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Welding Study for Vacuum Vessel of Compass-Upgrade Fusion Reactor (OBSOLETE)

[redacted]

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1 INTRODUCTION

The COMPASS-UPGRADE fusion reactor project puts very high and complex requirements on its individual parts and sub-systems. In particular, the vacuum vessel is one of the most critical components with very difficult operating conditions (elevated working temperature, high mechanical and electromagnetic loading) and thus with very high requirements on material properties and integrity, but also with very stringent dimensional tolerances. For these reasons it is also of key importance to pay high attention to the proper choice and evaluation of the intended manufacturing procedures.

The vacuum vessel (VV) is a very complex welded assembly, see the general view of its suggested design in Figure 1.1. (It has to be understood that this depiction serves for illustrative purpose only, because during elaboration of the welding study, partial design modifications were still ongoing or under consideration.) One of the key goals of this document is thus to suggest a vital idea of the general manufacturing process of the vessel, where very significant efforts will be spent with proposal of the welding assembly process and its parameters to very high level of detail to help the future manufacturer to understand all the aspects and critical areas of manufacturability.

The use of welding processes is in practice inevitably associated with occurrence of welding induced distortions. These are in the case of the vacuum vessel understood as very problematic factor for meeting the required dimensional tolerances. Therefore, a very important part of this study is dedicated to prediction of the distortions corresponding to the specific welding process proposal. These predictions will be done based on techniques of numerical simulation, more exactly transient thermo-mechanical analysis of the welding process, using the finite element method based software SYSWELD. Results of the simulations will be applied for suggestion of suitable compensation steps and counter measures in order to keep the distortions under control and thus guarantee the practical feasibility of the entire manufacturing process and to reach the required dimensional tolerances.

The purpose of this study can be summarized as a proposal and analysis of welding technology for future manufacturer, to be able to assess the critical points of the manufacturing process. At the same time, it must be emphasized that the study was prepared based on specified inputs existing in certain stage of design phase and thus for the future real manufacturing phase the final material parameters and later implemented design and process changes should be considered and analysed carefully.

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Figure 1.1 – View of the vacuum vessel assembly

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In this context, the name "Inconel 625" shall be understood as any alloy with chemical composition according DIN 17744/17750, UNS N06625/UNS N26625 or ASTM B443. The reason for giving the name is that this is a commonly used industry habit. Irrespective of the trade name of the alloy, manufacturer or registered trademark etc., the Contracting Authority/Buyer (Institute of Plasma Physics of the CAS) requires to use alloy with specific chemical composition, see Technical Specification, section 4.1.2.

2 DEFINITION OF THE SUITABLE MANUFACTURING PROCEDURE FOR WELDING OF THE VACUUM VESSEL

2.1 Selection of the suitable input material grade and formats

The material grade selected for manufacturing of the vacuum vessel is Ni-Cr-Mo alloy INCONEL 625. This material provides excellent corrosion resistance and very high mechanical strength in wide range of temperatures up to the level of around 700°C. For welding of this material grade, welding wires or electrodes on Ni-Cr-Mo basis should be selected, which will ensure the weld metal to be homogenous with the base material.

2.1.1 Proposal of type and format of individual parts of the vacuum vessel

The main body of the vacuum vessel (toroidal shell) is expected to be assembled from several main components, see also Figure 2.1. In the corner areas on internal radius two forged rings are considered. The other components of the main body (referred as inner cylindrical shell, outer cylindrical shell, cones an annuluses) shell be made of sheet metal, typically by cutting and in some cases followed by bending or rolling.

The components of ports situated on perimeter of the outer cylindrical shell will be prepared from sheet metal of suitable thickness by cutting (in case of flanges) or by cutting followed by bending (in case of port shells). Analogically, components of the tubular ports fitting to cones and annuluses will be prepared by cutting from sheet metal (flanges) and by cutting from pipes (port shells). The different types of adapters, which are to be welded on inner wall of the vessel, will be manufactured by cutting and milling from sheet metal.

For many of the above mentioned components, there is considered application of material allowance added to the nominal CAD dimensions (this can mean, for instance, increasing the initial thickness of the given component). The allowance generally enables to compensate the welding induced distortions in the phase of final machining of the subassemblies or assemblies. The specific values of suggested allowance magnitude are typically mentioned in appropriate areas throughout the section 2.2, where detailed description of the entire manufacturing process is given. A comprehensive summary of the material suggested allowance values is also given in the chapter 4.

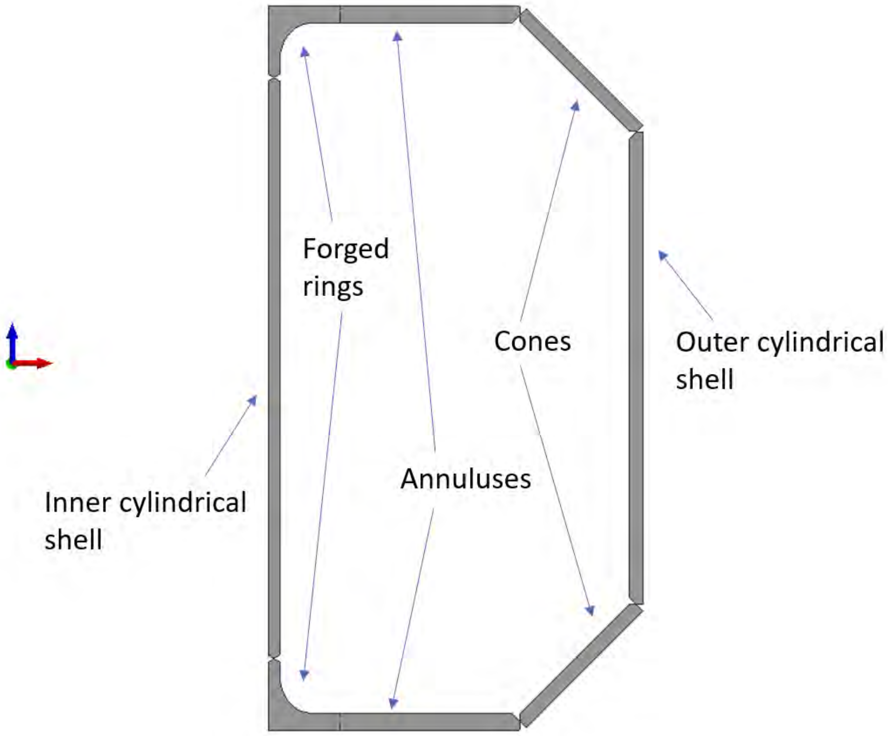

Figure 2.1 – Section cut of the main shell of VV, brake-down to individual components

With respect to high number of relevant load cases of the VV and quantity of penetrations of the main shell of the vessel (in locations of different ports) and thus interruptions of the material, it is very difficult to clearly define the optimal rolling direction (or orientation of the individual parts versus the rolling direction of the input sheet metal).

Regarding possible reduction of the welding induced distortions, it is suitable to apply the minimum possible number of weld joints, which in case of manufacturing components like cones, inner and outer cylindrical shell etc., means to reduce to maximum extent the circumferential splitting of the material into multiple subcomponents. Also in terms of welding and the induced distortions, it is generally more suitable to orient the rolling direction horizontally (in circumferential direction of the vessel), which means that the direction of welds connecting the subcomponents will be perpendicular to the rolling direction. At the same time, it is most suitable to choose the orientation of the parts with respect to the rolling direction and also with respect to the prevailing stress and loading directions of the VV. As well for these reasons we find as optimal to align the rolling direction with horizontal (circumferential) direction, where we assume the dominant modes of loading will be in the direction of plasma flow, i.e. again along the VV circumference. The specific suggestions of the orientation of individual parts with respect to the direction of sheet metal rolling is again given below in section 2.2.

2.1.2 Reference values of mechanical properties

As part of the elaboration of the welding study, attention was also paid to the determination or estimation of material properties of the VV and its individual parts. This was done by researching of relevant literature and also in the form of preliminary market consultations with material producers and potential material suppliers.

Regarding components made of rolled sheets, we consider as a relevant source the material certificate of Arcelor, see annex 1. It is the case for hot-rolled and subsequently annealed sheets with a thickness of 20 mm. The document gives the mechanical properties of the final product (sheet) at the room temperature and at elevated temperature of 450°C. For the room temperature, the results of 3 tensile tests of samples taken in different areas of the sheet are given. The average values are as follows:

Yield strength … $R_{p0,2}$ = 488 MPa,

Tensile strength … R_m = 912 MPa,

Elongation … A = 55 %.

In case of temperature of 450°C, the results of only one tensile test are given, with the following values:

Yield strength … $R_{p0,2}$ = 373 MPa,

Tensile strength … R_m = 801 MPa,

Elongation … A = 51 %.

The above given values are also in relatively good agreement with the material specification of the Special Metals company, which presents the data reproduced in the graph in Figure 2.2 as typical values for hot-rolled and annealed sheets. Thus, for the room temperature, we can read from the graph approximately the following values:

Yield strength … $R_{p0,2}$ = 425 MPa,

Tensile strength … R_m = 950 MPa,

Elongation … A = 50 %.

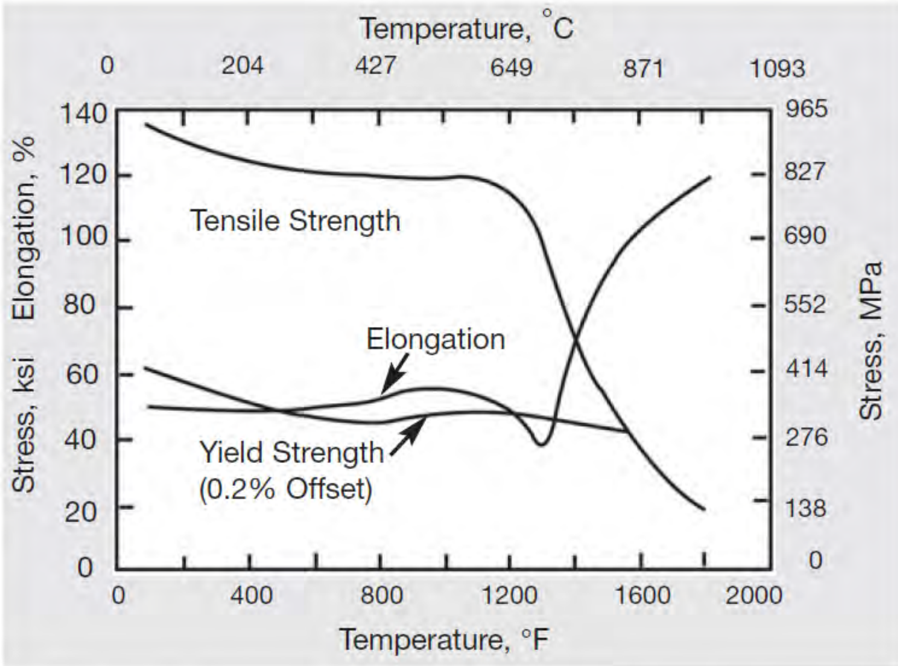

Figure 4. High-temperature tensile properties of cold-rolled annealed sheet.

Figure 2.2 – Values of $R_{p0,2}$, R_m, A versus temperature based on Special Metals document (typical data for hot rolled and annealed sheets)

Regarding the use of forgings, it was unfortunately not possible to obtain any specific information or guarantees on the level of mechanical properties from potential suppliers during the interim pre-trade consultations. Such information is normally provided in the form of a material certificate only within the scope of delivery of a specific forging. We however do not see any reasons, why the mechanical properties of such a forging should be at a substantially lower level than those mentioned above for rolled sheets.

Regarding the properties of the weld metal or area of weld joints, here we can refer to the Böhler inspection certificate, see annex 2. This document lists the mechanical properties of the Inconel 625-based weld metal at room temperature as follows:

Yield strength … $R_{p0,2}$ ≥ 460 MPa,

Tensile strength … R_m ≥ 740 MPa,

Elongation … A ≥ 30 %.

In this context, the name "Inconel 625" shall be understood as any alloy with chemical composition according DIN 17744/17750, UNS N06625/UNS N26625 or ASTM B443. The reason for giving the name is that this is a commonly used industry habit. Irrespective of the trade name of the alloy, manufacturer or registered trademark etc., the Contracting Authority/Buyer (Institute of Plasma Physics of the CAS) requires to use alloy with specific chemical composition, see Technical Specification, section 4.1.2.

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Here we should realize that these data are declared as the minimum guaranteed values, hence typical values should be higher.

Another source that can be mentioned is again the material specification of Special Metals. In the graph reproduced in Figure 2.3 the variation of mechanical properties with temperature is shown, this time for the case of samples oriented transversely through a welded joint. For room temperature we can read approximately the following values:

Yield strength … $R_{p0,2}$ = 470 MPa,

Tensile strength … R_m = 848 MPa,

Elongation … A = 37 %.

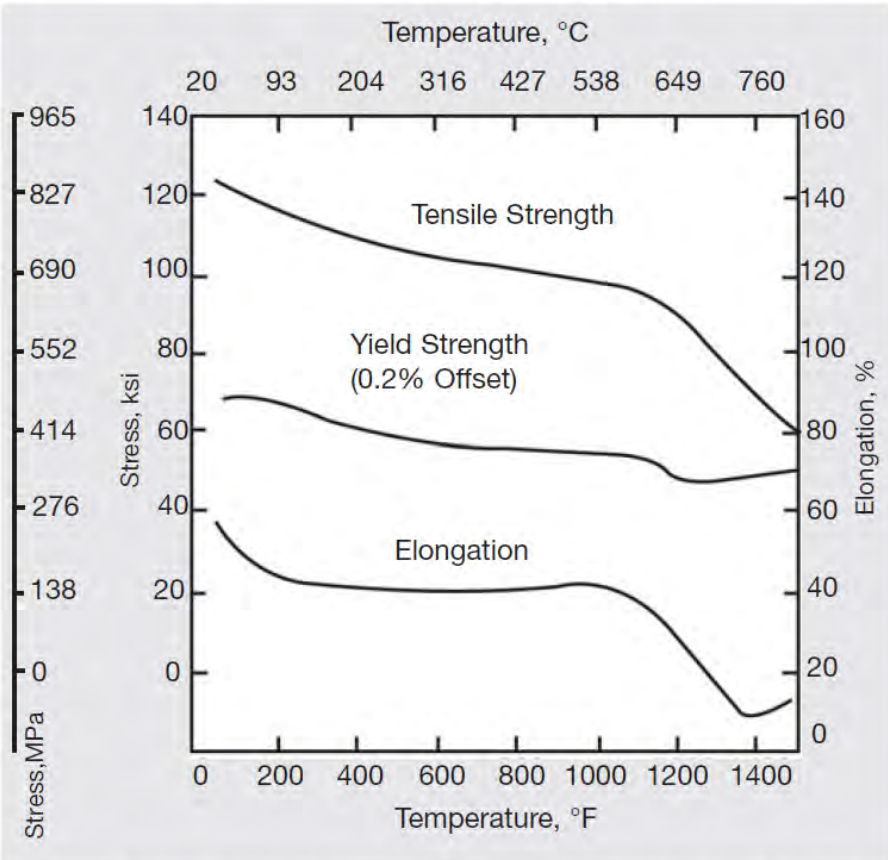

Figure 19. High-temperature tensile properties of transverse specimens of INCONEL alloy 625 welds (½-in. solution-treated plate; gas-tungsten-arc process with INCONEL Filler Metal 625).

Figure 2.3 – Values of $R_{p0,2}$, R_m, A versus temperature based on Special Metals document (transversal samples from weld joints)

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2.2 Proposal of manufacturing and welding procedure of the vacuum vessel

The aim of this part of the document is to present a proposal of the procedure of manufacturing and welding assembly of the vacuum vessel of the fusion reactor COMPASS-UPGRADE. There are described individual basic components and their expected preparation from raw material products. There is suggested the procedure of assembling the basic components into lower assemblies and further into higher level assemblies, till the completion of the full vessel assembly. There are also specified the considered welding technologies, including proposals for the geometry of weld bevels and welding parameters.

The entire assembly procedure of the VV is very complex process having large number of successive operation (which will be discussed in detail in this sub-chapter). The main concept is based on splitting of production procedure into building of two main sub-assemblies, as schematically illustrated Figure 2.4, i.e. the so-called inner and outer subassemblies. (The figure is strongly simplified as it shows only parts of the main shell, but in reality also the other substructures such as various adapters, ports, etc. will be included.) Hence the inner sub-assembly will consist of the outer cylindrical shell and forged rings, on which also all adapters located on the inner surfaces of these components of the main shell will be further welded. The outer sub-assembly will consist primarily of the outer cylindrical shell and both cones and annuluses, but again it will be consequently completed with all types of ports and adapters. All welds on these main sub-assemblies are assumed to be performed using conventional fusion welding technology, more specifically MIG method, in order to keep manufacturing costs at low level and at the same time to reach high productivity. The following final assembly of the entire VV will therefore consist in the fit-up of both the main sub-assemblies and performing of the last two welding operations at the interfaces of forged rings and annuluses. Exclusively for this welding operation, there is assumed the use of electron beam welding (EBW) technology, which during this critical point of the manufacturing process should already cause only very limited deformation increment.

