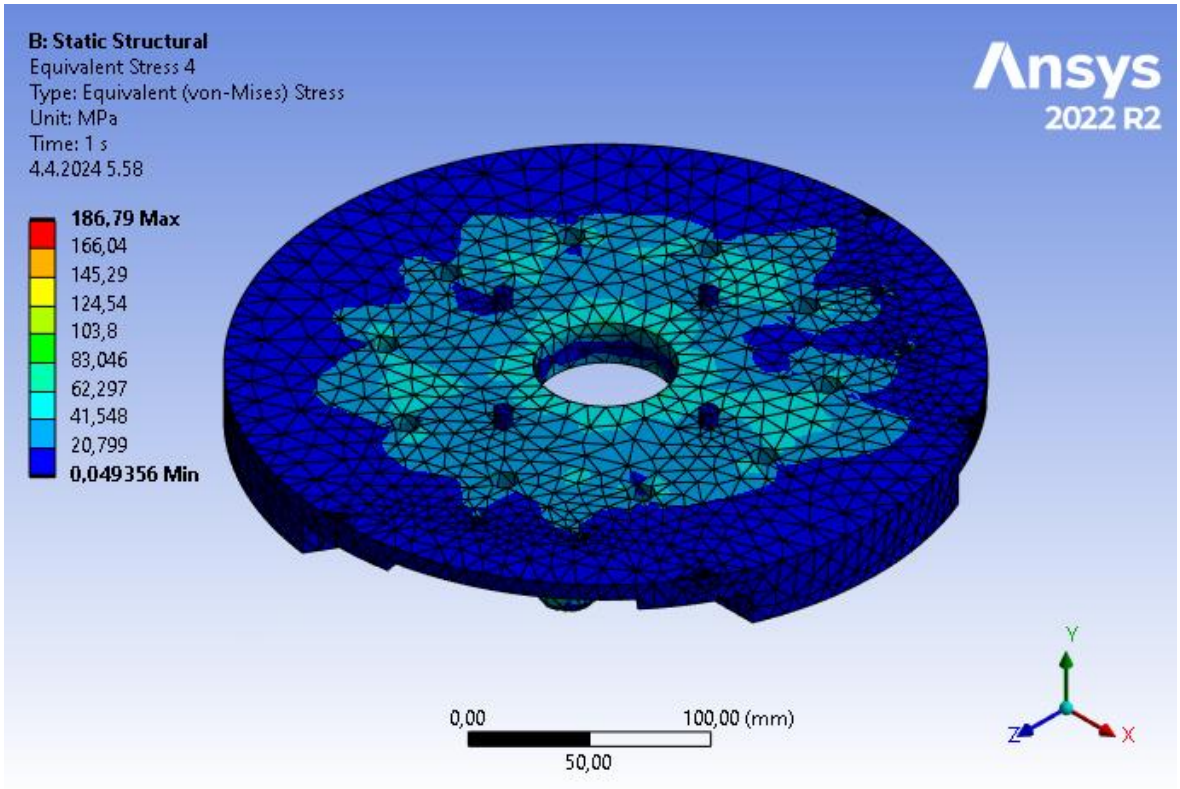

Figure 17. Von Mises stress distribution of parts 1.

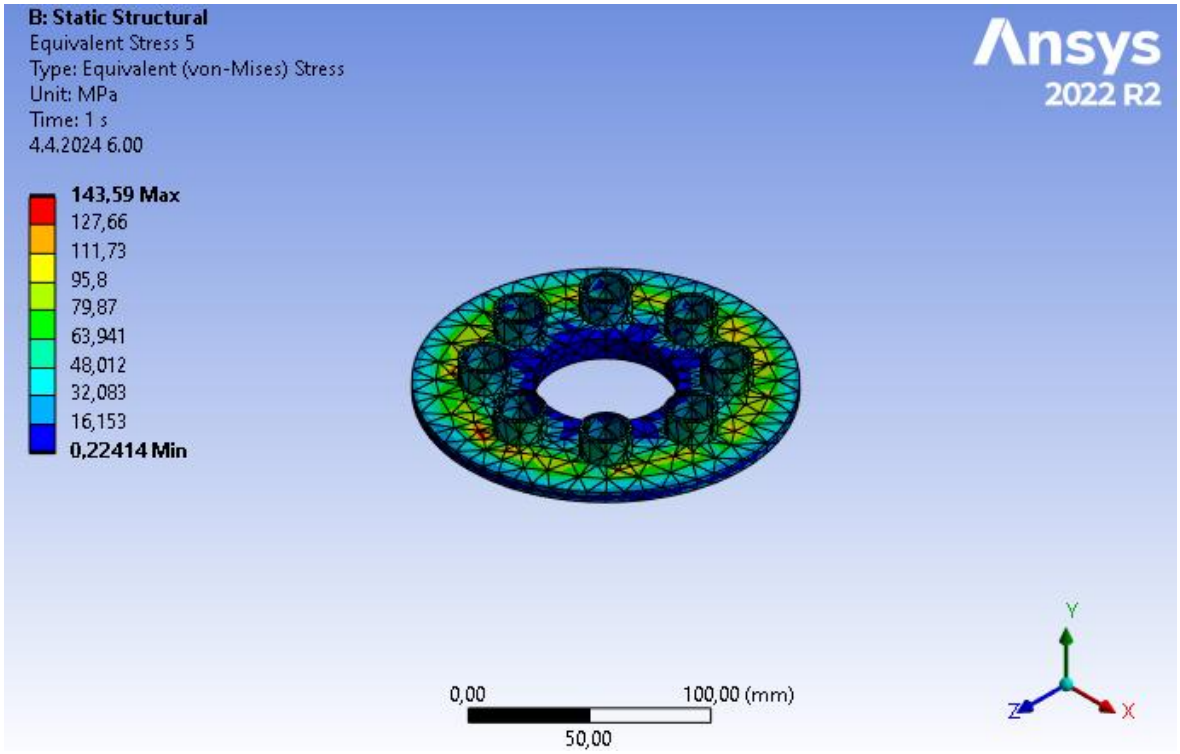

Figure 18. Von Mises stress distribution of parts 2.

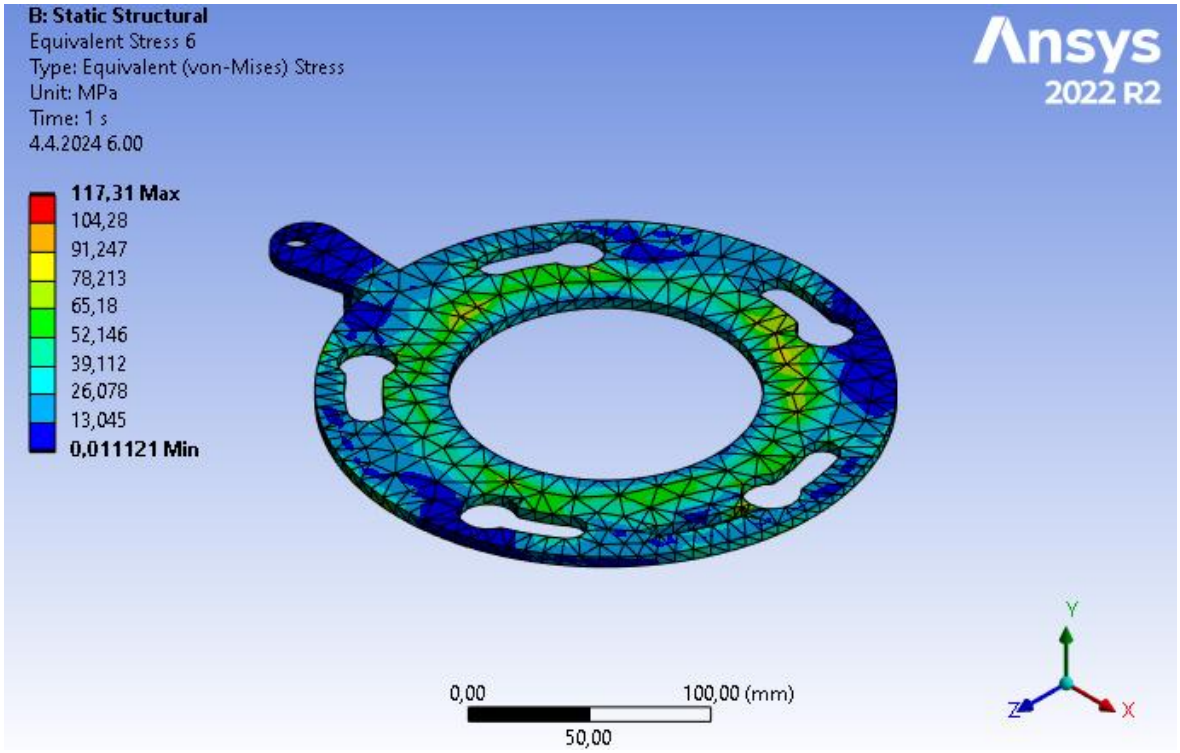

Figure 19. Von Mises stress distribution of parts 3.