Much more detailed description of the individual phases of the entire manufacturing process is given in the following sub-sections.

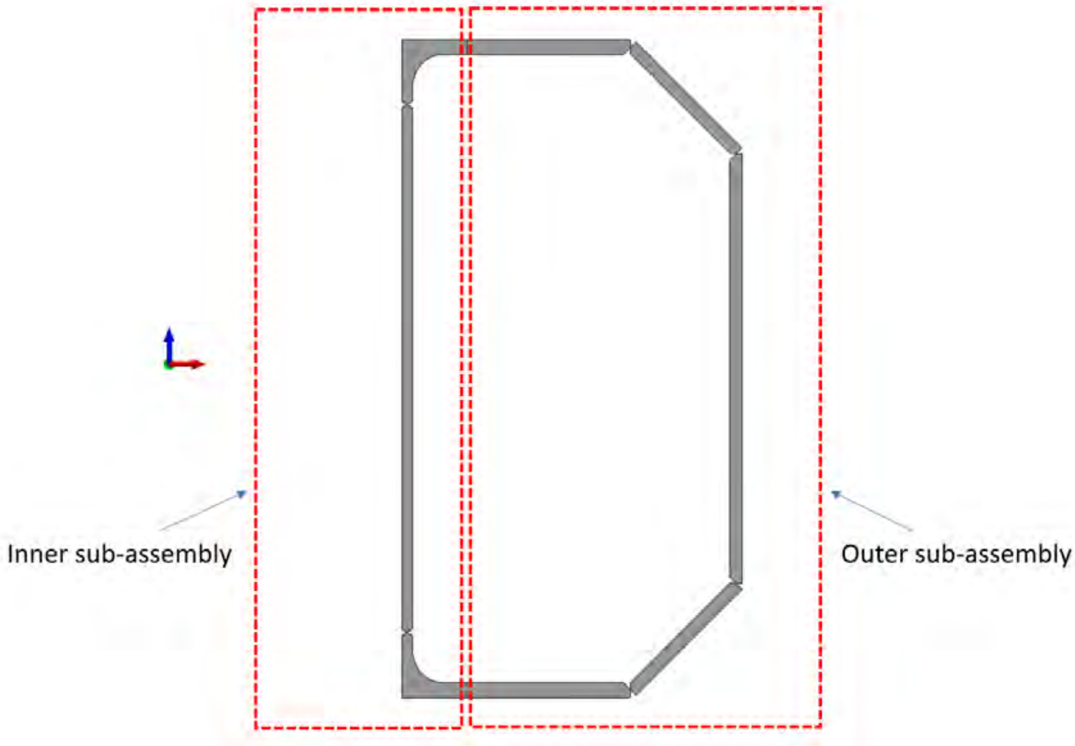

Figure 2.4 – Subdivision into inner and outer sub-assemblies shown in section-cut through the main shell of the VV

2.2.1 Preparation of individual parts and basic sub-assemblies

Description of the individual parts composing the main shell of the vacuum vessel has already been given in section 2.1.1. The main shell will be further equipped on the outer surface with various types of ports (gateways) and on the inner surface with different types of adapters for fixing the necessary equipment inside the VV. This section describes the preparation of individual parts or their joining into lower sub-assemblies, such that they can then be used for building of the two main sub-assemblies.

Inner cylindrical shell

For the inner cylindrical shell, see Figure 2.5, it is assumed that it's manufacturing will be done from only one piece of sheet metal, so with only one connecting weld at the ends of the sheet metal after roll bending. A sheet metal with a thickness of 23 mm, i.e. with nominal thickness according to the CAD design of the VV (no manufacturing allowance to thickness), is considered as the input material. The position of the cut blank on the supplied sheet will be chosen in such a way that the future circumferential direction of the shell will lie in the rolling direction. The dimension of the blank sheet has to be incremented by specified material allowance (see chapter 3 for details).

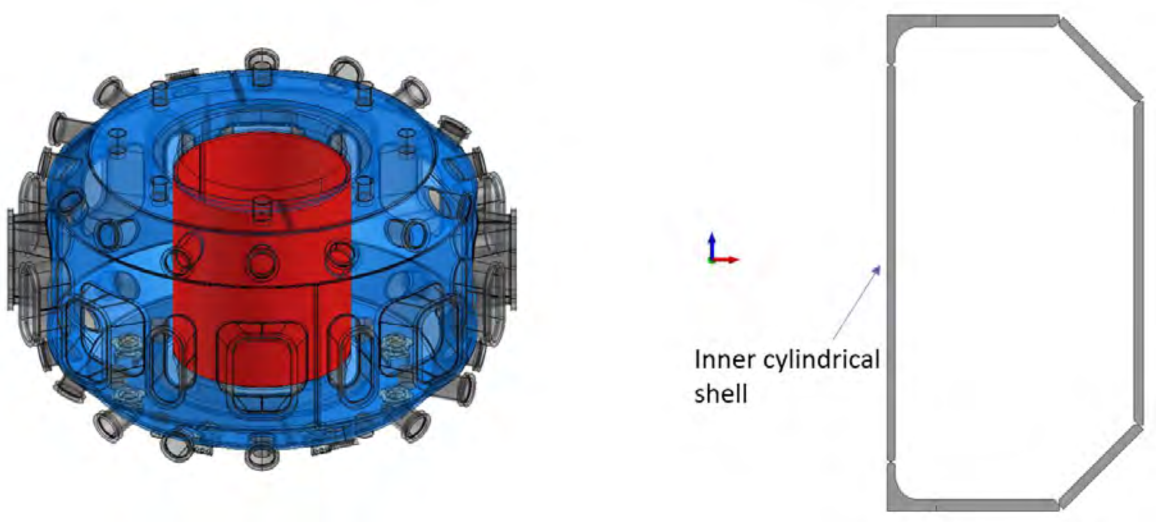

Figure 2.5 – The inner cylindrical shell within the VV assembly

Then preparation of welded bevels will be done on the flat blank sheet. These will be of two types:

Firstly, the weld bevel for connecting the inner cylindrical shell edges after roll bending (Figure 2.6) will be of X-shape, bevel opening angle 60°, root gap size 2 mm, asymmetrical bevel with depth of 2/3 of the sheet thickness on the inner side (towards the inside of the vessel) and 1/3 of thickness on the outer side.

Second, the bevel for welding the inner cylindrical shell to the forged rings (Figure 2.7) will be again of X-shape, bevel opening angle 60° and root gap size 2 mm, but of symmetrical shape (identical bevel depth on both sides).

Subsequently, the sheet will be rolled, the edges afterward fitted to declared root gap (2 mm), tack-welded and afterwards welded. The welding method will be MIG, the expected total number of welding passes to complete the weld is 12 (including the expected weld overlay height of about 2 to 3 mm). The expected layout of the individual weld passes inside the asymmetrical bevel is according to Figure 2.6. The proposed welding parameters are given in Table 2.1. With respect to the design of the VV, this specific type of weld (asymmetrical X weld with a bevel depth ratio of 2/3 vs. 1/3) is proposed to cause the minimum possible deformation of the shell from ideal cylindrical shape. In case that significant deformations occur, the shape will be mechanically corrected (roll bending) to the required dimensions.

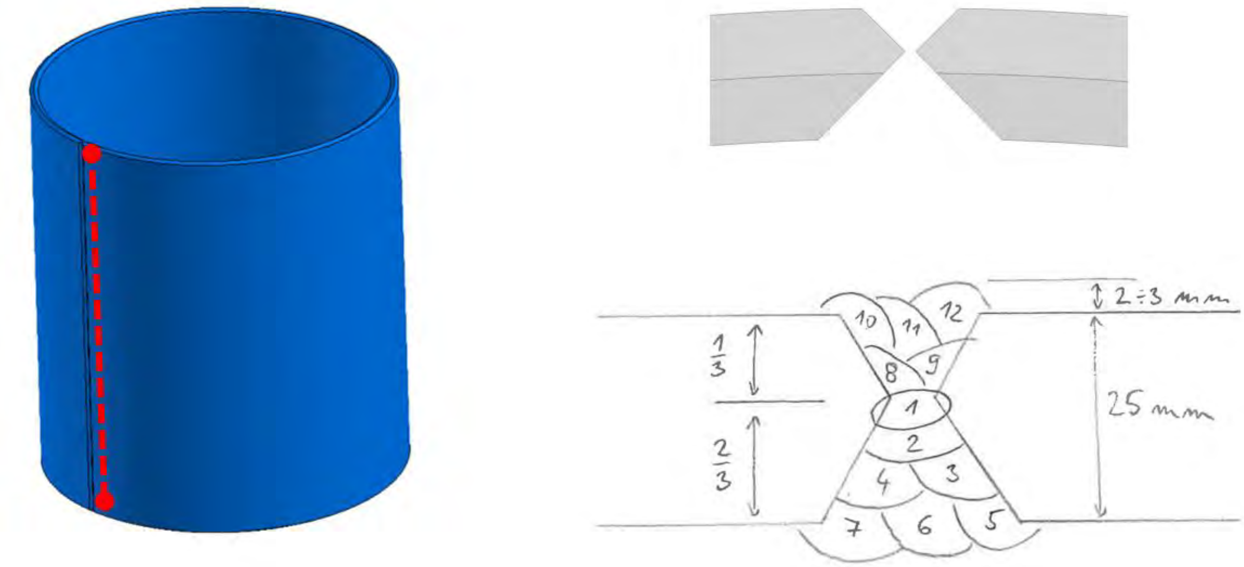

Figure 2.6 – The weld for connecting edges of the inner cylindrical shell after roll bending, the corresponding bevel shape and layout of weld passes

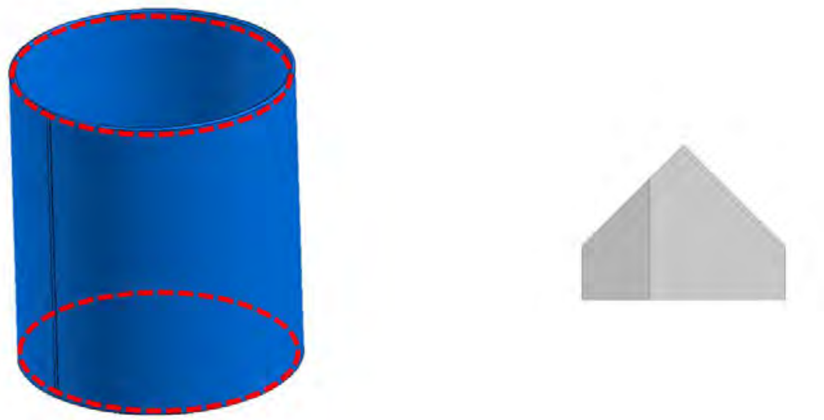

Figure 2.7 – The welds for connecting the inner cylindrical shell to forged rings and the bevel shape on the side of the cylindrical shell component

Table 2.1 – Suggested welding parameters for connecting weld of the inner cylindrical shell

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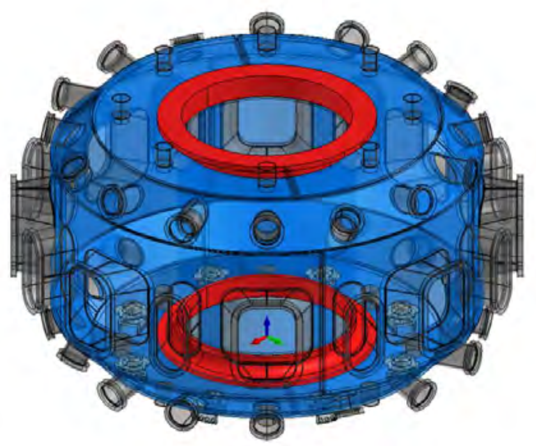
Forged rings

The forged rings (see Figure 2.8) shall be delivered in required dimension by the selected forging supplier. Compared to the CAD dimension of the vessel, certain modifications (material allowance) are required to be applied for the dimensions of the standalone component. This applies to the horizontal part of the ring (towards annuluses), where the wall thickness has to be increased and further also the length (radial dimension) of this part is to be increased (see chapter 3 for details). This is due to technological requirements and to enable compensation of manufacturing distortions expected during the further welding operations. On the other hand, no such precautions are required for the vertical part of the ring (towards the inner cylindrical shell), thus in here the CAD dimensions remain relevant.



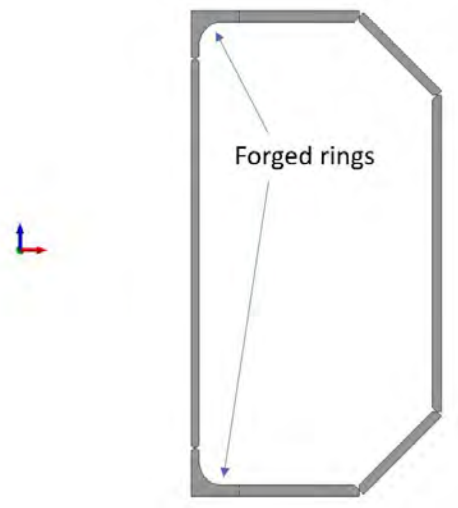


Figure 2.8 – The forged rings within the VV assembly

On the vertical part of the forging, edge preparation has to be performed (see Figure 2.9), it will be the same as on the side of the inner cylindrical shell itself, i.e. for circumferential weld which will be of symmetrical X-shape, bevel opening angle 60°.

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The horizontal part of the forging towards the annulus remains in this phase without any further treatment, this will be performed later, after welding the entire inner sub-assembly.

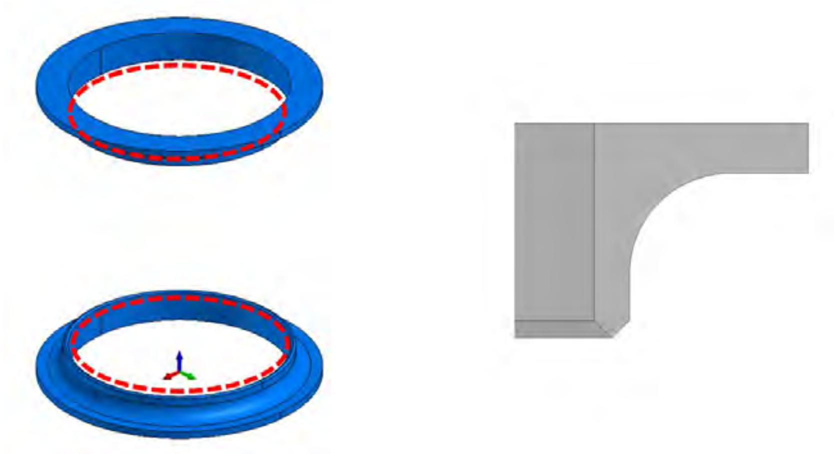

Figure 2.9 – The welds for connecting the forged rings to the inner cylindrical shell and the corresponding bevel shape

Annuluses and support column adapters

In case of the annulus components (see Figure 2.10), it is expected that they will be made of 2 pieces of blank sheet metal. These will be cut in the shape of the letter C with thickness of 35 mm (i.e. nominal according to CAD). The proposed orientation of the blank with respect to the rolling direction is shown in Figure 2.11. The blanks are originally prepared without holes for ports or adapters to maintain the highest possible stiffness of the parts. On the edge of future internal radius of the annulus, material allowance has to be left during cutting, (see chapter 3 for details).