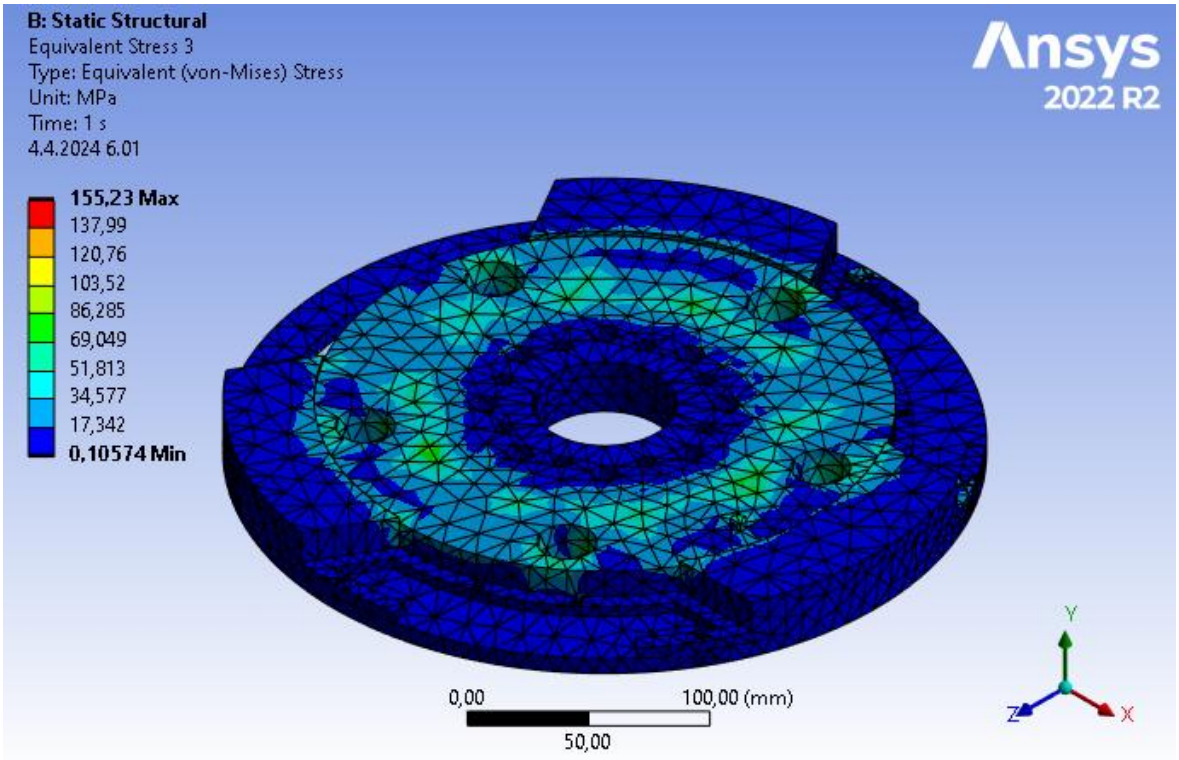

Figure 20. Von Mises stress distribution of parts 4.

The internal results could not be seen in the overall shear stress distribution diagram of the quick changer, so the shear stress distribution diagrams of the four parts were viewed separately (Figure 21, Figure 22, Figure 23, Figure 24). Part 1 has a maximum shear stress of 82.756 MPa and a minimum of -94.814 MPa. Part 2 has a maximum shear stress of 33.857 MPa and a minimum of -37.813 MPa. Part 3 has a maximum shear stress of 33.098 MPa and a minimum of -30.499 MPa. Part 4 has a maximum shear stress of 50.23 MPa and a minimum of -62.115 MPa.

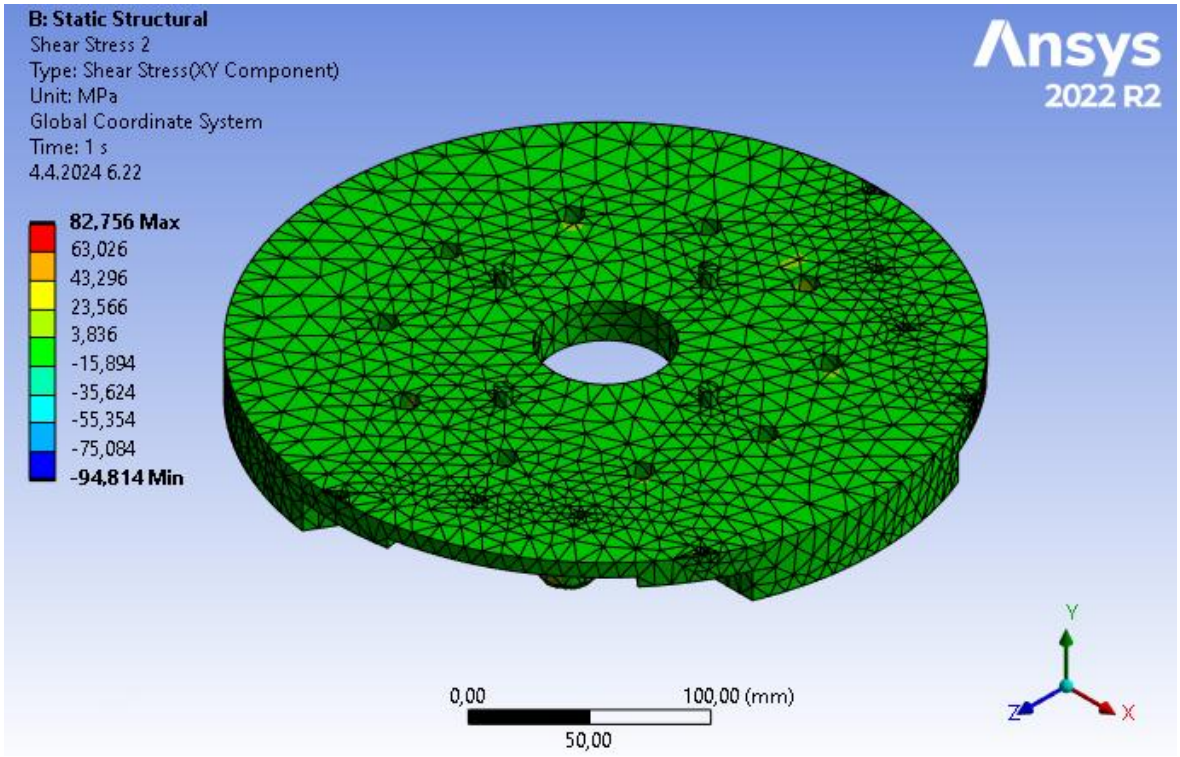

Figure 21. Shear stress distribution of part 1.

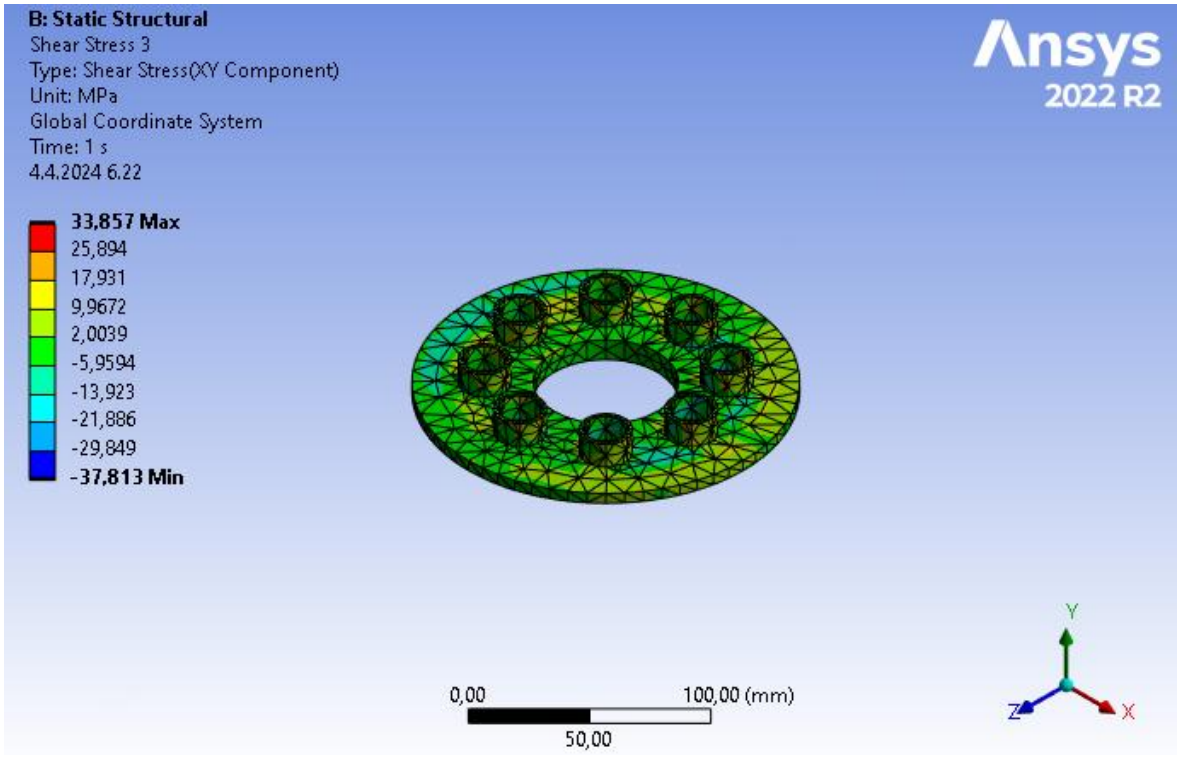

Figure 22. Shear stress distribution of part 2.