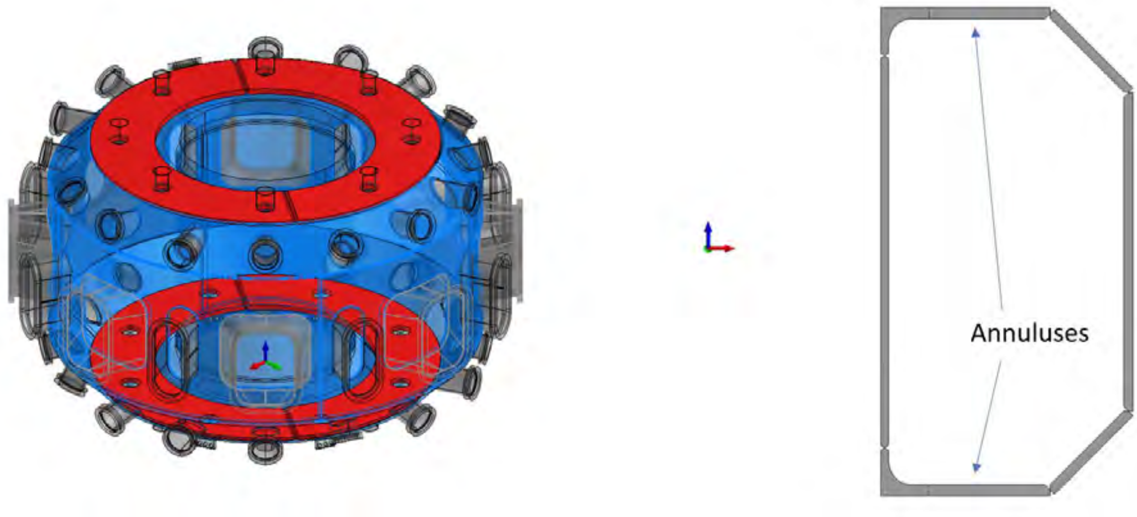

Figure 2.10 – The annuluses within the VV assembly

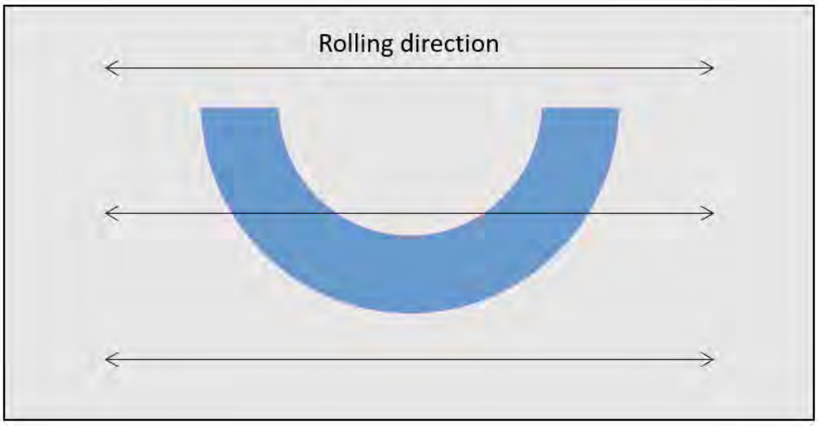

Figure 2.11 – Recommended orientation of the blank versus rolling direction of the sheet metal

The basic sub-assembly of the annulus will then be made by welding of these two parts of the sheets. Thus, firstly there will be done preparation of bevels on the interface edges for symmetrical weld of X-shape, bevel opening angle 60°, root gap size 2 mm (see Figure 2.12). Subsequently, both pieces will be welded. The expected number of weld passes to complete the joint is 16, with the assumed scheme of layout again according to Figure 2.12, the welding method is MIG and suggested welding parameters as per Table 2.2. In case that during this welding operation significant deformations would occur for the annulus sub-assembly, mechanical straightening shall be applied.

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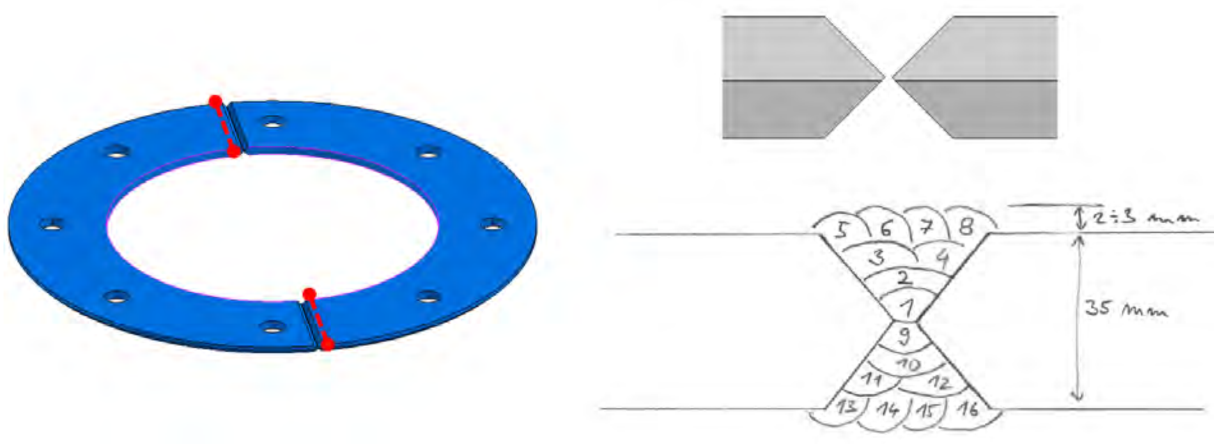

Figure 2.12 – The welds for connecting 2 parts of annulus, the corresponding bevel shape and layout of weld passes

Table 2.2 – Suggested welding parameters for connecting welds on annulus and for the 1/2 V weld of support column adapters

On the welded basic subassembly of annulus, there will be subsequently done bevel preparation on the edge to be latter connected to cone component. On the side of the annulus component, there will be cut the edge from internal side to 1/2 thickness and with the weld surface angle of 45°, see Figure 2.13. This together with a corresponding treatment on the edge of cone will result into preparation for a symmetric weld of X-shape (more details about the corresponding welding operation are given below in sub-section 2.2.3).

The edge of the annulus towards the forged rings remains in this phase without any further treatment, this will be performed later, after welding the entire outer sub-assembly of the VV.

For the basic sub-assembly of the upper annulus, the preparation phase is in this moment finished and the component is ready for installation within the outer sub-assembly.

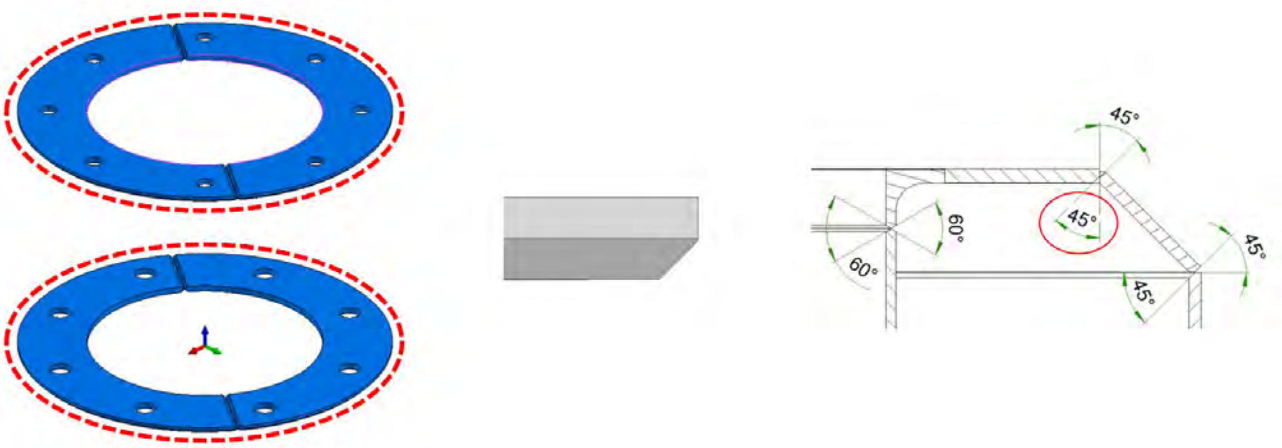

Figure 2.13 – Bevel preparation for the welds to cones

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In case of the lower annulus, however, the welding of adapters for support columns is to be done at the level of this basic sub-assembly, see also the situation in Figure 2.14. This is mainly due to the fact that the welds of these adapters are very massive, and there is therefore certain concern that significant deformations will occur during their welding (which will also be analysed by numerical simulation). The possibility of mechanical straightening is then significantly more realistic on the standalone basic sub-assembly of the annulus, than if this subassembly would have already been built into a higher assembly.

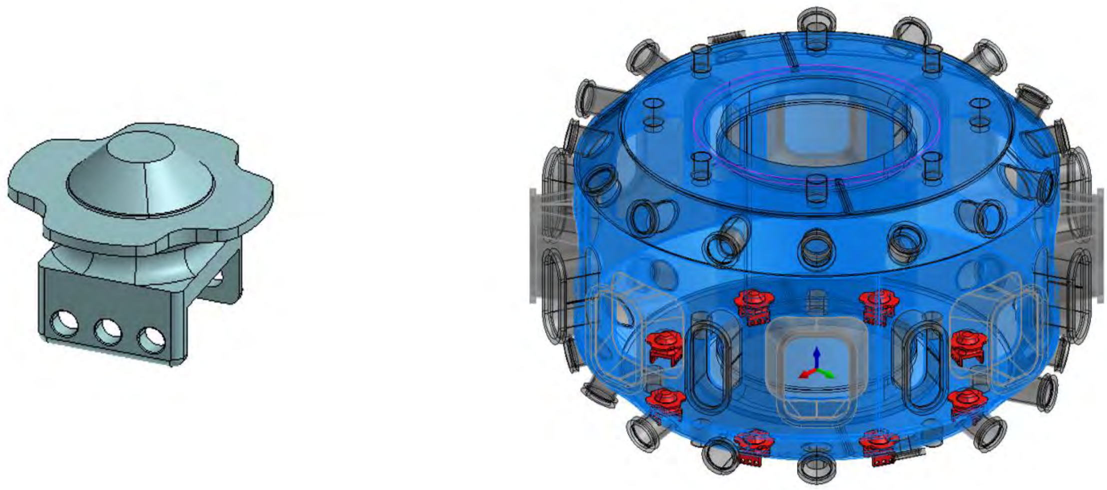

Figure 2.14 – The support column adapter and position of these adapters within the VV assembly

In terms of preparation of this welding operation, holes are first prepared in the annulus component with a diameter corresponding to the diameter of the adapter pin. Next, the bevel will be prepared on the adapter pin, see Figure 2.15, which is for weld of 1/2 V-shape, with bevel opening angle 45° and a depth of 33 mm (the remaining 2 mm will serve as a centring in the prepared hole in the annulus. After fit-up of the adapters and tack-welding the welding will be performed from inside into the 1/2 V bevel. The scheme of the assumed layout of weld passes is shown in Figure 2.16 (left), so there is expected to be deposited about 22 passes, the welding method is MIG and suggested welding parameters are again according to Table 2.2.

Then follows deposition of fillet weld from the outer side. In this case no bevel preparation is required, it is fillet weld of size a7, which is supposed to have 3 weld passes, with the assumed layout of weld passes as per Figure 2.16 (right). The suggested welding method is again MIG and proposed welding parameters for this weld are given in Table 2.3. As already mentioned, if there will occur any significant deformations of this basic sub-assembly after welding the adapters, they should be corrected by mechanical straightening.

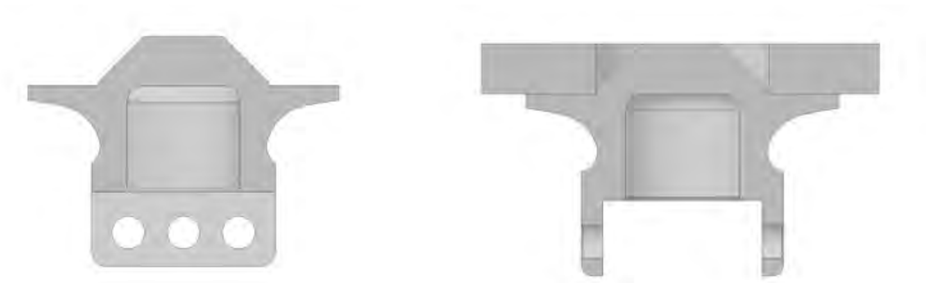

Figure 2.15 – Bevel preparation on the support adapter and fit-up with annulus

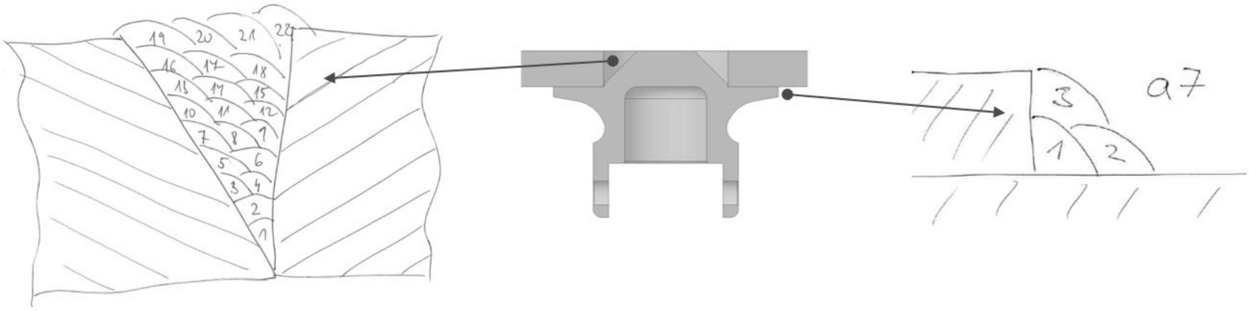

Figure 2.16 – The weld of support column adapter to annulus – inner side (left) and outer side (right), schematics of weld passes deposition layout

Table 2.3 – Suggested welding parameters for the a7 fillet weld of support column adapters

Cones

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The cones (see Figure 2.17) are expected to be made of 2 pieces of blank sheet metal. The blanks will be again cut in the shape of the letter C with the thickness of 30 mm (i.e. nominal according to CAD). The proposed orientation of the blanks with respect to the rolling direction is also similar as above in Figure 2.11. The blanks are originally prepared without any holes for ports to maintain the highest possible stiffness during manufacturing of these basic cone sub-assemblies and also during the later phase of manufacturing the main shell of the outer sub-assembly of the VV.

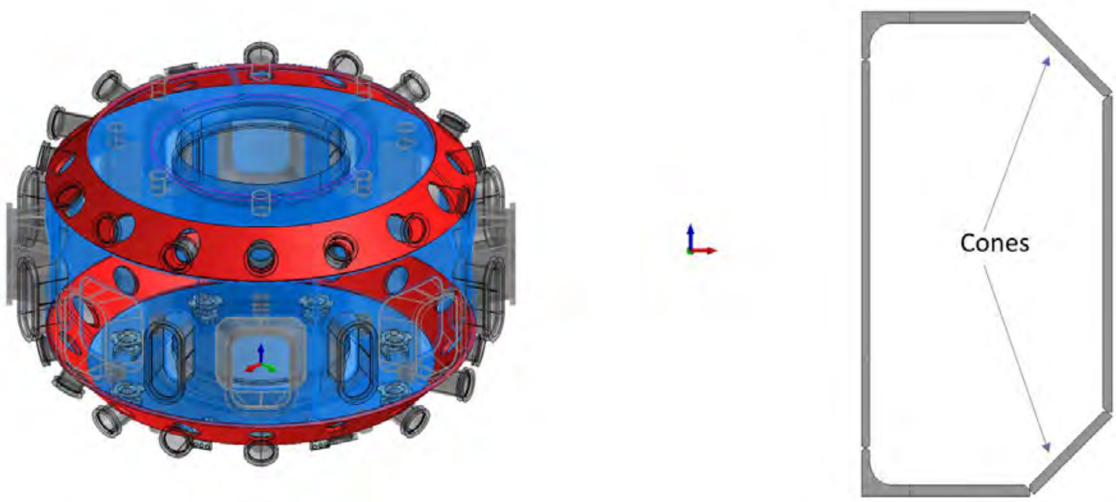

Figure 2.17 – The cones within the VV assembly

In the process of manufacturing the basic sub-assemblies of cones, bevels will first be prepared on one edge of the C sheets, where the first connecting weld of both parts will be made (in this phase the blanks are still kept in planar shape). It will be a symmetrical bevel for weld of X-shape (i.e. ratio of the bevel depth 1/2 - 1/2 from both sides), bevel opening angle 60°, root gap size 2 mm (see Figure 2.18). After fit-up of the two parts, this first connecting weld is deposited. The welding method will be MIG, expected number of passes is 14 and layout of individual passes again according to Figure 2.18. The suggested welding parameters are given in Table 2.4.

In the next step, the bevel for the second connecting weld will be prepared. This one is suggested as non-symmetric for weld of X-shape with ratio of bevel dept 2/3 from the outer side and 1/3 from the inner side, bevel opening angle 60°, root gap size 2 mm (see again Figure 2.18). Subsequently, the sheets are rolled into the conical shape and then this second connecting weld is made. Expected number of weld passes is 14 with layout of deposition according to Figure 2.18. The welding method is MIG and suggested welding parameters according to Table 2.4. The configuration of the second connecting weld is chosen to cause minimum possible deformation.

Nevertheless, in case that an unacceptable magnitude of deformation occurs, there shall be applied and additional rolling to correct the cone shape into desired tolerances.