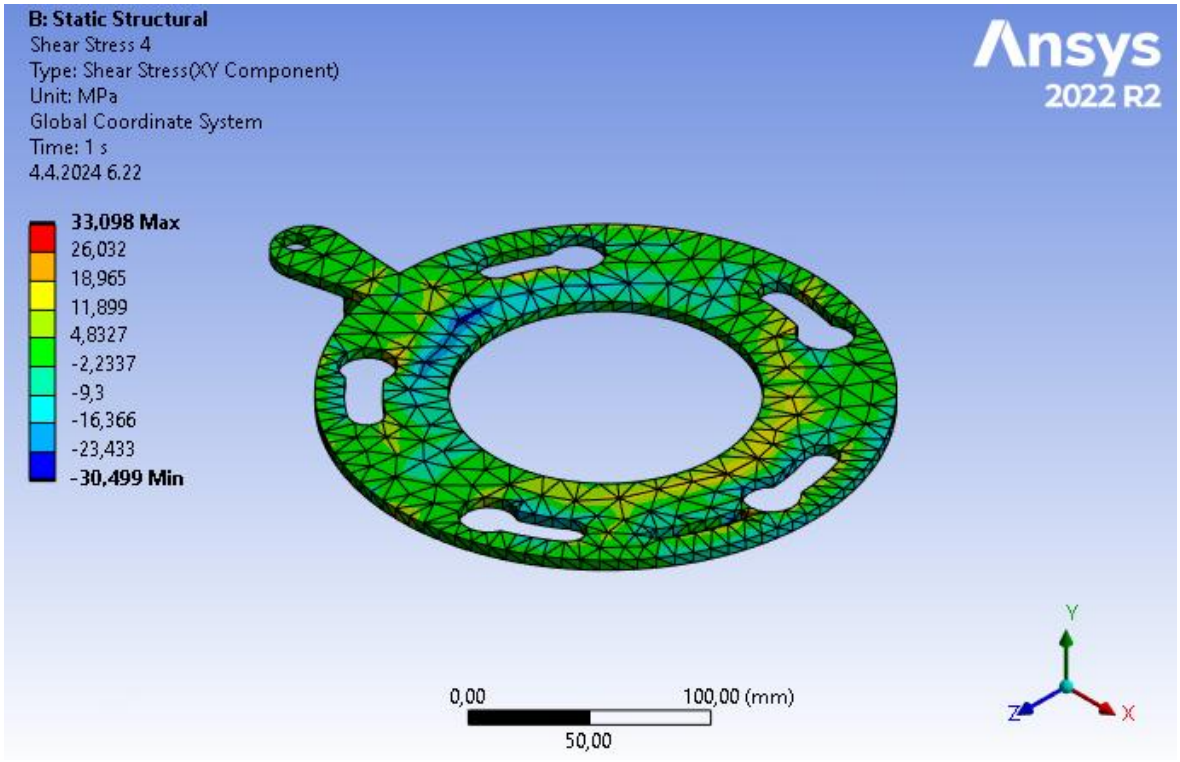

Figure 23. Shear stress distribution of part 3.

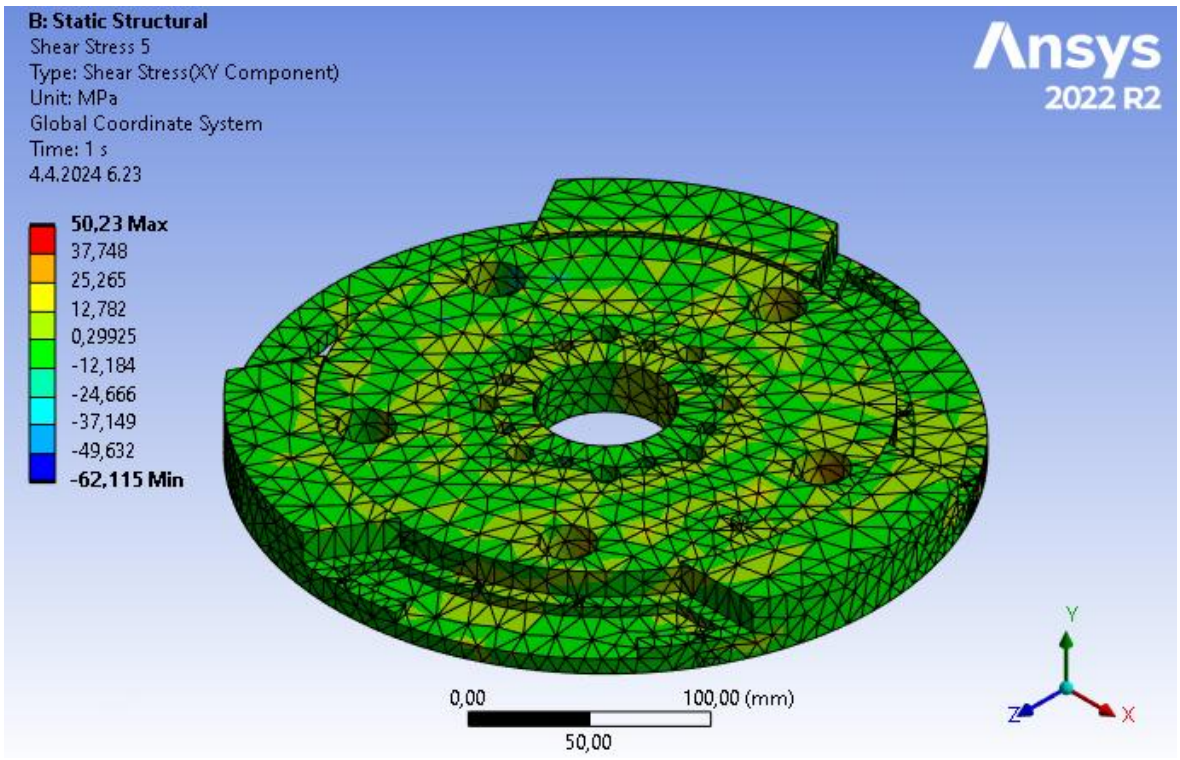

Figure 24. Shear stress distribution of part 4.

View the total deformation of 4 parts (Figure 25, Figure 26, Figure 27, Figure 28). The maximum deformation of part 1 is 0.311mm, the minimum is 0.042mm, and the average deformation is 0.168mm. The maximum deformation of part 2 is 0.169mm, the minimum is 0.017mm, and the average deformation is 0.029mm. The maximum deformation of part 3 is 0.255mm, the minimum is 0.033mm, and the average deformation is 0.158mm. The maximum deformation of part 4 is 0.135mm, the minimum is 0mm, and the average deformation is 0.054mm.

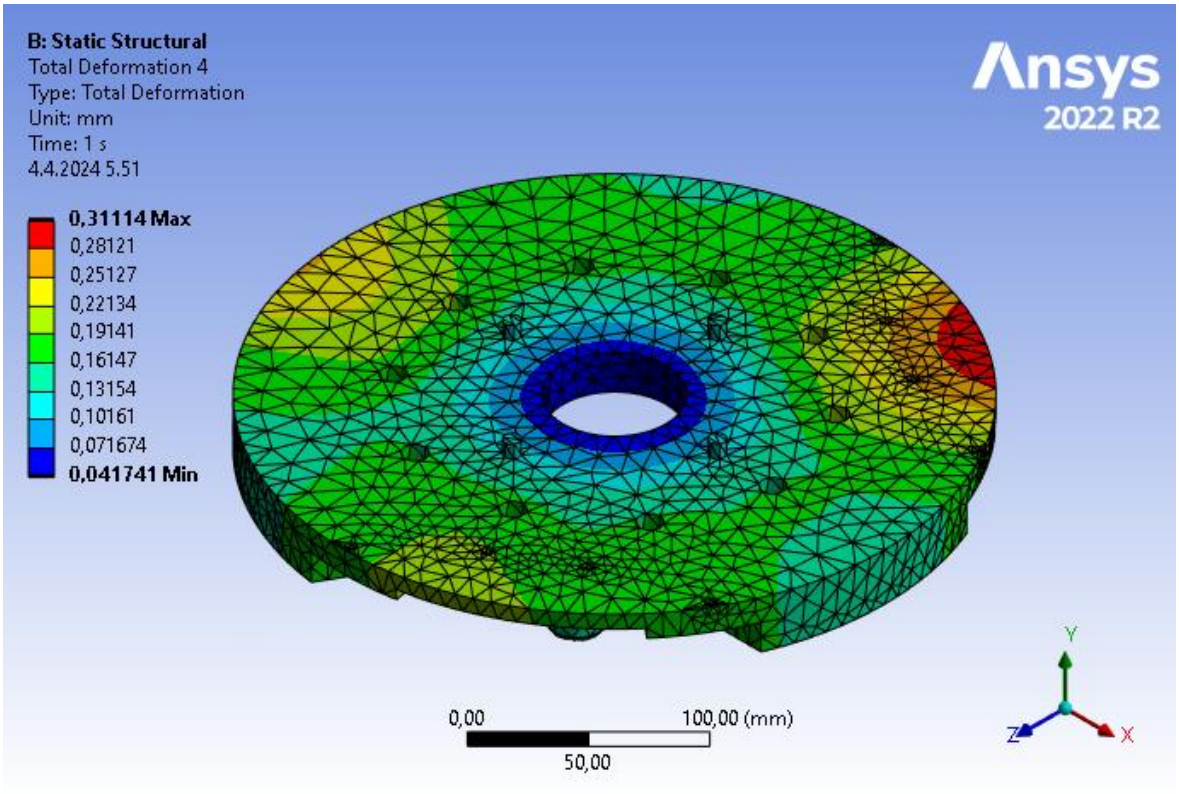

Figure 25. Total deformation of part 1.