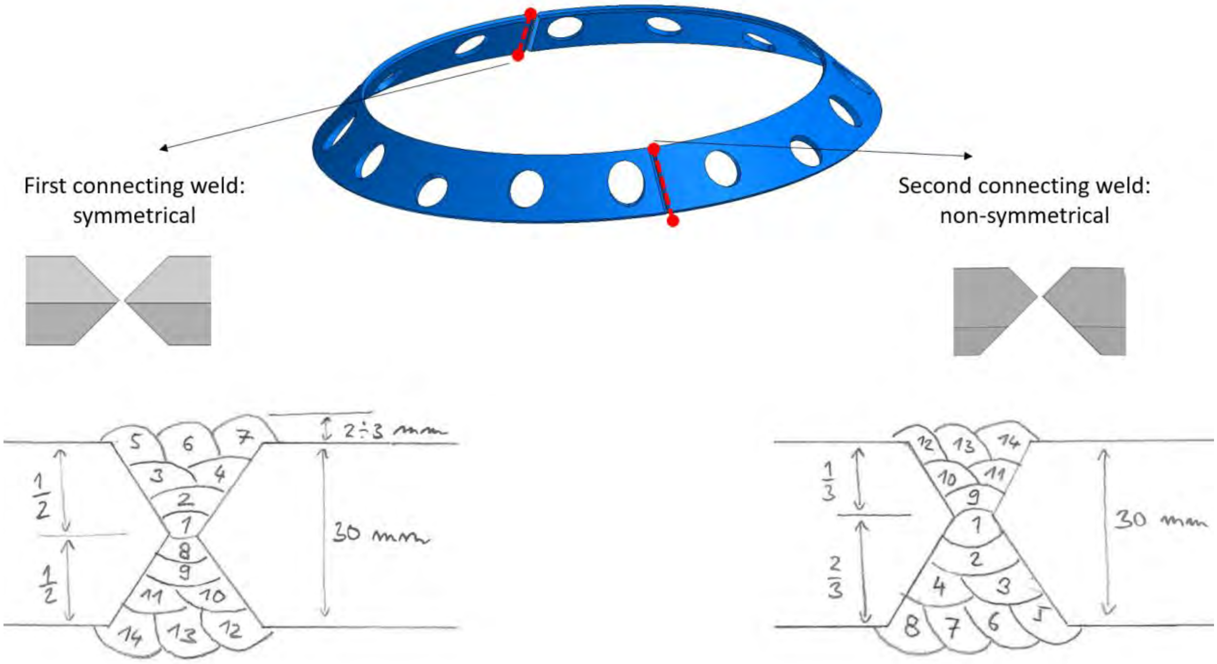

Figure 2.18 – Connecting welds on cone, the corresponding bevel shape and layout of weld passes

Table 2.4 – Suggested welding parameters for connecting welds on cones

Finally, the preparation of bevels on the welded basic sub-assemblies of cones needs to be done on the circumferential edges for the future welding with annuluses and with the outer cylindrical shell. In this case, both of the edges are to be cut from internal side to 1/2 thickness and with the weld surface angle of 45°, see Figure 2.19. This treatment of the edges on cones together with a corresponding preparation on the edges of annuluses and outer cylindrical shell will result into formation of bevels for symmetric welds of X-shape (more details about the corresponding welding operation are given below in sub-section 2.2.3).

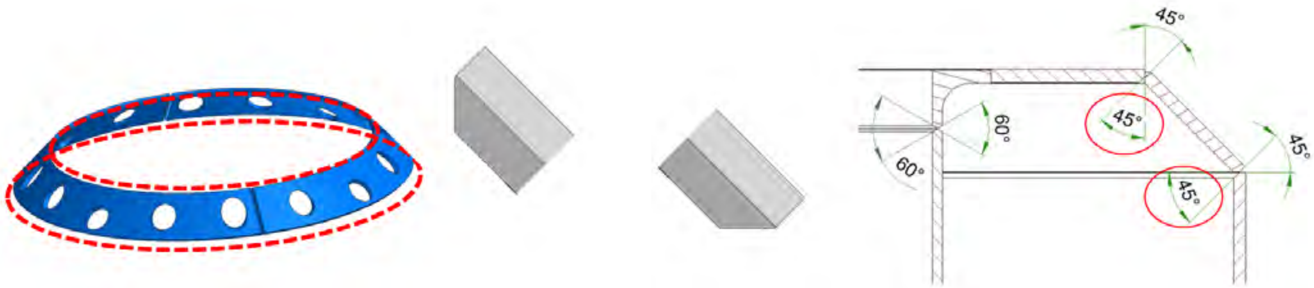

Figure 2.19 – Bevel preparation for the welds to annulus and to outer cylindrical shell

Outer cylindrical shell

The preparation of the outer cylindrical shell component (see Figure 2.20), is in principle very similar to the previously described case of cones. Due to its relatively large dimensions it has to be composed of 2 pieces of sheet metal blanks the dimensions, this basic subassembly will have to consist of two pieces with a thickness of 30 mm. The position of the blank on the supplied sheet metal will be chosen so that the future circumferential direction of the outer cylindrical shell component will lie in the rolling direction of the sheet. The blanks are initially cut without any holes for ports to maintain the highest possible stiffness during all the assembly operation preceding the installation of the ports.

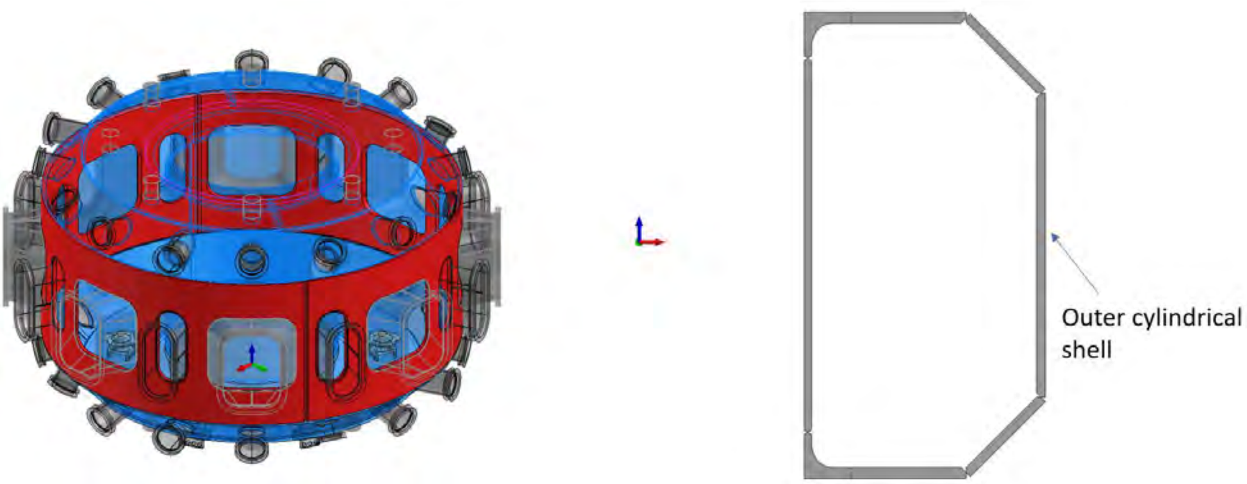

Figure 2.20 – The outer cylindrical shell within the VV assembly

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To create the basic subassembly of the outer cylindrical shell, there are firstly prepared bevels on one edge of the blanks, where the first connecting weld of both parts will be made. It will be a symmetrical bevel for weld of X-shape (i.e. ratio of the bevel depth 1/2 - 1/2 from both sides), bevel opening angle 60°, root gap size 2 mm (see Figure 2.21). After fit-up of the two parts, this first connecting weld is deposited. The welding method will be MIG, expected number of passes is 14 and layout of individual passes again according to see Figure 2.21. The suggested welding parameters are according to Table 2.5.

Next, bevel preparation for the second connecting weld will be done. It is suggested as non-symmetric for weld of X-shape with ratio of bevel dept 2/3 from the outer side and 1/3 from the inner side, bevel opening angle 60°, root gap size 2 mm (see again Figure 2.21). Subsequently, the sheets are rolled into cylindrical shape and then the second connecting weld is made. Expected number of weld passes is 14 with layout of deposition as per Figure 2.21 again. The welding method is MIG and suggested welding parameters according to Table 2.5. The configuration of the second connecting weld is chosen to cause minimum possible deformation. Nevertheless, in case that an unacceptable magnitude of deformation occurs, there shall be applied and additional rolling to correct the cylindrical shell shape into desired tolerances.

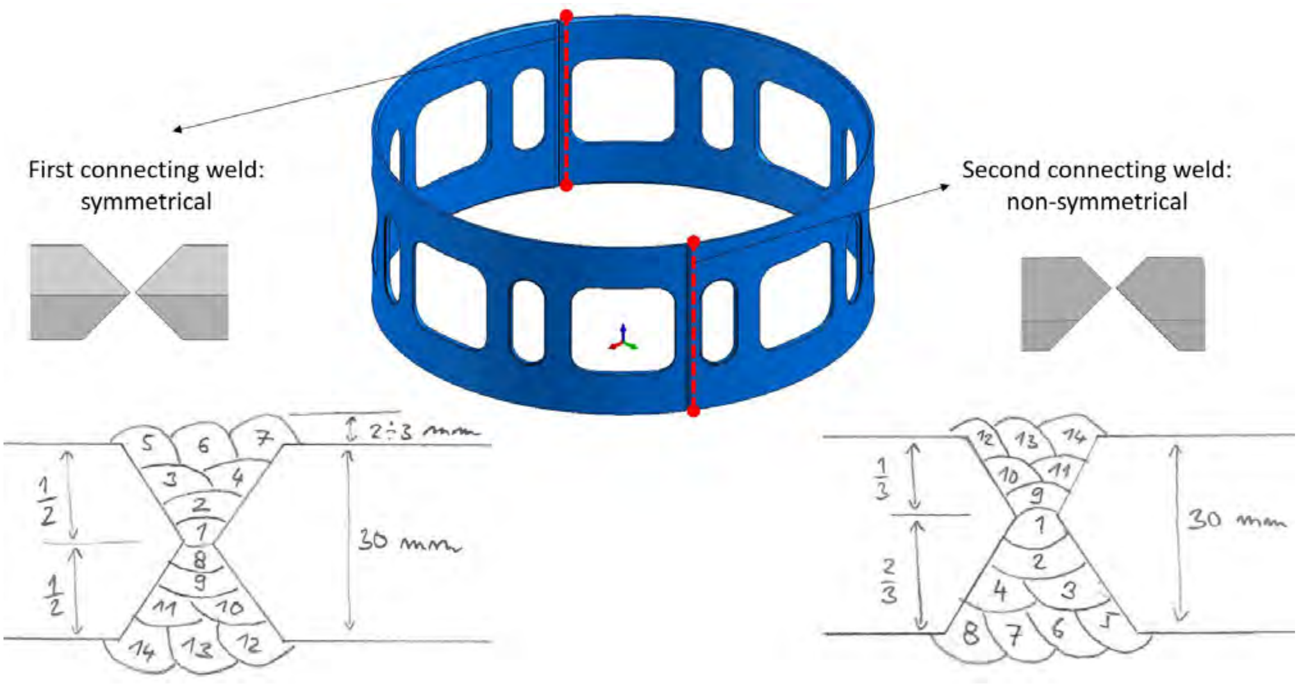

Figure 2.21 – Connecting welds of the outer cylindrical shell, the corresponding bevel shape and layout of weld passes

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Table 2.5 – Suggested welding parameters for connecting welds on the outer cylindrical shell

Finally, the preparation of bevels on the welded basic sub-assembly of the outer cylindrical shell has to be done on its circumferential edges for the future welding with cones. This is done by cutting the edges from internal side to 1/2 thickness and with the weld surface angle of 45°, see Figure 2.22. This treatment of edges of the outer cylindrical shell together with a corresponding one on the side of annuluses will result into preparation bevels for symmetric welds of X-shape (more details about the corresponding welding operation are given below in sub-section 2.2.3).

Figure 2.22 – Bevel preparation for the welds to cones

MX ports

The MX ports (see Figure 2.23) will be composed of a sheet metal shell and a flange.

The shell will consist of two bent sheets, which we assume to be manufactured with thickness of 8 mm (the nominal thickness according to CAD was 7 mm, but sheets of such thickness are not available on the market). We recommend choosing the orientation of the blanks on the supplied sheet metal so that the rolling direction will correspond to future circumferential direction of the port shell.

For preparation of the flange blanks prior to welding there is recommended application of material allowance of 10 mm on thickness and 5 mm on the outer contours (see also chapter 3).

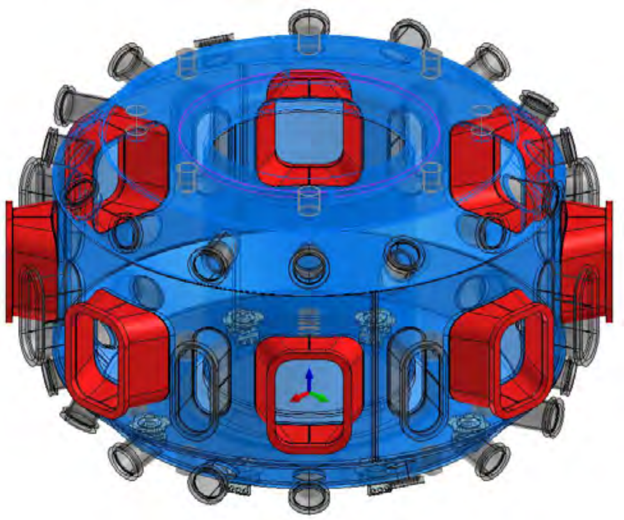

Figure 2.23 – The MX ports within the VV assembly

On the cut blanks of the shell there must be firstly done preparation of bevels of the connecting welds, see Figure 2.24. The bevel will be symmetrical for weld of X-shape, bevel opening angle 60°, root gap size 2 mm. After bending of the sheets, fit-up of the two parts of the shell and tack-welding the connecting welds will be deposited. The welding method will be MIG, expected number of passes is 4 (2 passes from the inner and 2 passes from the outer side). The suggested welding parameters are according to Table 2.6. In case the welding induced distortions of the shell occur, a mechanical correction will be needed at this point.

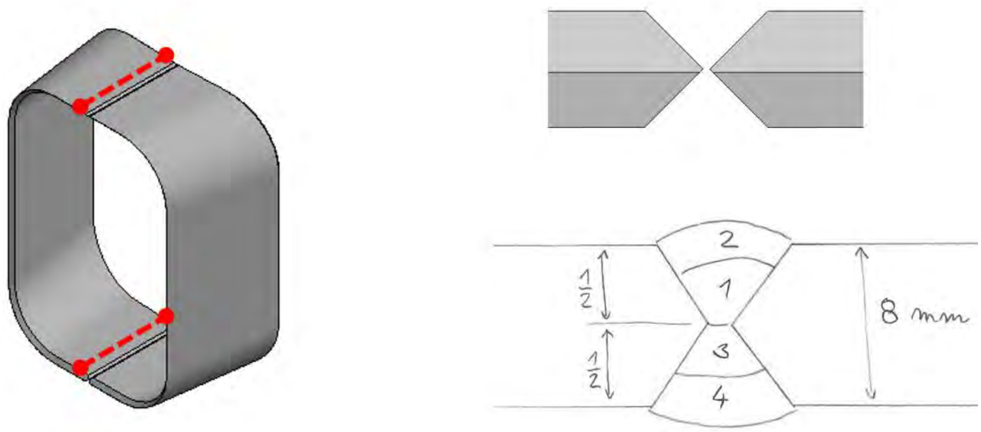

Figure 2.24 – Connecting welds of the MX port shell, the corresponding bevel shape and layout of weld passes

Table 2.6 – Suggested welding parameters for welding of MX ports

Next, the preparation of the bevels will be done on the edges of the port shell for the connection of the flange and also for the connection to the main wall of the vacuum vessel (see details in Figure 2.25).

On the flange side, it is a 1/2 V bevel with opening angle of 45° prepared on the inner side of the shell, root gap of 2 mm is considered.

On the side towards the main wall of VV the preparation for an asymmetrical weld will be done. On the outer side of the port shell a bevel with depth of 2/3 t and an opening angle of 45° will be done, so this results into preparation for a 1/2 V-shape weld from the outside of the port. On the inner side of the port shell the bevel with depth of 1/3 t and an opening angle of 30° will be done. But for this weld, preparation will have to be done in later manufacturing phase also on the VV wall itself. Firstly, a hole with corresponding dimensions has to be cut in the wall. In this case, the cutting surface through the VV wall will follow the direction of the inner surface of the port shell. Further, the outer edge of the hole will be cut, to create a bevel surface with depth of 1/3 of the port shell thickness and an opening angle of 30°. This results in preparation for a V-shape weld, with depth of 1/3 of the port shell thickness and total opening angle of 60° from the inside of the port. For joining of the port shell to the VV wall, root gap of 2 mm is considered.

Consequently, the joining of the port shell to the flange is performed. The weld is expected to have 2 passes with layout of deposition as per Figure 2.26. The welding method is MIG and suggested welding parameters are again according to Table 2.6.

Welding of these basic sub-assemblies of the MX ports to the vessel wall will then be done during the phase of the entire outer sub-assembly manufacturing. The corresponding weld joint is expected to have 3 passes with layout of deposition shown again in Figure 2.26. The welding method is MIG and welding parameters suggested in Table 2.6 remain applicable also for this weld.

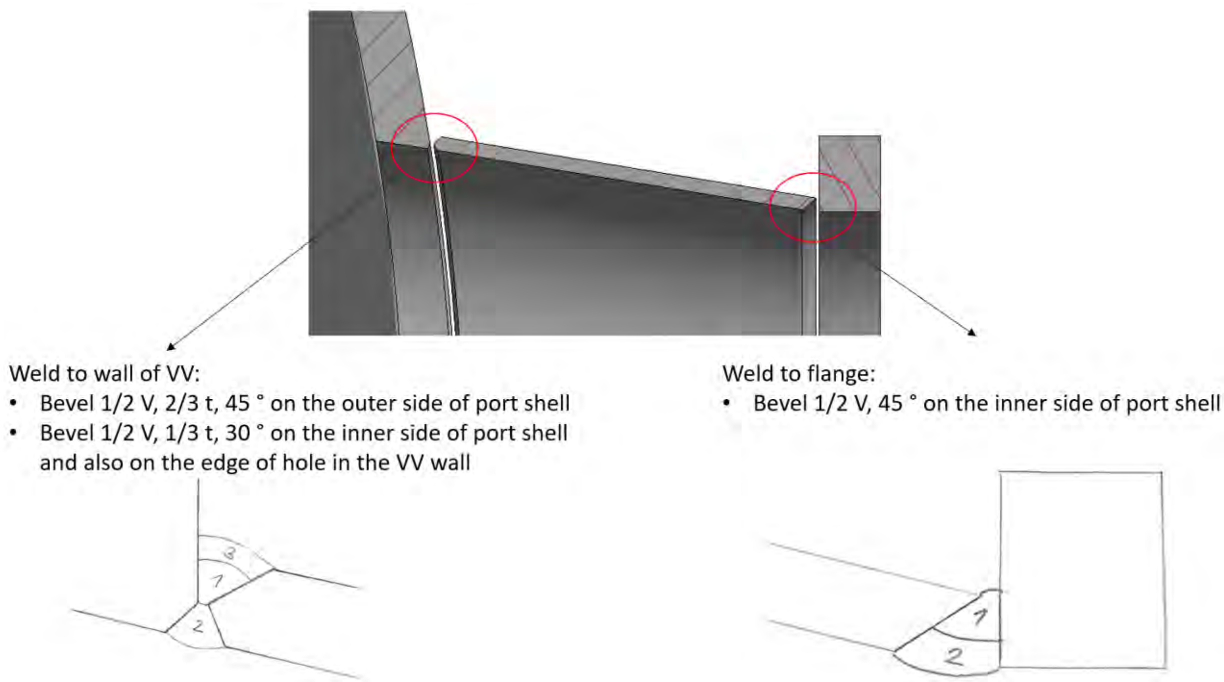

Figure 2.25 – Preparation of weld bevels and corresponding schematics of weld passes layout for joints of the MX port shell to its flange and to the VV wall

MN ports

The MN ports are built from an oval shell and a thick-walled flange (see Figure 2.26).

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The shell will be manufactured from one piece of sheet metal blank, which will be bent and connected by welding. For the reasons mentioned above in case of MX ports, the thickness of the shell is considered to be 8.

The flange blanks have to be cut including material allowances, which are 10 mm on thickness and 5 mm on the outer contours (see also chapter 3).

The bevel of the weld joint to connect the port shell (see Figure 2.27) will be prepared on the flat blank before bending. It is a symmetrical bevel for weld of X-shape, bevel opening angle 60°, root gap size 2 mm. After bending of the sheet, proper fit-up of the edges and tack-welding the connecting welds will be deposited. The welding method will be MIG, expected number of passes is 4 (2 passes from the inner and 2 passes from the outer side), the suggested welding parameters are according to Table 2.7. In case of need, the eventual welding induced distortions of the shell will be mechanically corrected at this stage.

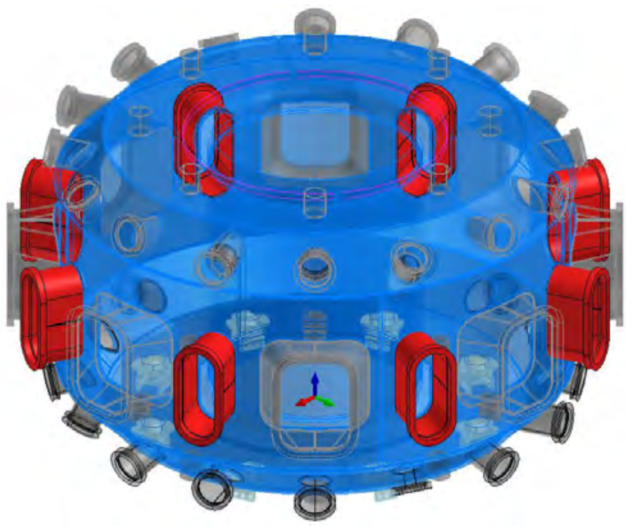

Figure 2.26 – The MN ports within the VV assembly

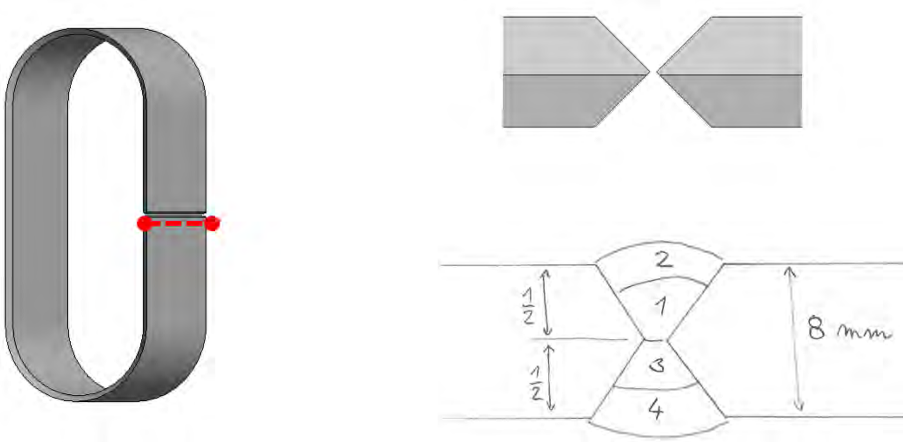

Figure 2.27 – Connecting weld of the MN port shell, the corresponding bevel shape and layout of weld passes

Table 2.7 – Suggested welding parameters for welding of MN ports

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There follows preparation of bevels on the edges of the port shell for the weld joints to the flange and to the wall of the vessel (see details in Figure 2.28).

On the flange side, it is a 1/2 V bevel with opening angle of 45° prepared on the inner side of the shell, root gap of 2 mm is considered.

On the side towards the main wall of VV there is again a 1/2 V bevel with opening angle of 45° on the inner side of the shell. But for this weld, the bevel preparation affects also the VV wall itself. Firstly, a hole with corresponding dimensions has to be cut in the wall. Further, a groove will be cut on the outer circumference of the hole with depth of 10 mm and edge cut under and angel of 45°. Like that, after the port will be fit-up with the wall there will be formed a 1/2 V bevel with an angle of 45° also on the outer side of the port shell (see again Figure 2.28). As well for joining of the port shell to the VV wall, root gap of 2 mm is considered.

Consequently, the joining of the port shell to the flange is performed. The weld is expected to have 2 passes with layout of deposition as per Figure 2.28. The welding method is MIG and suggested welding parameters are again according to Table 2.7.

Welding of the basic sub-assemblies of the MN ports to the vessel wall will be done during the phase of the entire outer sub-assembly manufacturing. The corresponding weld joint is expected to have 3 passes with layout of deposition shown again in Figure 2.28. The welding method is MIG and welding parameters suggested in Table 2.7 remain applicable also for this weld.

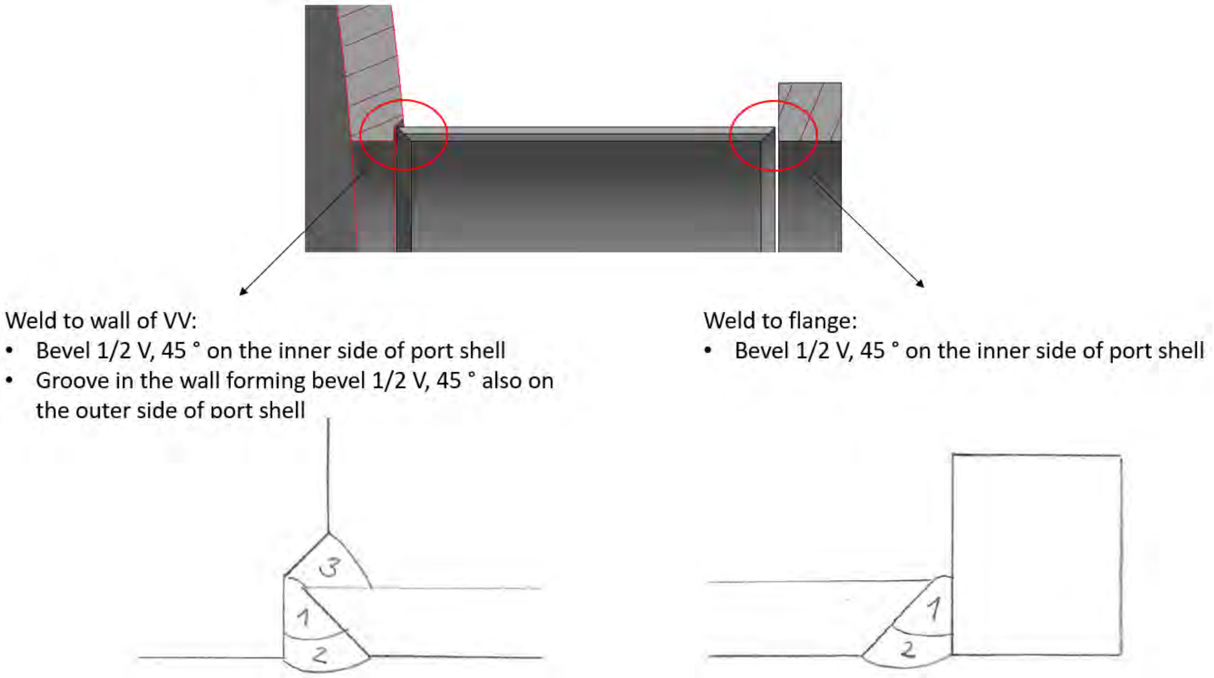

Figure 2.28 – Preparation of weld bevels and corresponding schematics of weld passes layout for joints of the MN port shell to its flange and to the VV wall

Vertical ports

The vertical ports are positioned within the VV assembly in the area of annuluses (see Figure 2.29) and should be joined to the main shell of the vessel during the phase of the entire outer sub-assembly manufacturing. Their presence in this zone is however a potential obstacle for practical feasibility of EBW process which is expected to be used for final joining of the full VV assembly along the annuluses and forged rings interface. For this reason, the length of the ports initially joined to the vessel wall has to be limited to maximum about 120 mm. The extension of the port length to higher dimension and installation of flanges thus needs to be postponed to a later phase, after the entire VV assembly will be joined

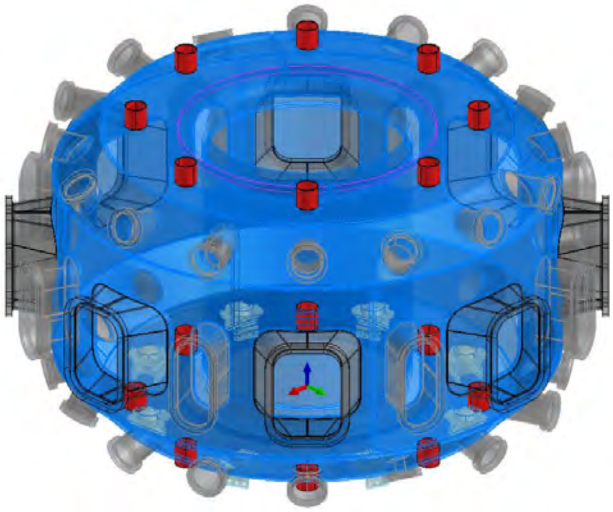

Figure 2.29 – The vertical ports within the VV assembly

The segment of the port shell to be joined directly with annulus is of tubular shape and is expected to be manufactured from a pipe with dimensions of 101,3 x 5 mm. Bevel preparation needs to be done on the pipe edge, it will be of 1/2 V shape and with opening angle of 45°, see Figure 2.30. Root gap of 2 mm is considered for the weld joint.

Welding of these segments of the vertical ports to the vessel wall will be done during the phase of the entire outer sub-assembly manufacturing. The corresponding weld joint is expected to have 2 passes (with layout of deposition shown again in Figure 2.30), where during deposition of the second pass, the fillet of size a3 will be formed. The welding method will be MIG, the suggested welding parameters are given in Table 2.8.

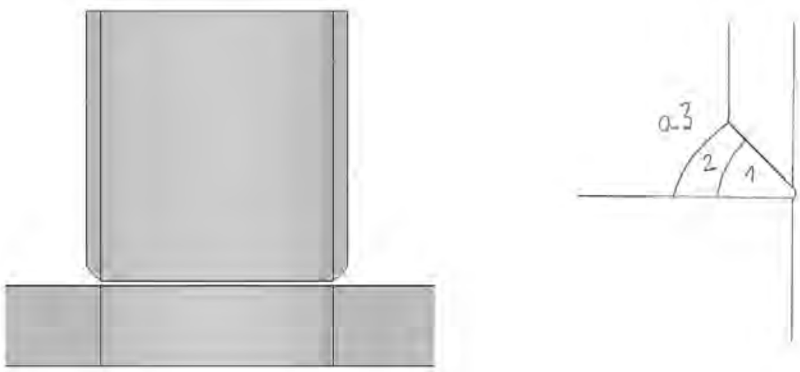

Figure 2.30 – Preparation of weld bevel and corresponding schematics of weld passes layout for joint of the vertical port shell to the VV wall

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Table 2.8 – Suggested welding parameters for welding of vertical ports

Ports DUX / DLX, DUH / DLH and DUC / DLC

These tubular ports are passing through the wall of the VV in the area of cones, see Figure 2.31. The 3 types differ in the angle of the port axis versus the vessel wall surface. However, there are many common aspects in their design, like identical diameter and wall thickness of the port shell or identical dimension of their flanges. Therefore, common approach can be chosen for the welding process.

The shell of these ports should be manufactured from pipes with dimensions of 168,3 x 5 mm. The flange blanks have to be cut including material allowances, which are suggested as 10 mm on thickness and 5 mm on the outer contours (see also chapter 3).

For joining of the port shell to the flange, a groove on the inner edge of the flange will be prepared, which after fit-up with the tubular shell will result in 1/2 V bevel with an opening angle of 45° and root gap of 2 mm, see Figure 2.32. Tack-welding is done and afterwards the weld deposition is performed. The weld joint is expected to have 2 passes (with layout of deposition shown again in Figure 2.32), The welding method will be MIG, the suggested welding parameters are given in Table 2.9.