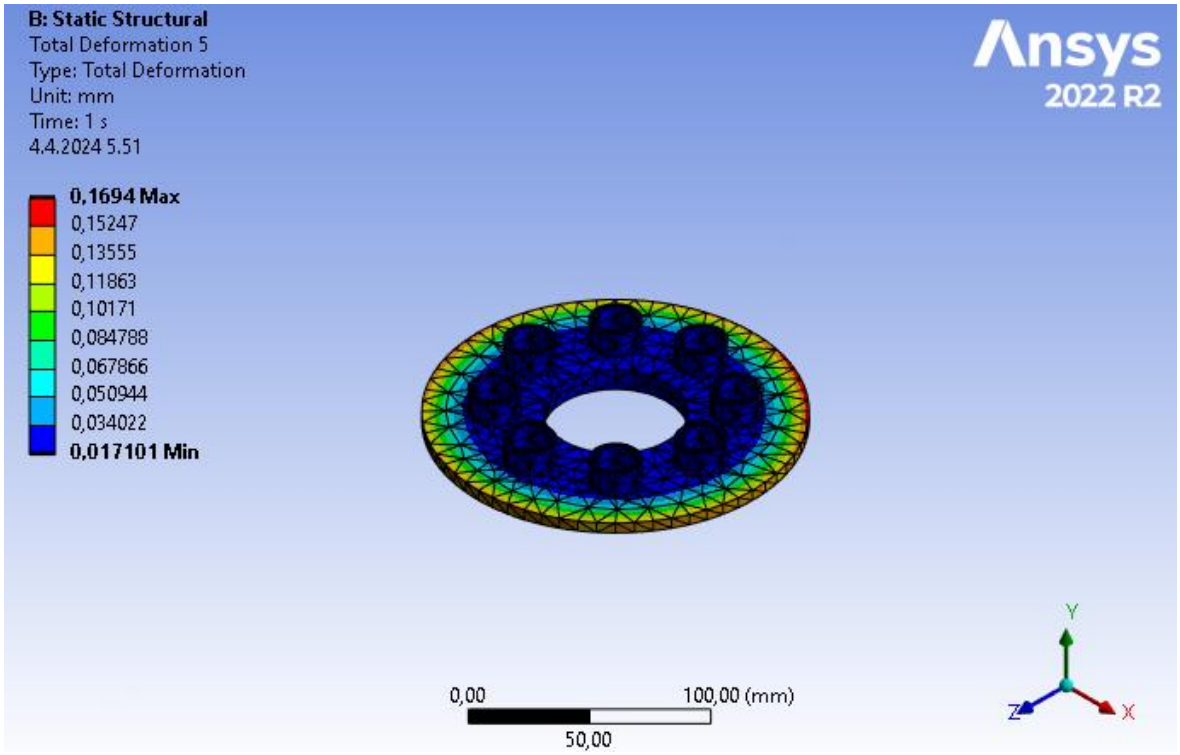

Figure 26. Total deformation of part 2.

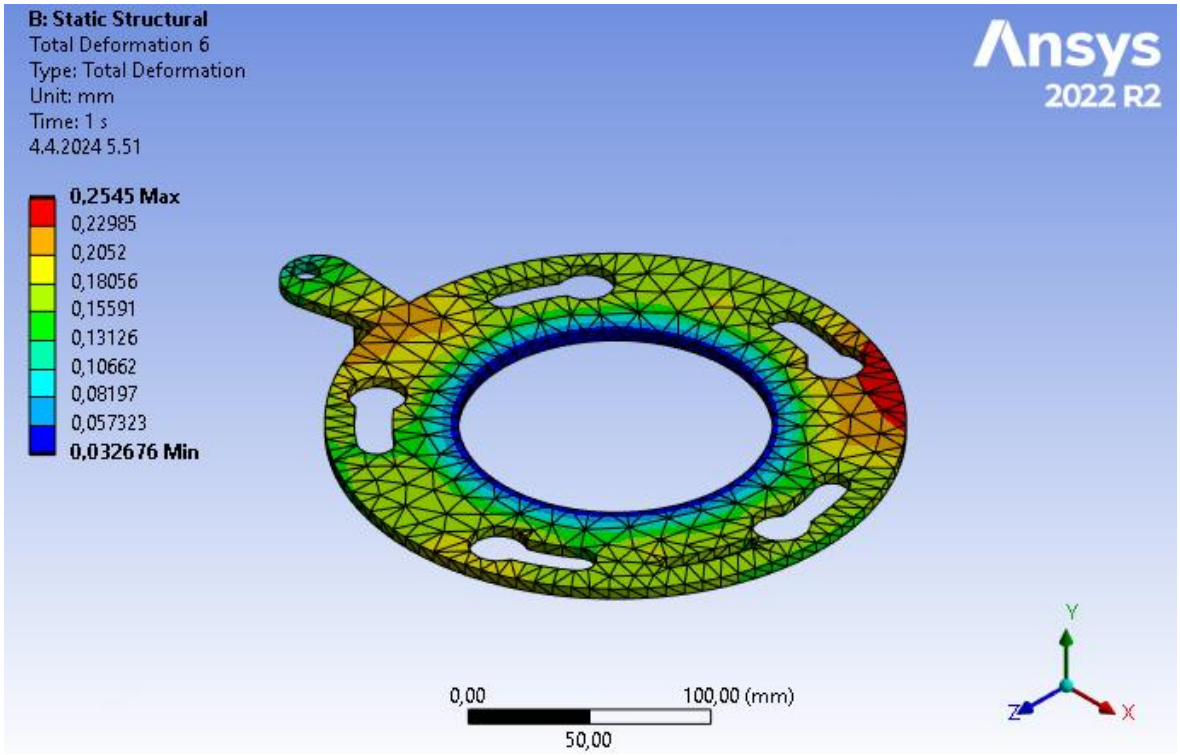

Figure 27. Total deformation of part 3.

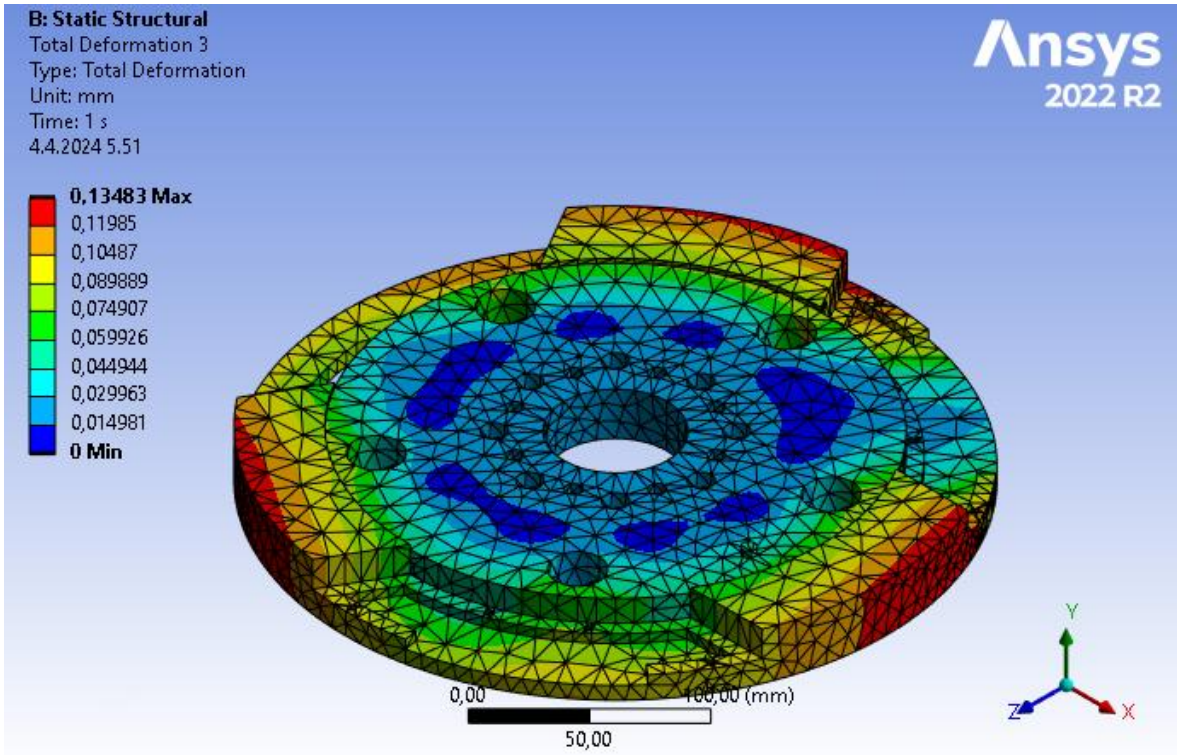

Figure 28. Total deformation of part 4.

Part 1 is the most deformed part, and the maximum deformation is at the edge of the outer surface where the part is connected to the end-effector or tool. The maximum deformation of all 4 parts is at their outermost point. The closer to the centre of the part, the smaller the deformation.