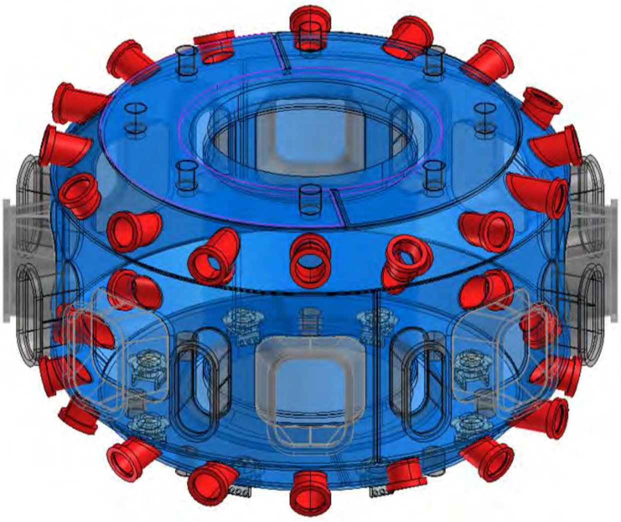

Figure 2.31 – The DUX / DLX, DUH / DLH and DUC / DLC ports within the VV assembly

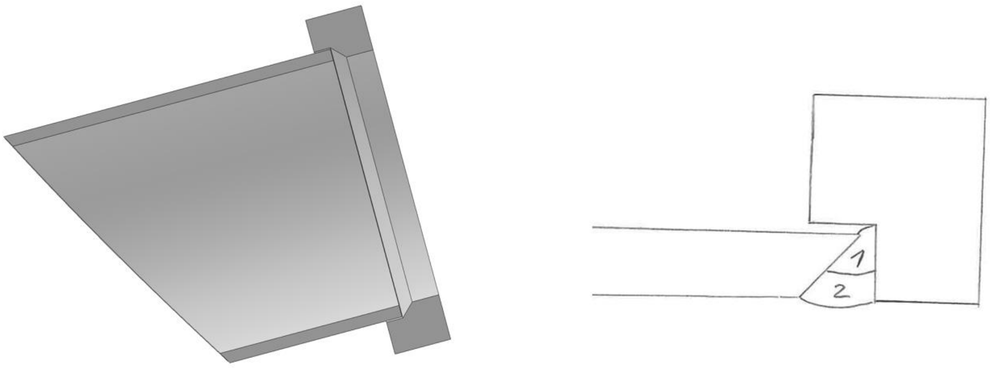

Figure 2.32 – Preparation of weld bevel and corresponding schematics of weld passes layout for joining flanges of DUX/DLX, DUH/DLH and DUC/DLC ports

Table 2.9 – Suggested welding parameters for welding of DUX/DLX, DUH/DLH and DUC/DLC ports

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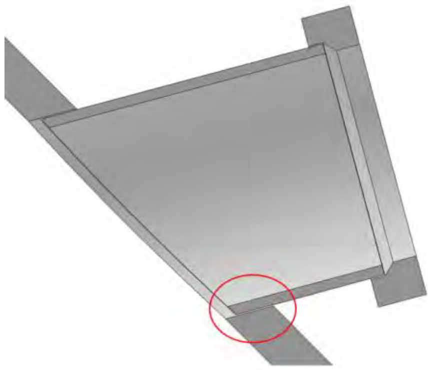
Welding of the port shells to the vessel wall will be done during the phase of the entire outer sub-assembly manufacturing. In this case it is suggested to machine the holes in the vessel wall with exact dimension corresponding to the port shell outer diameter. Afterwards the pipe of the port shell will be fitted into the hole tightly in a way demonstrated in Figure 2.33. After tack-welding, the joining of the port shell to the wall is performed. It is considered that the weld on the internal side of the wall should be done as first, which is a fillet weld of a5 size and with 2 passes, then on the external side of the wall a fillet weld of a3 size and only 1 pass will be done (see details in Figure 2.33). For both of the welds the welding method MIG is considered and welding parameters according to Table 2.9.



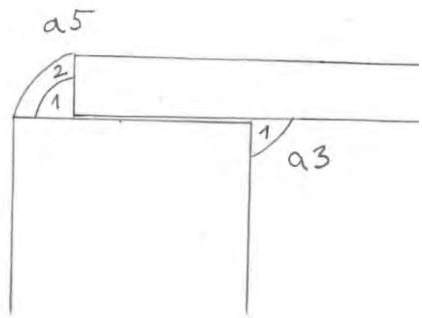


Figure 2.33 – Welds of ports DUX/DLX, DUH/DLH, DUC/DLC to the VV wall

Adapters

Various types of adapters are to be welded in different positions of the internal surface of the VV. The adapters are rather massive blocks of material, which after joining to the vessel wall will serve as mounting points for installation of various equipment inside the vessel. In spite of the fact that the different types of adapters differ in shape and also in position of installation inside the vessel, quite common strategy can be chosen for their manufacturing and welding.

The manufacturing of the individual adapters will be done by cutting from sheet metal of suitable thickness and afterwards milling into desired shape and dimension. However, material allowances with minimum magnitude of 5 mm are required to be applied in perpendicular direction over any functional surface of the adapter (see also chapter 3). To avoid excessive concentration of stresses during service loading of the vessel, sharp corners and interruptions of weld joints to the vessel wall are to be avoided on the perimeter of the adapter bodies. For this reason, radiuses of minimum size of 5 mm are recommended and are to be used in the corner portions of different adapters (see Figure 2.34). The weld joints will be done continuously around the adapters and will therefore seal the interface spaces between the adapter bodies and the vessel wall completely. But because of need to enable evacuation of these spaces, it is suggested to drill some vent holes of suitable diameter into the adapter body before welding (see Figure 2.34).

For the welding operation itself, it is suggested preparation of weld bevel in the side of the adapter with 1/2 Y shape, with root gap of 2 mm, opening angle of 45° and depth of 6 mm (see Figure 2.35). After appropriate fit up of the adapter and tack-welding the weld joint will be deposited. Except filling of the prepared weld bevel there is supposed a filet of a6 size to be formed. It is supposed that the weld will be completed in 3 welding passes (see details again in Figure 2.35). The considered welding method is MIG and the suggested welding parameters are given in Table 2.10.

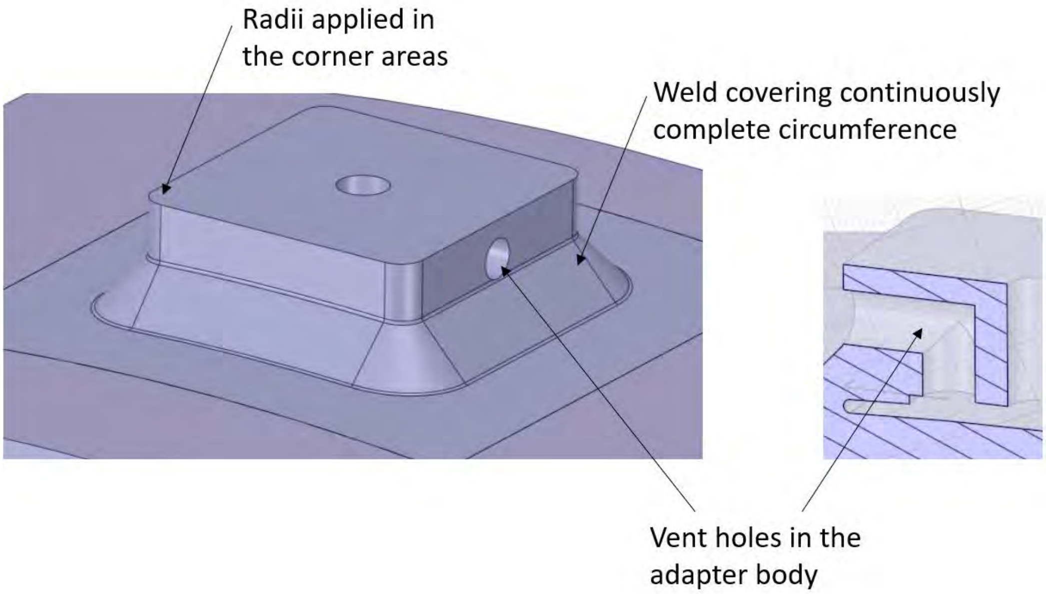


Figure 2.34 – Proposed approach for manufacturing and welding adapters illustrated on the case of HFS adapter

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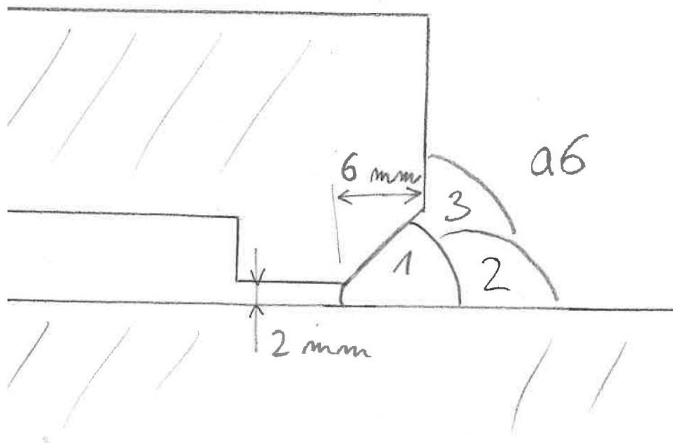

Figure 2.35 – Weld bevel and corresponding schematics of weld passes layout for joining of adapters to vessel wall

Table 2.10 – Suggested welding parameters for welding of adapters

2.2.2 Welding of the inner sub-assembly

The inner sub-assembly (see Figure 2.36) is one of the two main sub-assemblies considered in the suggested manufacturing procedure of the vacuum vessel assembly. It will be made of individual parts and basic sub-assemblies already prepared as described above in section 2.2.1. More specifically, this sub-assembly corresponds to a section of the main shell corresponding to both forged rings and inner cylindrical shell. It further consists of adapters that are welded on the inner wall of the vessel in this domain, i.e. HFS adapters (for fixing the elements of the first wall) welded to the inner cylindrical shell and adapters of divertor welded to the forged rings.

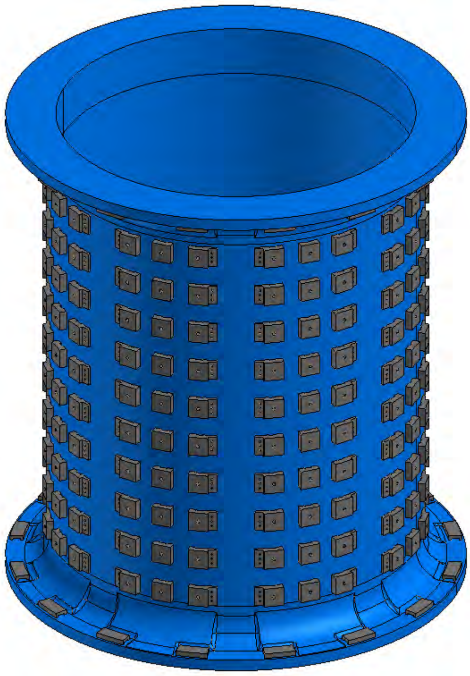

Figure 2.36 – The inner sub-assembly

In the first phase, the parts of the main shell are to be joined, it means the forged rings will be connected with the inner cylindrical shell. The parts need to be aligned including root gap of 2 mm per each of the welds. Due to the bevels prepared on edges of the individual parts (as described previously in section 2.2.1) the set-up for two circumferential welds of X-shape will be done. Tack-welding has to be performed considering the length of individual tacks of approx. 25 to 30 mm and spacing among them of approx. 0.5 m. Afterward the circumferential welds are performed. It is expected that these welds will consist of 12 passes distributed symmetrically in the weld bevel according to schematic sketch in Figure 2.37. The suggested welding method is MIG and the proposed welding parameters are given in Table 2.11

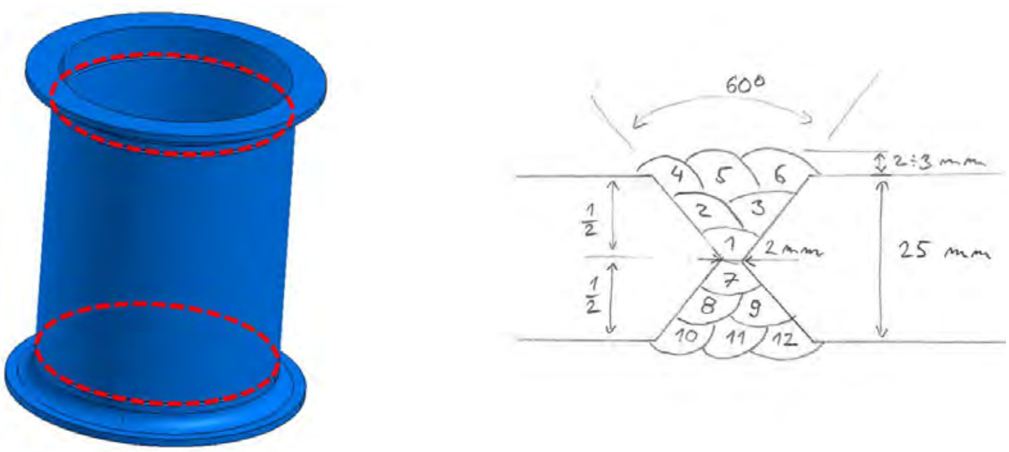

Figure 2.37 – Circumferential welds of the inner sub-assembly, the corresponding bevel shape and layout of weld passes

Table 2.11 – Suggested welding parameters for circumferential welds on the inner sub-assembly

Further, the adapters shall be welded to the appropriate position of the vessel wall. It is suggested to perform firstly welding of the HSF adapters to the domain of inner cylindrical shell. The adapters have to be positioned on the wall properly and tack-welded. Afterward the welding is done following the configuration and parameters suggested previously in section 2.2.1. Regarding the welding sequence, it is suggested that weld on one adapter is always fully completed before proceeding with another adapter. It is also recommended to complete firstly one horizontal (circumferential) row of these adapters before starting with another one. But regarding the process of adding adapters in one horizontal row, there should be avoided to keep adding the adapter continuously in circumferential direction. In the opposite, the adapters should be added following a suitable sequence alternating around the circumference (as schematically illustrated in Figure 2.38) which will result in more regular distribution of welding induced distortions with respect to circumferential direction.

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Afterwards also the divertor adapters shall be welded to the domains of forged ring following analogous process strategy.

It has to be emphasized that from technological point of view there need to be implemented partial modification regarding the design of the vessel or more exactly regarding position of some of the adapters, compared to the specific design proposal, which was input for the study. This is seen essential to guarantee the feasibility and quality of the process. It concerns the first rows of HFS adapters which are closest to the circumferential welds between forged rings and inner cylindrical shell. These should be moved partly closer to the meridian line of the vessel to avoid interaction of the welds on adapters with the circumferential welds. Even more critical is the necessity to adjust the position of the divertor adapters with respect to the edge of horizontal part of the forged rings (or with respect to position of junction lines between forged rings and annuluses). Here it is mandatory to avoid interaction of the EB welding operation with weld of the divertor adapters.

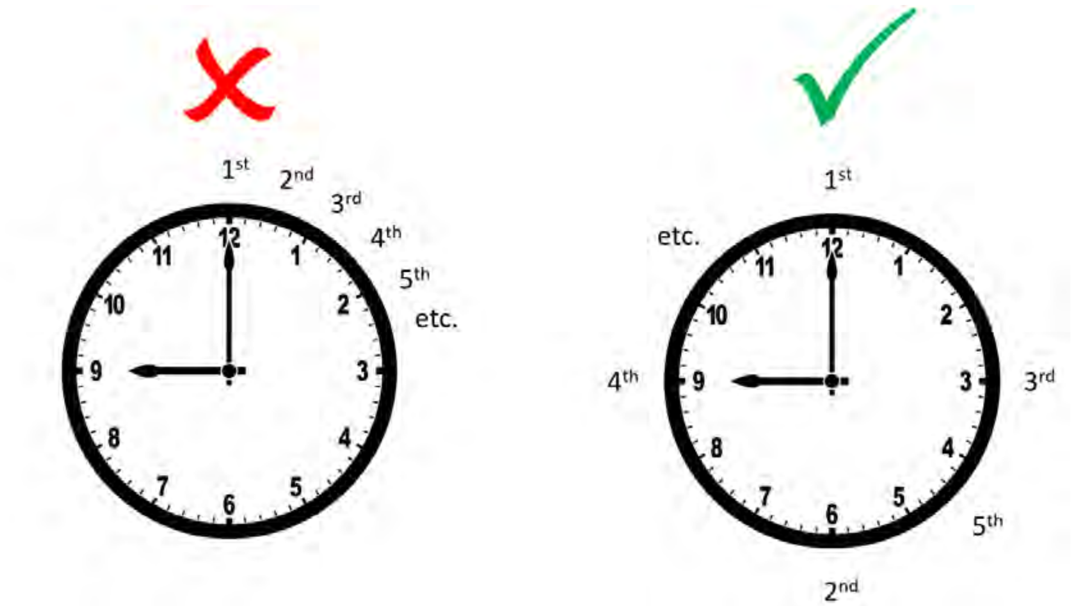


Figure 2.38 – Schematic depiction of recommended welding sequence of adapters around the circumference of the vessel

2.2.3 *Welding of the outer sub-assembly*

Manufacturing of the outer sub-assembly (see Figure 2.39) starts with the phase of assembly of the components of the main shell, it means the annuluses and cones with the outer cylindrical shell. Edge preparations have to be done on of the individual components, as it was described previously in section 2.2.1, which after positioning of the individual components together will result into formation of bevels for symmetrical welds of X-shape (see Figure 2.40). It should be reminded that formation of root gap of 2 mm is required for all of these welds.