3.3 Manufacturing

There are two main steps to manufacture the parts for the quick changer. Firstly, the aluminium alloy blank is machined using a CNC machine to create the shape and structure of the part. After that, a layer of titanium diboride is added to the surface of the part using magnetron sputtering. This makes the parts wear-resistant, corrosion-resistant, and radiation-resistant, which greatly increases the service life of the quick changer.

3.3.1 CNC machining of quick changer parts

There are many ways to manufacture quick changers, such as CNC machining, stamping, casting, or 3D printing, etc. CNC machining can produce parts with complex shapes and

high tolerances, which is suitable for the manufacture of precision components. Moreover, CNC machined parts have better surface quality, which can reduce the need for subsequent surface processing. However, the cost is higher, and the processing time is longer.

Stamping is suitable for mass production, featured by fast production speed and low production cost. There is a high degree of consistency and repeatability between parts. Stamping requires special moulds, which can be produced quickly and in large quantities after preparing the stamping moulds. However, the initial cost up front is high, and it is not suitable for frequent design modifications. Most importantly, compared to CNC machining, stamping has limitations on the shape and complexity of the part.

Casting can produce parts with complex shapes, and internal cavity structures and curved shapes within the part are easier to realise. In addition, casting can reduce the cost per part for high mass production. However, parts produced by casting have rougher surfaces and may require additional machining and surface preparation to achieve the required geometric accuracy and surface finish. And like stamping, it requires expensive moulds and a large initial investment.

3D printing, also known as additive manufacturing, can produce complex designs that are difficult to achieve with traditional manufacturing methods. Examples include complex internal structures and irregular geometries. It can speed up the process from design to manufacturing prototypes and is suitable for rapid iteration and customised production of parts. However, for mass production, the current cost and speed of production are not as good as traditional manufacturing methods. And although the technology is improving, additive manufacturing can be difficult for 7075 aluminium alloys.

According to the DFMA principle, the selection of the optimal manufacturing process needs to consider the complexity of the part, the expected production volume and cost constraints. For the 7075 aluminium alloy quick changer that requires high precision, complex geometry, and small production volume, I choose CNC for machining. And after machining, a film of titanium diboride is added to the outside surface of the part by magnetron sputtering.

Using a 3-axis CNC machine, a flat rectangular aluminium alloy metal blank is selected for manufacturing. Analysed using SolidWorks CAM. The coordinate system was set at the center of the surface of the blank and the tool was entered from directly above, machining

the upper surface before the lower surface. In addition, when processing hard materials such as 7075 aluminium alloy, cutting fluid is required to cool the tool and workpiece to reduce wear and improve machining efficiency and quality. The manufacturing process for the 4 parts is the same. Take part 2 as an example, the following is the manufacturing process for it.

The first step is rough milling the metal blank with a flat-bottomed cutter (Figure 29). A large amount of material is quickly removed from the workpiece to quickly machine the workpiece roughly to the shape and size required in preparation for following machining operations. Rough milling uses relatively high cutting and feed speeds to achieve efficient material remove.

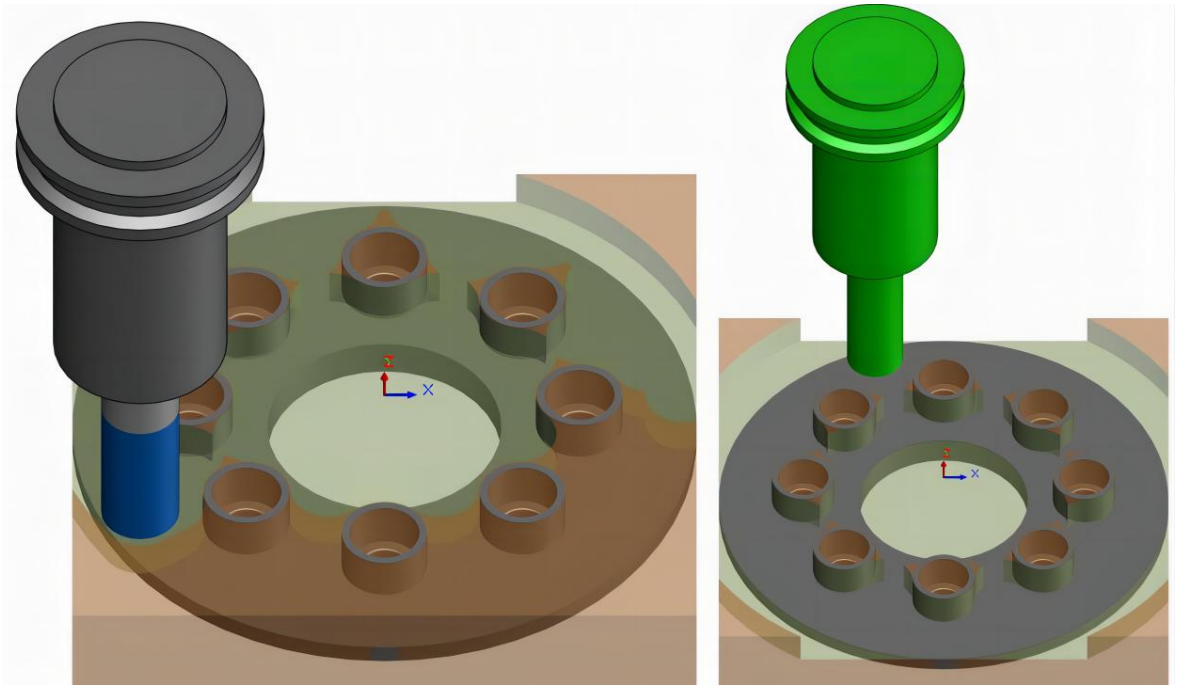

Figure 29. Rough milling of part.

The second step is contour milling with a flat bottom cutter (Figure 30). This is a more delicate machining method compared to rough milling and is used to produce accurate contours or shapes. Use this method to machine complex contour shapes, including straight lines, curves, or bevelled surfaces. Contour milling requires high accuracy and good surface quality. Therefore, the cutting speed, feed rate and depth of cut will be much

slower compared to rough milling to ensure that the required geometric accuracy and surface finish is achieved.

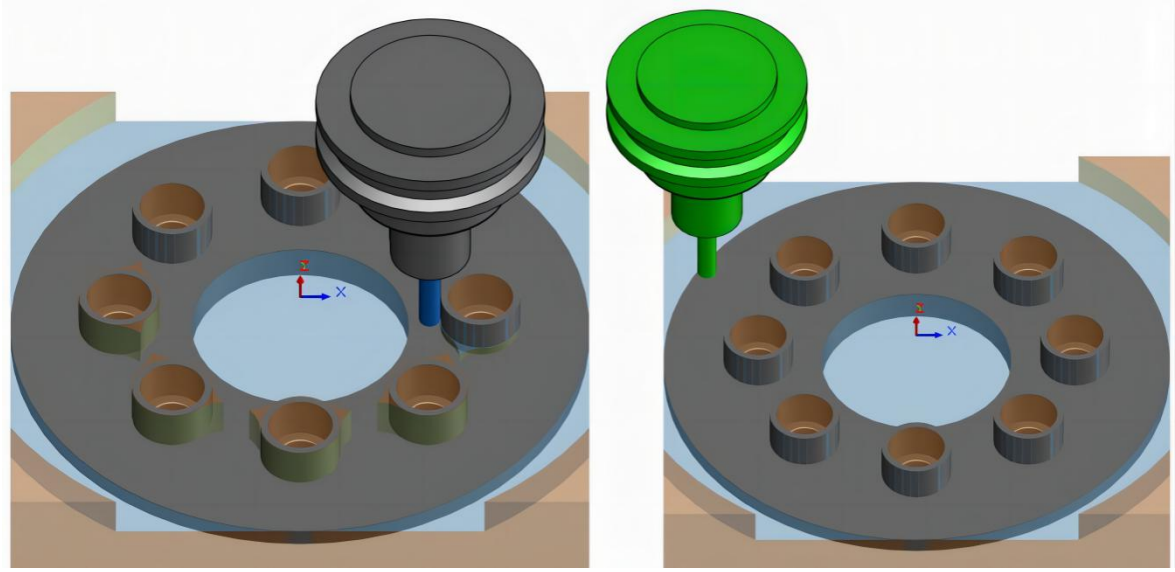

Figure 30. Contour milling of part.

The third step is to use a center drill to perform center drilling on part 2. This creates an accurate center point on the surface of the part, which serves to guide the subsequent use of a larger drill bit. This effectively prevents the drill bit from deviating from the predetermined position or damaging the material when starting the drilling process, thereby facilitating easier and more accurate deep hole drilling, especially when working with hard materials such as 7075 aluminium alloy.

The fourth step is to drilling using a drill (Figure 31). This is a simple process in which the drill bit cuts the material by means of a rotational movement. An axial force is applied to the drill, which feeds directly into the material axially.