In the first step, the outer cylindrical shell is fitted-up with cones and the parts are tack-welded. The tacks with length of 25 to 30 mm and spacing among them of about 0.5 m are considered. Consequently, also the annuluses are added and tack-welded to cones. Finally, in this pre-assembly stage, the tubular reinforcements (see details in chapter 3) are inserted into the area between annuluses and the flat blanks at their ends are tack-welded to the inner surface of the annuluses.

After that, the four circumferential welds (see Figure 2.40) can be deposited. It is expected that they will be composed of about 16 welding passes, the suggested welding method is MIG and welding parameters according to Table 2.12.

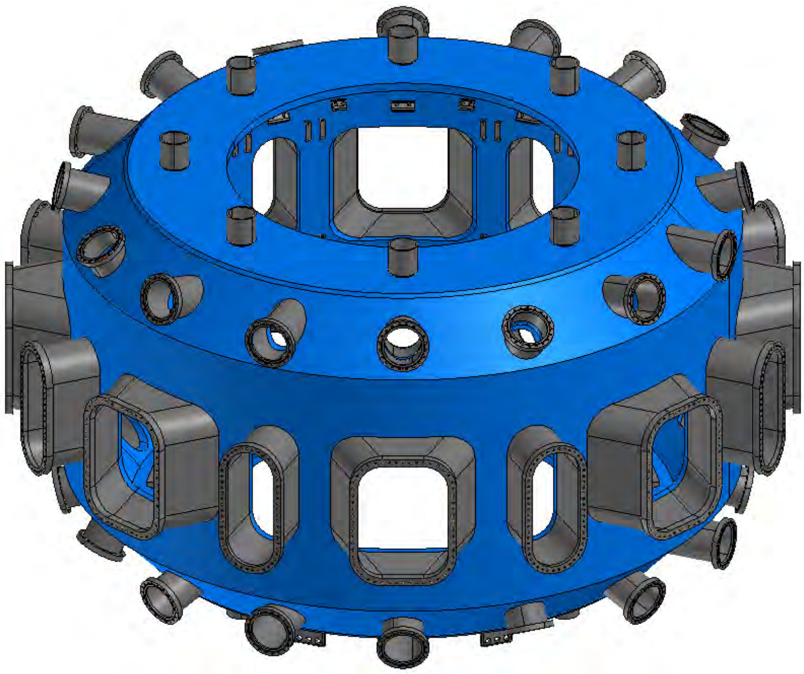


Figure 2.39 – The outer sub-assembly

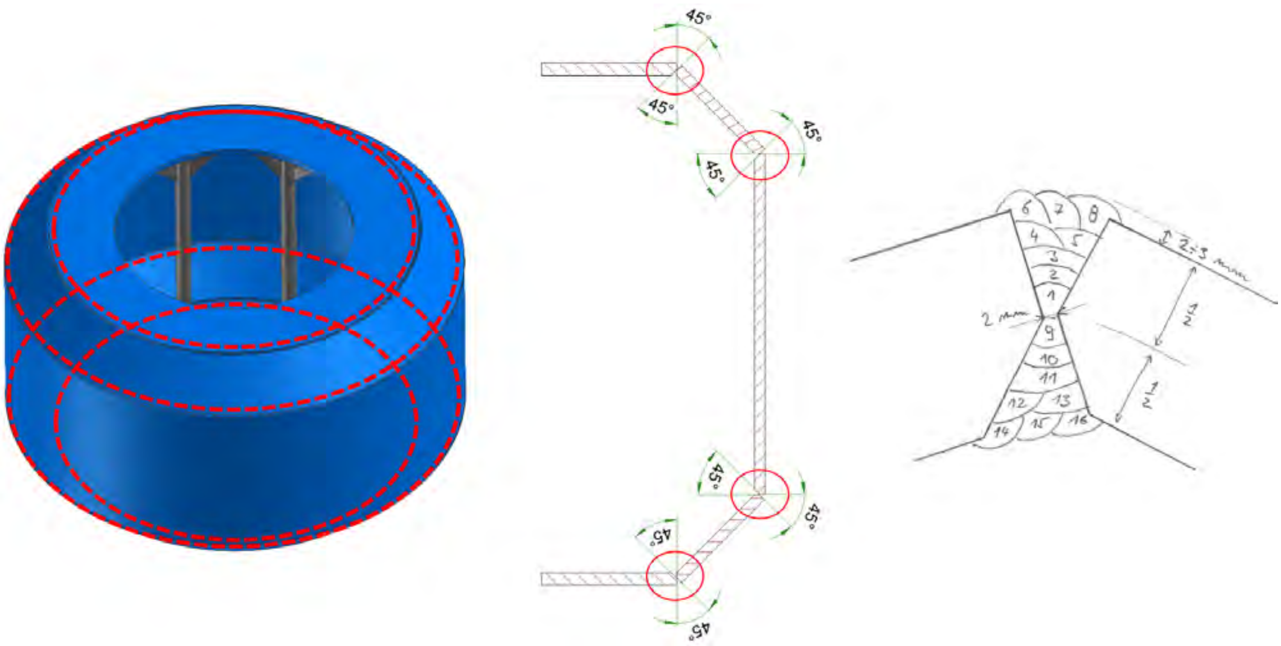


Figure 2.40 – Circumferential welds of the outer sub-assembly, the corresponding bevel shape and layout of weld passes

Table 2.12 – Suggested welding parameters for circumferential welds on the outer sub-assembly

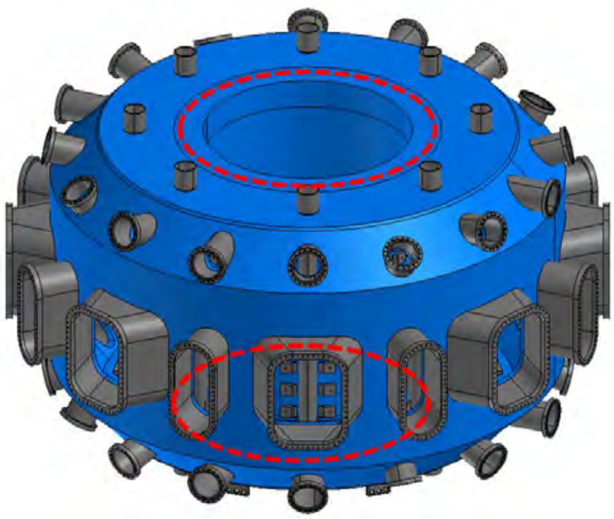
After joining of the main shell, the sub-assembly with ports has to be done. This starts with phase of machining holes of corresponding dimensions and as per specific type of the port and weld, eventually also preparation of bevels on edges of the holes (for details inspect section 2.2.1). Considering that the port shells are already welded with their flanges, the fit-up and tack-welding of all the ports to the vessel wall is needed to be done. Here it is to be reminded to respect the proposed root gaps of the individual welds. Afterwards the individual ports are to be welded to the main shell using the proper type of welds and welding parameters as defined above in section 2.2.1. Regarding the order of completion of welds on the individual ports with respect to circumferential direction of the vessel there is again to be chosen a suitable alternating sequence, which was illustrated in Figure 2.38.

Finally, the different types of the adapters are to be welded to the inner surface of the main shell, which in this case includes combined adapters of divertor and passive stabilization system in the area of annuluses, adapters of passive stabilization system in the area of outer cylindrical shell and adapters of outer limiter in the area of the outer cylindrical shell. It is supposed that all the adapters will be positioned to the vessel wall properly and tack-welded. Afterwards, welding of the individual adapters is to be done following parameters described above in section 2.2.1. The completion of individual joints with respect to circumferential direction of the vessel should again follow a suitable alternating sequence described in Figure 2.38.

Another key point to remind is that the tubular reinforcements inserted between annuluses are to be kept in place during all the above described operations (opening of holes, welding ports and welding adapters). And they must be kept in place also after the outer sub-assembly is finished, to avoid significant increment of deformations before the final joining of the entire vessel is done.

2.2.4 Final assembly of the vacuum vessel

The final assembly of the vacuum vessel (see Figure 2.41) basically corresponds to axial insertion of the inner sub-assembly into the outer one and their joining along the interfaces of the annuluses with the forged rings. This last two welds are suggested to be done by electron beam welding process with penetration through the complete wall thickness, because it is critical that this joining operation will already induce the minimum possible increment of distortions.



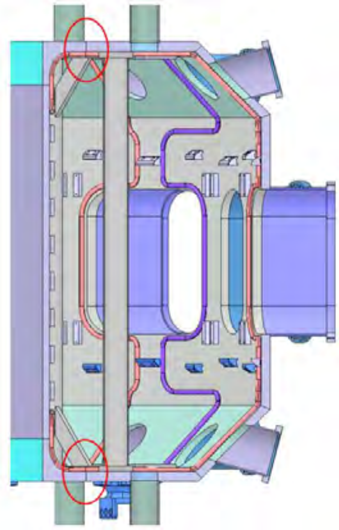


Figure 2.41 – Position of EB welds to finalize the VV assembly

However, prior the welding process itself can be done, some preliminary steps will be necessary.

Firstly, it is needed to guarantee effective compensation of welding induced distortions arising during the phases of the inner and outer sub-assemblies manufacturing to reach sufficient quality of horizontal fit-up of the free edges of annuluses on the outer sub-assembly side and free edges of forged rings on the inner sub-assembly side. This must be ensured through suitable precautions like application of material allowances or usage of reinforcements (as it was described in previous sections of this chapter and as summarized in chapter 3).

Further, there is requested to subject both the finished inner and outer sub-assemblies to vibration stress relieving operation. This is to ensure their dimensional stability during next stages of the process.

Also, before the assembly of the main subassemblies is done and thus the internal volume of the vessel is closed, the final machining of internal surfaces of the inner and outer sub-assemblies must be done, where necessary. This will typically concern the functional surfaces of adapters.

Regarding the phase of execution of the EB welding process itself, here we have to expect that it will have to be done in a specialized manufacturing facility different from the one of the main sub-assemblies manufacturer. Therefore, it is also necessary to take into account the need of transport between these plants.

It is expected that the final machining of the EB weld surfaces (square preparation of edges of annuluses and forged rings) to the required dimensions and surface quality will be already in responsibility of the EB welding facility. This applies also for the operation of the initial fit-up and fixation of the main sub-assemblies prior to the welding itself.

As it was already mentioned the EB welds are supposed to be done with full penetration through the vessel wall thickness thus each of the joints will have only one pass. The preliminary estimate of the welding parameters of the EB process in terms of the imposed heat is given in Table 2.13

Table 2.13 – Estimate of welding parameters of the EB joining process

It should be reminded again, that the tubular reinforcements inserted in the area of outer sub-assembly are not to be removed before the EB joining of the vessel will be finished, because otherwise significant increment of distortions could occur in the outer sub-assembly domain.

Further it must be mentioned that to guarantee feasibility and quality of the EB welding process there will have to be implemented partial changes of the vessel design compared to the specific design proposal, which was input for the study. The reason of these requirements is to avoid interaction of the EB joints with any other weld joints and to provide good access of the EB gun to the joint area. More exactly we find necessary to resolve the following points:

- The circumferential EB welds may not interact with welds of the divertor adapters to the vessel wall. The divertor adapters are positioned on the internal surface of forged rigs and very close to the edge to be joined with annulus. With respect to the required size of the weld of the divertor adapter, for the current design proposal, this weld is then interfering with the EB weld area. It is therefore necessary to either move the position of the divertor adapters in radial direction towards axis of rotation of the vessel or to modify external radius of forged rings edge and internal radius of annuluses and thus to move the junction line radially outwards.

- The length of vertical port pipes welded to the annuluses prior to the final joining of the vessel must be limited in order to not obstruct access of the EB gun to the joint area. The maximum allowable length of the port for this stage is seen as 120 mm. After the EB joining of the vessel will be finished the vertical port can be prolonged by welding additional pipe segments to those joint already to the vessel wall.
- The EB weld may not interact with pipes of the heating/cooling system, which are to be installed inside the vessel. This means that in the zone of the circumferential EB welds the pipes may not touch the vessel wall or also any weld joint of the pipes to the wall may not be present. It is necessary to implement suitable design modification of the pipe loops locally or globally to satisfy the mentioned requirements.

3 ENSURING OF PRESCRIBED TOLERANCES AND PRECAUTIONS AGAINST DISTORTIONS

A common way to control deformations of welded assemblies in industrial practice is the use of various clamping systems or reinforcements, which increases the rigidity of the assembly during the welding process and thus leads to a reduction in the resulting deformations. In the case of VV, however, the possibility of applying this type of precautions is very problematic. This is partly due to the complex shape of the entire assembly and also due to the large number of subassemblies and equipment that are welded to various areas of the VV, including its inner surfaces. For these reasons, it is necessary to ensure sufficient space for material handling, access of welders and various equipment. This leads to limits of the number of reinforcements and their dimensions, which can be applied in this case.

In the current manufacturing proposal, there is therefore envisaged the use of reinforcements only in the area of the outer sub-assembly. In there, tubular braces shall be inserted in the space between annuluses and thus preventing excessive axial and angular distortions of the outer sub-assembly (mainly in the zones of cones and annuluses). These reinforcements are suggested to be made of pipes with outer diameter of 88.9 mm and 4 mm wall thickness with flat blanks of sheet metal with thickness of 20 mm and flat stiffening webs welded at the ends (see also Figure 3.1). The stiffeners in total quantity of 8 pieces will be inserted with equidistant spacing after initial fit-up of the components of main shell of the outer sub-assembly and tack-welded to inner surface of annuluses. Afterward the stiffeners have to be kept in place not only through the entire manufacturing procedure of the outer sub-assembly (including welding of ports and adapter), but also till final assembly of the inner and outer sub-assemblies and completing the EBW process. This is of key importance, because eventual removal of the stiffeners before the EBW joining would lead to significant release effects and additional increment of distortion of the outer sub-assembly and thus to critical misalignment of the annulus and forged ring edges.

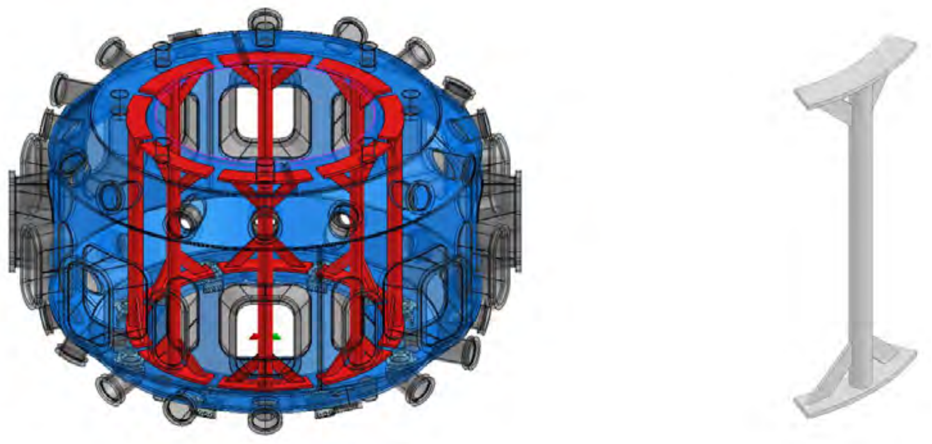


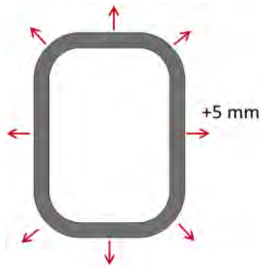
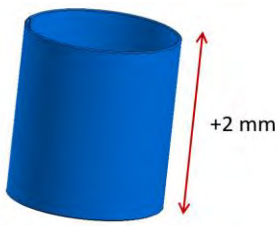
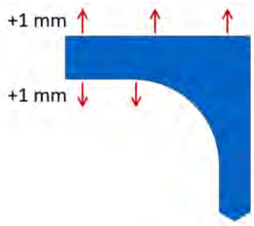
Figure 3.1 – Reinforcements for the outer sub-assembly of the VV

Another type of precautions, which is thus suggested to be used quite widely in the case of the VV assembly is application of the material allowances and a suitable initial pre-positioning or pre-deformation for selected parts of the assembly. This means that the initial fit-up of some of the assemblies or sub-assemblies before welding will be intentionally done outside the nominal CAD dimensions, where the initial deviations are selected as inverse value of the expected welding induced distortion. Thus the dimensions after welding should be quite close to the required ones. Moreover, for the most critical locations the sufficient material allowance will also enable to correct the dimensions by machining after welding.

In Table 3.1 is given a summary of magnitude of the material allowances suggested for manufacturing of the individual parts of the VV assembly. (For the parts or locations where no value is explicitly mentioned, simply the CAD dimensions apply as the manufacturing ones). The specified values were in large extent defined based on results of numerical simulations of welding induced distortions as presented in chapter 5. However, it should be emphasized that in terms of correct interpretation of the suitable initial fit-up of individual assemblies before welding, one needs to consider not only the values of component allowance magnitudes, but also the corresponding values of root gaps of the corresponding weld joints as they were defined in chapter 2. Further it should be understood that for some parts or locations there are also additional reasons to apply material allowance, like for instance specific surface quality requirements of the finished VV.