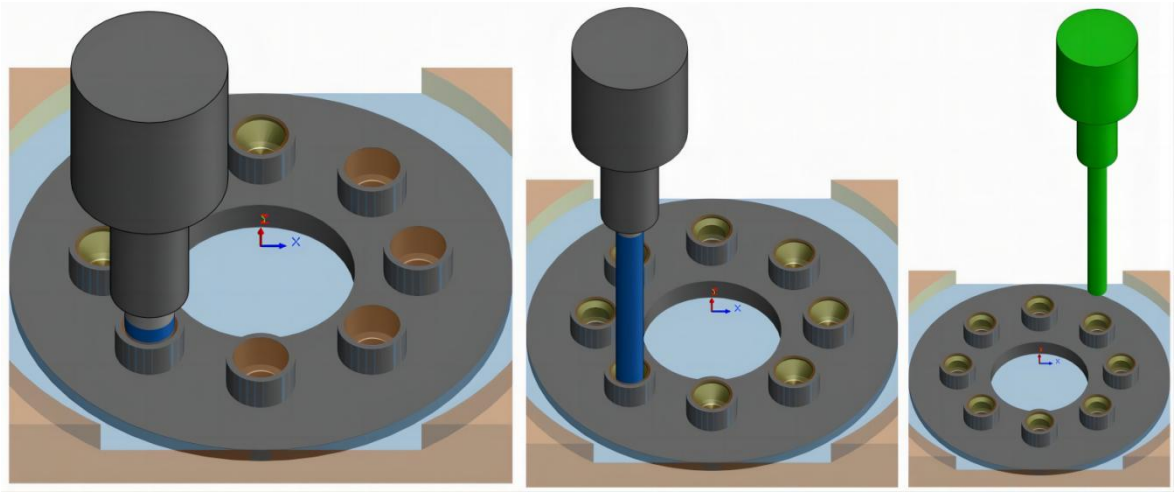

Figure 31. Drilling holes in part.

Finally, the drill is used to counterbore the holes (Figure 32). Counterbore drilling is the process of cutting a flat-bottomed cylindrical expansion into the end of an existing hole. It is used to accommodate the head of the fastener, ensuring that the screw can be embedded flatly into the surface of the part so that the head of the screw is flush with the surface of the part, avoiding protrusions that could cause interference with other parts. Additionally, since the quick changer is subjected to high loads, counterbore prevents the screw from moving or loosening under stress.

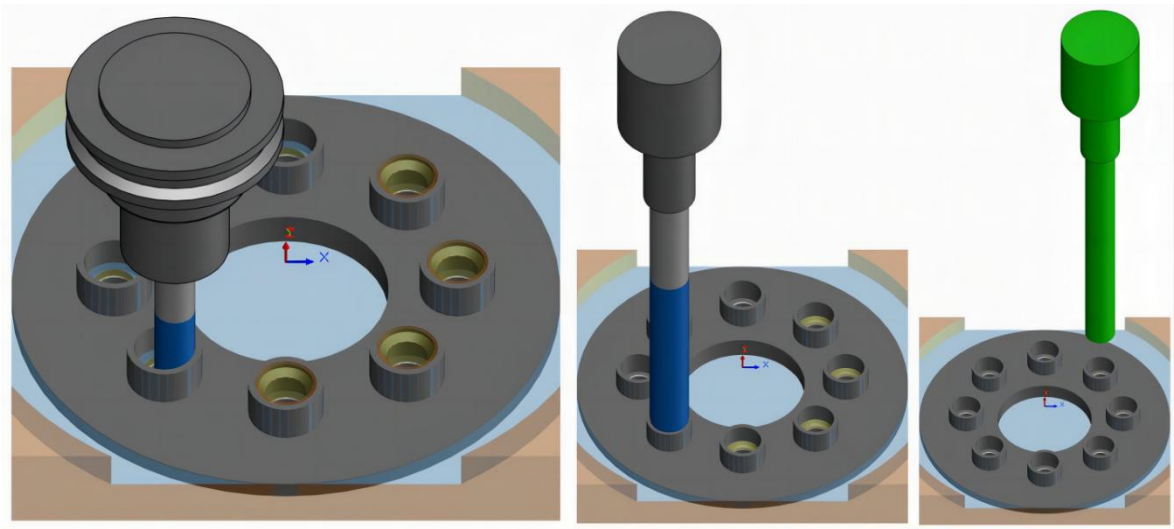

Figure 32. Counterbore for part.

Table 2. Tool data for Part 2.

Steps	Tool	Tool Holder	XY FeedRate [mm/min]	Z FeedRate [mm/min]	Spindle speed [rpm]	Total toolpath length [mm]	Total toolpath time [min]
Rough milling 1	20MM CRB 2FL 38 LOC	C40-M20EM3	742.749	185.687	3322.964	15092.161	17.426
Rough milling 2	20MM CRB 2FL 38 LOC	C40-M20EM3	742.749	185.687	3322.964	887.650	1.132
Contour milling 1	6MM CRB 2FL 19 LOC	C40-M06EM2	1645.920	411.480	12000.000	4219.194	2.391
Contour milling 2	20MM CRB 2FL 38 LOC	C40-M20EM3	742.749	185.687	3322.964	261.516	0.312
Center drilling	10MM X 90DEG CRB SPOT DRILL	C40-32ERP412	500.000	200.000	3000.000	391.078	0.222
Drilling	19.0mm JOBBER DRILL	C40-32ERP412	500.000	250.000	1300.000	1148.726	0.776
Rough milling 3	6MM CRB 2FL 19 LOC	C40-M06EM2	1645.920	411.480	12000.000	38055.692	22.370
Contour milling 3	6MM CRB 2FL 19 LOC	C40-M06EM2	1645.920	411.480	12000.000	2344.030	1.241

Table 2 shows the CAM tool travelling data for part 2. The part 1 and part 4 are manufactured in the same five steps above as part 2. These include rough milling, contour milling, center drilling, drilling holes, and counterbore drilling. Other than that, part 3 does not have the final step of counterbore. The rest of the processes are the same.

3.3.1 Titanium diboride thin films deposited by magnetron sputtering

Currently, a variety of methods can be used to produce titanium diboride coatings. These include chemical vapour deposition, pulsed laser deposition, magnetron sputtering, reactive sputtering, plasma enhanced CVD, and ion beam sputtering etc. Among these many methods, magnetron sputtering is the most common and widely used technique. Because of its low deposition temperature, fast deposition rate, and the non-use of toxic gases. Therefore, this method produces titanium diboride films without contamination and with superior quality (Sanchez et al., 2011; Rupa et al., 2009). In addition, magnetron sputtering allows the use of substrates with complex geometries, which is very suitable for quick-changer parts (Sanchez et al., 2011). So, I chose to use magnetron sputtering to add a titanium diboride coating to the quick changer.

The target was firstly prepared by stacking the titanium diboride will powder in the form of a disc with diameter of 50 mm and thickness of 3 mm. Subsequently, it was placed in a graphite furnace and in a flowing argon atmosphere sintered at 1800°C for 30 minutes. After that, the quick-changer parts were ultrasonically cleaned twice using acetone to ensure that the outer surface of the parts was clean. The parts were dried and placed in the sputtering chamber, and the system was vacuumed until the pressure was 0.4 Pa. Titanium diboride films were deposited on the parts for 20 min at room temperature (25 °C) using 120 W DC power and argon plasma. Due to plasma heating, the temperature of the part increased by about 40-45 °C after 20 minutes of film deposition. Finally, the deposited films were annealed in vacuum (Rupa et al., 2009; Mishra et al., 2006).

4 Analysis

In this section, the safety of the quick changer is evaluated based on the results of the finite element analysis. After that, the advantages and disadvantages of the designed quick changer are explained.

4.1 Safety assessment of quick changer

Safety assessment of quick changers using safety factors. It is the ratio between the yield strength of a material and the maximum stress the material is expected to be required to withstand. Safety factors play a vital role in engineering design and analysis, ensuring that structural and mechanical components have additional load carrying capacity under expected loads. This prevents structural failure even under extreme conditions or unexpected loads, thus increasing overall safety and reliability.

For example, unexpected situations may be encountered in practice, including overloading, extreme changes in environmental conditions or operational errors, and so on. A factor of safety can provide additional protection against structural damage or failure due to these unforeseen conditions. In addition, there are many uncertainties in the engineering design and analysis process, such as variations in material properties, defects in the manufacturing process, and inaccuracies in load evaluation. By using a safety factor, a buffer can be provided against these uncertainties to ensure a safe design.

It can be seen that the safety factor is 2.7035 when the design maximum load is 25000 N (Figure 33). The safety factor for part 1 is 2.7035, for part 2 is 3.517, for part 3 is 4.3047 and for part 4 is 3.2533 (Figure 34, Figure 35, Figure 36, Figure 37).

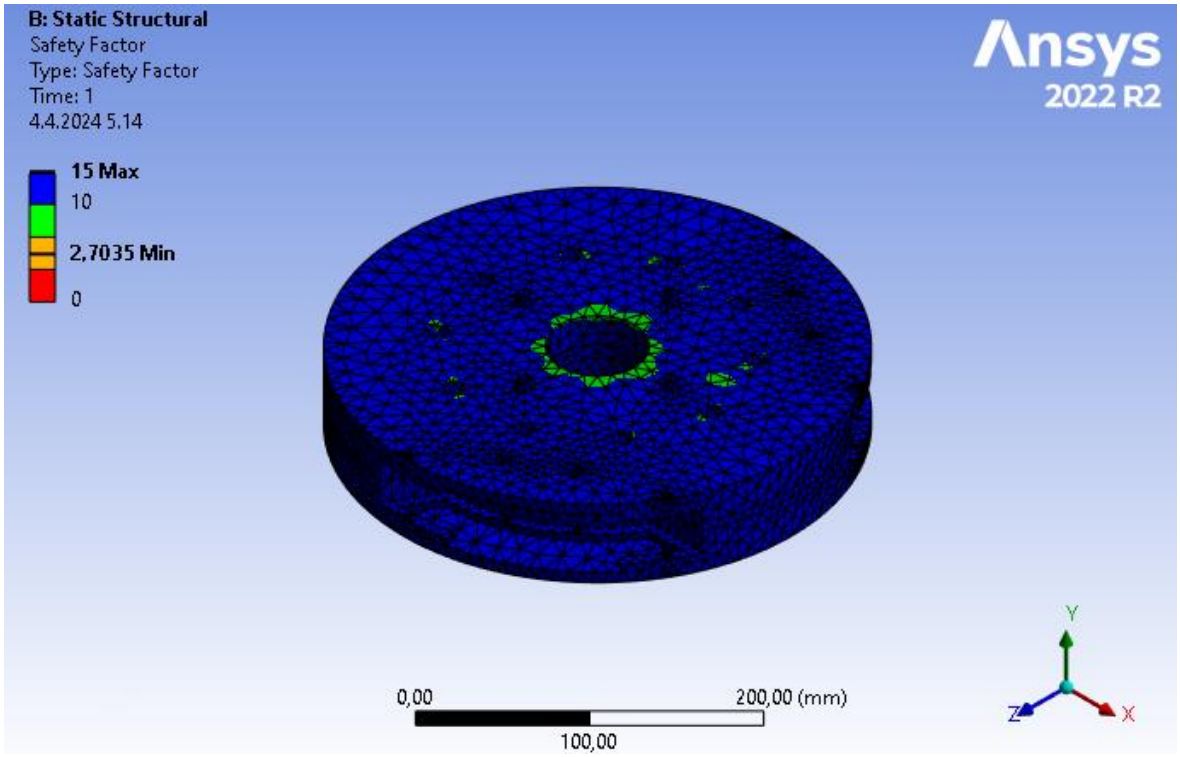

Figure 33. Analysis results of the overall safety factor of the quick changer.

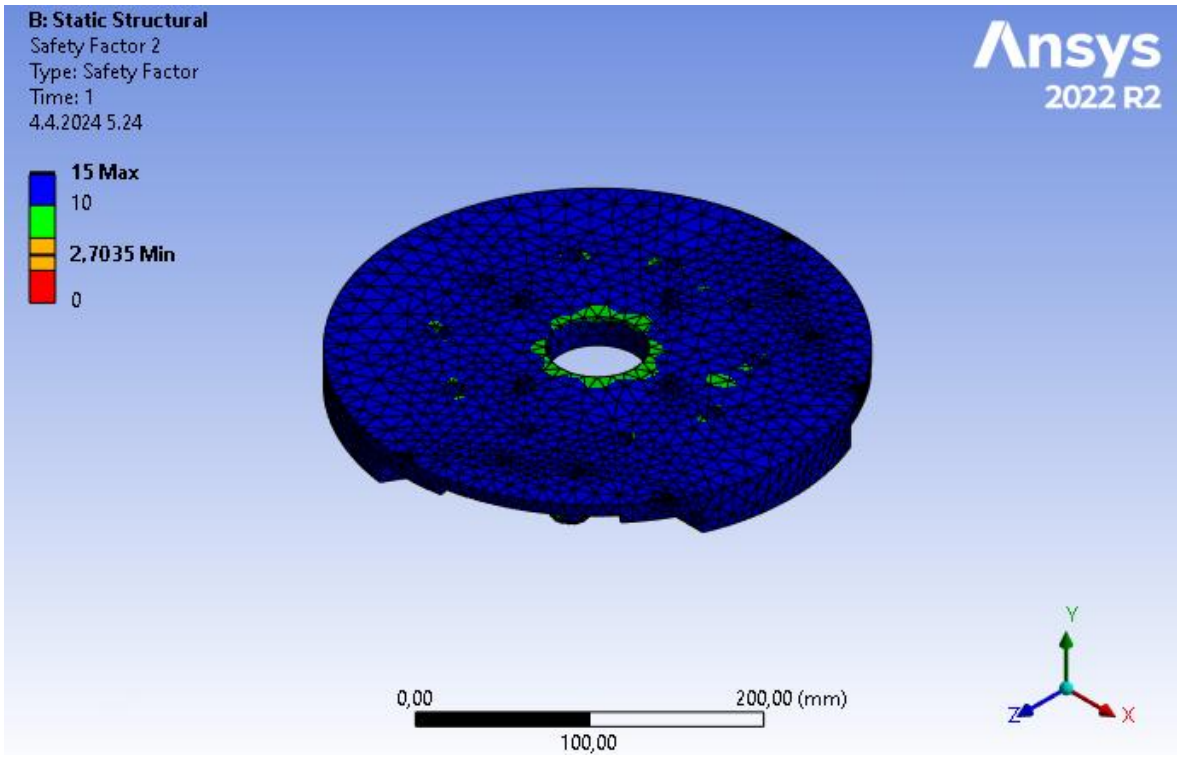

Figure 34. Safety factor analysis results of part 1.

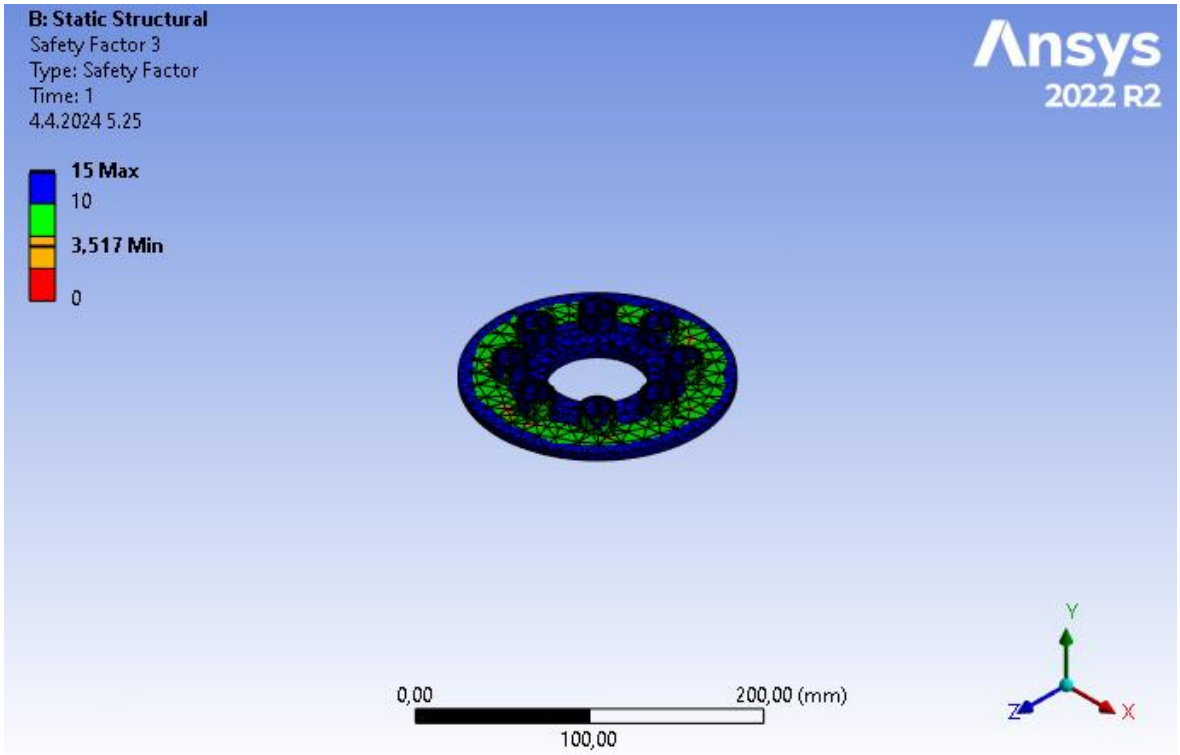

Figure 35. Safety factor analysis results of part 2.

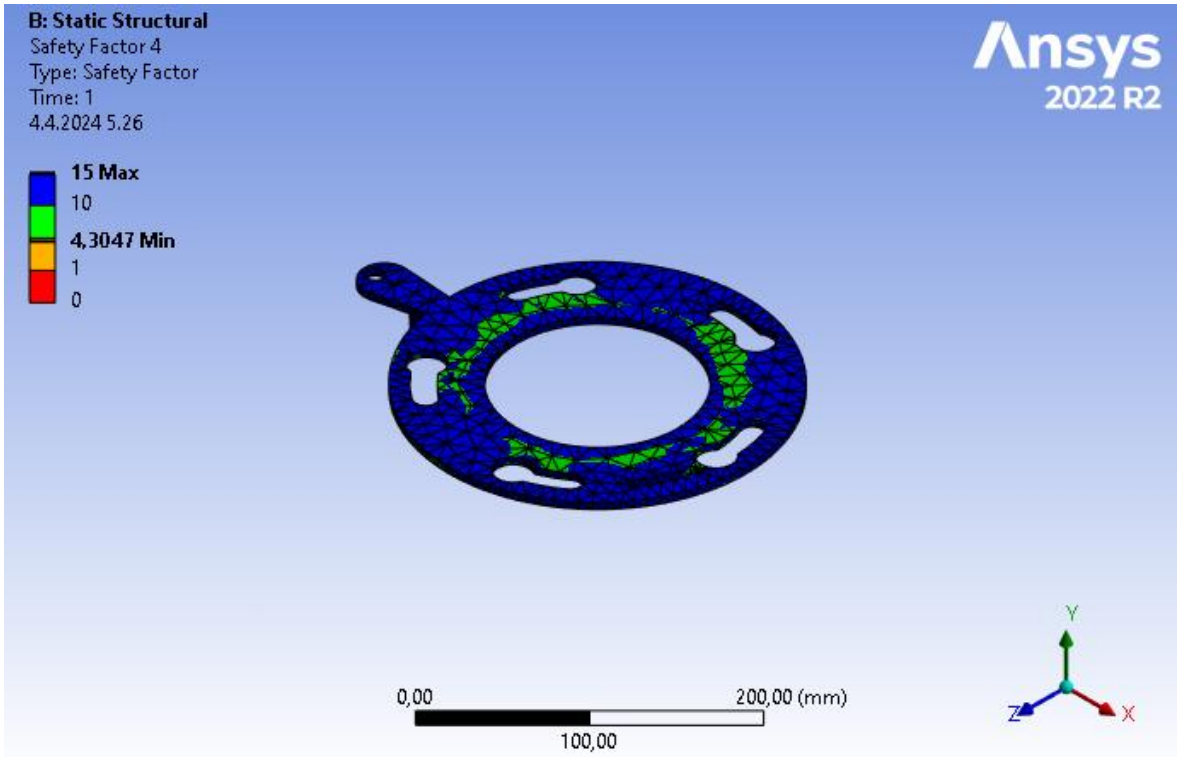

Figure 36. Safety factor analysis results of part 3.

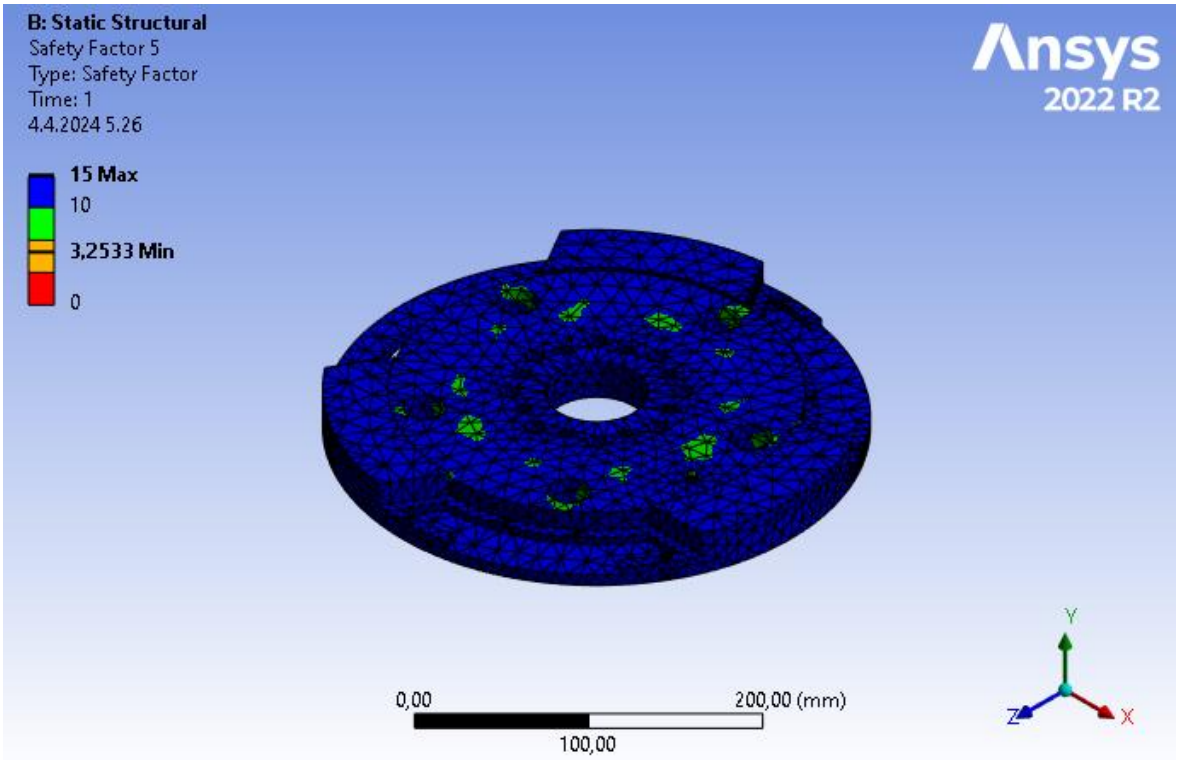

Figure 37. Safety factor analysis results of part 4.

Of the 4 parts, part 1 has the smallest safety factor. If the quick changer fails or is subjected to unexpected loads, part 1 will be the first to fracture and cause the quick changer to disintegrate.

4.2 Advantages and disadvantages of the designed quick changer

Titanium diboride (TiB2) is a hexagonally structured ceramic compound. Due to its crystal structure and atomic bonding, titanium diboride films have good mechanical and tribological properties, as well as excellent chemical and thermal stability (Munro, 2000). The titanium diboride film on the surface of the quick changer protects the device from erosion, corrosion, wear, oxidation. In addition, it also allows the device to function properly at high temperatures.

As a high hardness protective coating, titanium diboride provides better wear resistance under high contact pressure conditions and reduces the wear of the parts (Panich and Sun, 2005). The quick changer I designed is a rotating plate structure where part 3 is in contact with parts 1, 2, and 4. This causes part 3 to frequently friction with these three parts against

each other during the use of the quick changer. So, using titanium diboride as a protective coating will extend the life of the parts.

Neutron and gamma radiation are present in tokamak devices, and materials exposed to high-energy neutron bombardment may lead to degradation (Koyanagi et al., 2019). In addition, metallic materials exposed to neutrons become radioactive. This is caused by the activation of metallic materials by neutrons and the appearance of radioactive substances. Metal borides prevent this activation because boron absorbs neutrons, and titanium diboride can shield against neutrons and gamma radiation (Oh et al., 2021; Ko et al., 2022). Protected by the titanium diboride coating, the quick-change device will not fail due to neutron and gamma radiation inside the tokamak. This allows the quick-change device to be maintained with heavy manipulators deep inside the tokamak device.

The quick-change device I designed is wear, corrosion, and radiation resistant, but it also has some disadvantages. By analysing the data, we can know that the average von Mises stress of part 2 is 31.25 MPa, and that of part 3 is 30.054 MPa, while the average von Mises stress of part 4 is only 16.662 MPa. This indicates that the stresses on parts 2 and 3 are much greater than those on part 4. Long-term use of parts 2 and 3 is most likely to lead to metal fatigue, which also reduces the life of the quick changer. In addition, the largest stress is on part 1, which is 186.79 MPa. All these show that the structure of the quick changer designed by me is still not reasonable enough.

5 Discussion

In this section, the contents of the researched quick changer are summarized. Recommendations are also made on aspects of the quick changer that could be improved in the future based on the analyzed advantages and disadvantages.

5.1 Summary of the designed quick changer

In order to meet the maintenance needs of a nuclear fusion reactor, I designed and drew engineering drawings of a new quick-change device using SolidWorks. Then, using SolidWorks CAM, I gave the basic process of manufacturing it with a CNC machine. A titanium diboride film was added to the surface of the quick changer using magnetron sputtering to prevent the quick changer from being damaged by the radiation environment inside the tokamak device.

Additionally, I performed a static analysis of the quick changer using ANSYS to check the stability of the device structure under load conditions. Allowing a sufficient safety factor for the device ensures that the quick changer has additional load capacity under the expected load of 25,000N. It also prevents structural damage or failure due to some unforeseen conditions.

5.2 Directions for future improvements

The main thing is that the locking structure can be improved, this is because the stresses on parts 1, 2, 3 and 4 are not evenly distributed. The average maximum stress is part 2, then part 3. The maximum stress point is on part 1, while part 4 has the minimum stress in the whole structure, and there is a large gap with parts 1, 2 and 3. Therefore, another locking mechanism can be added to the center and outer edge of parts 1 and 4. In the case of locking, it is not only possible to connect the part 1 to the part 3, but it is also possible to have the parts 1 and 4 directly connected.

In addition, mechanism 4 is the key and weak place of the whole locking structure. However, the mechanism 4 has only 5 places, which is also a place for improvement. It can

be increased to 7 or more to reduce the maximum stress on part 1. Also, these two structural improvements will allow the stresses to be distributed more evenly on each part.

The choice of material for the quick changer can also be improved by using better materials to give the quick changer further performance. For example, the use of titanium diboride particulate reinforced AA7075 aluminium alloy as the material for the quick changer. This is a type of aluminium matrix composites (AMCs). It can be manufactured by compocasting, melt stirring casting, powder metallurgy, in situ casting, and squeeze casting. It improves the integral properties of the material by uniformly distributing titanium diboride particles in the AA7075 aluminium alloy matrix. This not only improves the mechanical properties, wear resistance and durability of the material, but also enhances its potential for use under extreme conditions such as high temperatures and high loads (Mohanavel et al., 2021; Michael Rajan et al., 2013).

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