In case of the annulus components, there can be also recommended certain initial pre-bending into slightly conical shape which will be inverse to the out-of-plane distortions of this component occurring during welding of the outer sub-assembly (as documented in section 5.3). This precaution will help to keep the surfaces of the annulus area in strictly horizontal position after the welding.

Table 3.1 – Summary of suggested values of the material allowances

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		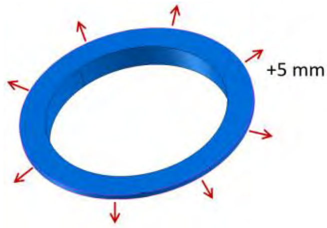
		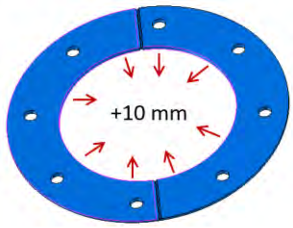
		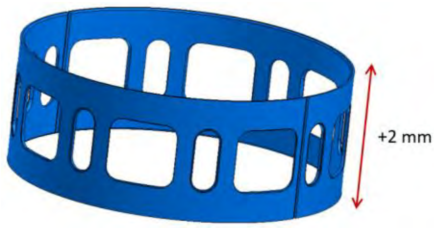

One more type of precaution is very critical to be applied after completing the welding assembly of the inner and outer sub-assemblies. It is strongly recommended to subject both of the sub-assemblies to vibration stress relieving operation. This shall be done before performing the final machining operation on these sub-assemblies. The reason is to ensure higher dimensional stability of the main sub-assemblies firstly during the machining operations itself, but as well with respect to trouble free EBW joining and for guaranteeing the final dimensional tolerances of the of the finished vacuum vessel. The final machining of the critical functional surfaces inside the vessel (like different types of adapters) has to be done before the VV is closed, it means on the inner and outer sub-assemblies still before they are assembled and EB welded. On the other hand, it is highly probable that the EBW process will have to be done in a specialized manufacturing facility different from the one of the main sub-assemblies manufacturer. Thus, during the shipping and transport on potentially long distance the sub-assemblies will be subject to mechanical shocks and vibrations. Without the application of the stress relieving operation there would arise a significant risk of further dimensional changes occurrence, which would be especially critical if causing further distortion of the functional surfaces or misalignment of the annulus and forged ring edges prior the EBW process.

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4 SELECTION OF THE SUITABLE WELDING PROCEDURE FOR JOINING THE ADAPTERS, HEATING AND COOLING PIPES

This chapter of the document is focused on specific components of the COMPASS-UPGRADE vacuum vessel, which are to be joined to the internal surface of the main wall. More exactly we speak about adapters, which serve as attachment points for various installations inside the vessel and about system of pipes, which will be used for heating and cooling of the whole structure. The key point is to suggest a suitable approach for connection on these components to the vessel wall, which will be fulfilling different functional requirements, like the structural integrity and others, which is discussed in detail in the two subsections thereinafter.

4.1 Adapters

There are several types of components referred as adapters in the construction of vacuum vessel. In general, they are massive blocks of material serving as mounting points for installation of various equipment inside the vessel. The aim of this part of the document is to study individual types of the adapters or especially their connection to the vessel wall (which is suggested to be done as weld joint of specified type and dimension) in terms of their ability to withstand prescribed loading.

The loading conditions were determined by ÚFP AV ČR and serve as input to perform numerical structural analysis of elastic stress distribution for the different adapter configurations. The individual load cases consist of combinations of components of forces and moments specific for the different scenarios of interest and will be detailed thereinafter.

The proposal of joining strategy of the adapters by welding to the vessel wall are described in chapter 2. But we can remind that even though the different adapters are of different geometrical configuration, there are many common aspects of the approach to be used. With respect to relatively high level of loading, the goal was to have connection surface between adapters and wall of vacuum vessel as big as possible. Therefore 1/2 Y shape weld with bevel depth of 6 mm covered yet by fillet weld of a6 size is recommended to be used. The welds are to be deposited all around the adapters (without any interruptions) to ensure homogenous connection and to avoid stress concentrations at the eventual weld ends acting as technological notches. To avoid excessive concentration of stresses in corner areas of the adapters, any sharp corners are to be replaced by corner radii (with radius of 5 mm or higher). For more details refer to section 2.2.1 and especially Figure 2.34.

To evaluate individual adapter`s ability to withstand pre-described load cases, the corresponding finite element models were prepared (they will be documented below in corresponding sub-section of this chapter). In general, they correspond to a sub-model scenario with representation of the adapter and weld shape and a simplified representation of the vessel wall in form of section of plate with corresponding thickness. The extremities of the plate section are fixed (rigidly constrained). Loads are applied with magnitudes and locations on the adapters according to the pre-described load cases. In terms of details of representation of the weld joints domain, there was adopted the effective notch stress approach according to the IIW (International Institute of Welding) standard 1823-07. In means that in the FE mesh of the weld joint areas, every weld notch (weld toes or weld roots) is represented by fictive notch radius of 1 mm, see below.

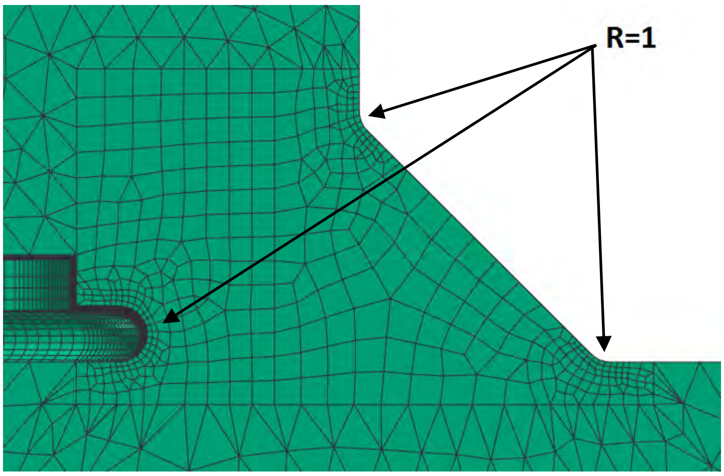

Figure 4.1 – Illustration of weld area FE mesh configuration with assumed fictive notch radii

From the simulation point of view, linear elastic analyses were are done. As results the fictive elastic values of Von-Mises stresses were watched (no plasticity effects are considered). These can be directly compared to yield stress of material at the assumed operating temperature of 500°C (approx. 370 MPa). The intention is to have maximum of the observed stresses with sufficient safety margin with respect to the yield stress (optimally below 2/3 of yield stress).

Below in this report there are discussed the maximum values of stresses identified in the analyses of the individual scenarios. For graphical depiction of the resulting stress contours, references are given to annex 4, which is presentation in MS PPT format.

4.1.1 HFS adapters

The HFS (high field side) adapters is generally a group of adapters located on internal surface of the inner cylindrical shell, which will serve for fixation of components of first wall. In terms of geometrical design, there exist 2 variants of configuration. The HFS-middle adapter is of regular shape with square contour and the HFS-side adapter is with slightly irregular shape with rectangular contour. Further in terms of considered loading, there are also two scenarios of interest. One loading scenario is considered for the first and last two rows of the adapters (it means the 2 rows next to junctions with forged rings of the main vessel shell) and another loading scenario is then relevant for the remaining rows of adapters closer to the meridian line of the vessel. There were analysed 4 configuration variants for the HSF group of adapters as described below.

HFS-middle adapters

In this paragraph we deal with HFS-middle adapters, where the considered load cases are relevant for the six rows of the adapters located closer to the meridian line of the vessel, see also the illustration in Figure 4.2.

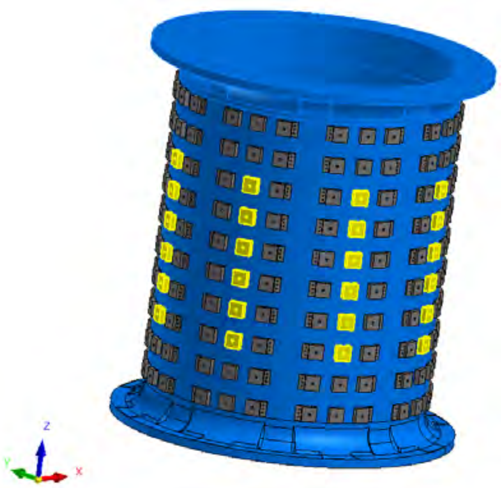

Figure 4.2 – HFS-middle adapters, six rows around the meridian line

Configuration of the finite element model for the corresponding analysis is depicted in Figure 4.3, together with illustration of applied boundary conditions and of the area where loads are distributed. The definition of corresponding load cases is then given below in Table 4.1.

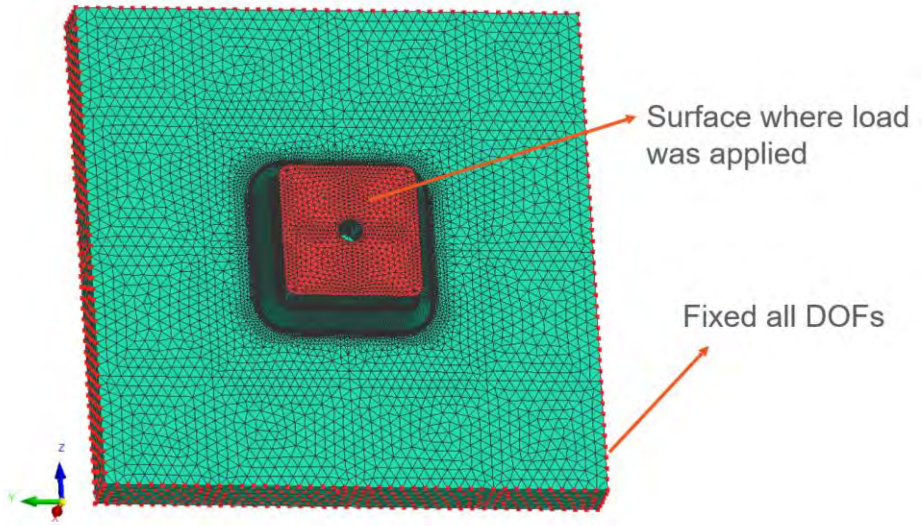

Figure 4.3 – FE model for HFS-middle adapter analysis

Table 4.1 – Pre-scribed/defined load cases for HFS adapters, six rows around the meridian line

The results in terms of contour plots of the fictive elastic von Mises stress distribution are given in annex 4, pages 6 and 7. More severe situation is for load case number 2, where the maximum stress value reached is 178 MPa and it is located in the tow notch of the weld joint in corner area or the adapter. Hence, for both of the examined load cases, the stresses are rather low and sufficient safety margin versus the yield strength of the material exists.

HFS-middle adapters – 2 upper and lower rows

In this case the analysis is done still for the same geometrical configuration of the adapter, however specifically for the location of the first two upper and lower rows of these adapters (close to the forged rings of the vessel, see also Figure 4.4), different loading conditions are considered. Hence the FE model used is still the same as presented above in Figure 4.3, but the relevant definition of load cases is given in Table 4.2.

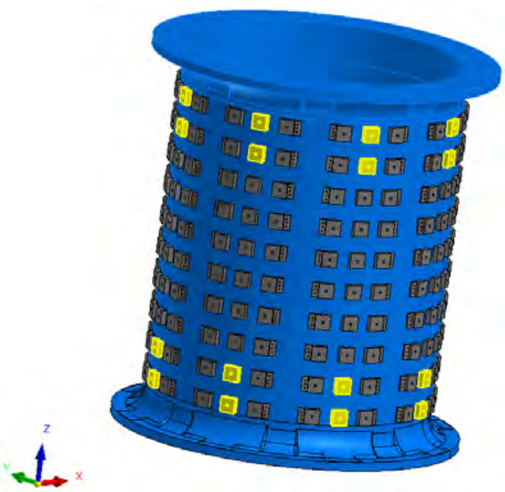

Figure 4.4 – HFS-middle adapters, two upper and lower rows

Table 4.2 – Pre-scribed/defined load cases for HFS adapters, two upper and lower rows

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Corresponding results in terms of contour plots of the fictive elastic von Mises stress are given in annex 4, pages 10 and 11. In this case, more critical situation is for load case number 1, where the maximum stress value reached is 338 MPa and it is located in the tow notch of the weld joint in corner area or the adapter. The mentioned value of maximum stress is not really higher than the considered yield strength of the material, however the safety margin is seen as rather low. It can be advised to perform certain local design modifications of the adapter. Because the peak stress is linked also to design concentrator effect of the corner area of the adapter, there can be suggested further increasing of the corner radii (the current FE model corresponds to R = 5 mm).

HFS-side adapters

The HFS-side adapter configuration corresponds to lateral columns in the HFS adapters arrays. In this paragraph we will more specifically deal with loading scenarios considered for six rows of the adapter, which are closer to the meridian line of the vessel (see Figure 4.5).

The finite element model used for this analysis is depicted in Figure 4.6, together with illustration of applied boundary conditions and of the area where loads are distributed. The considered load cases are actually identical as for the HFS-middle adapters in the equivalent location and hence are given by Table 4.1 above.

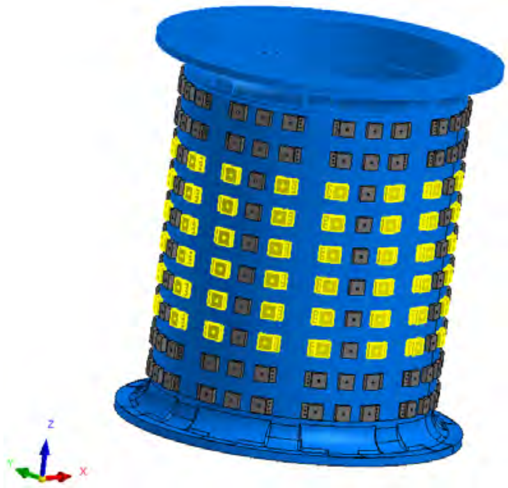

Figure 4.5 – HFS-side adapters, six rows around the meridian line

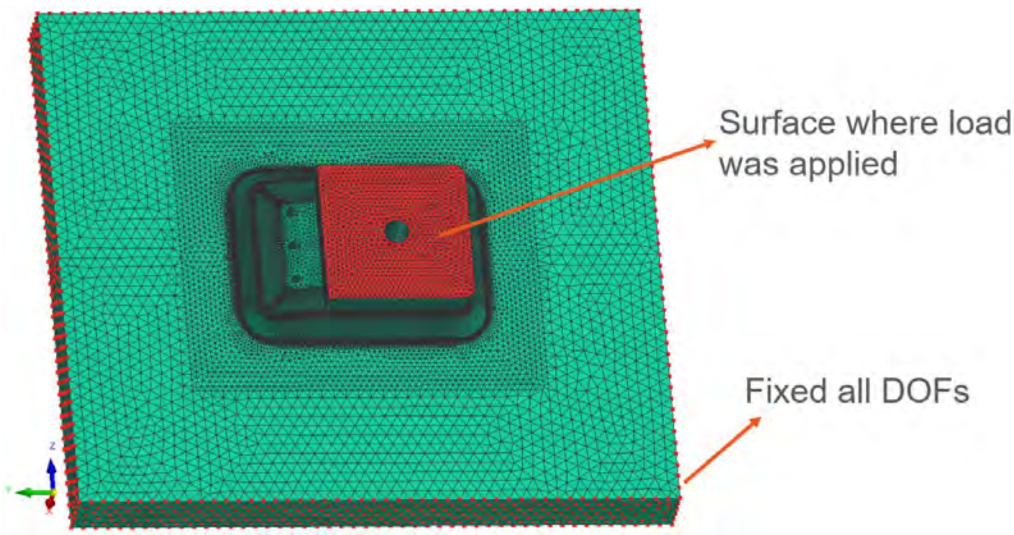

Figure 4.6 – FE model for HFS-side adapter analysis

The resulting contour plots of the fictive elastic von Mises stress corresponding to this analysis scenario are given in annex 4, pages 14 and 15. More severe situation is for load case number 2, where the maximum stress value reached is 179 MPa and it is located in the tow notch of the weld joint in corner area or the adapter. It can be therefore stated that for both of the examined load cases, the stresses are rather low and sufficient safety margin versus the yield strength of the material exists.

HFS-side adapters – 2 upper and lower rows

In this case the analysis is done again for geometrical configuration of HFS-side adapter, but for the situation of the first two upper and lower rows of these adapters (close to the forged rings of the vessel, see also Figure 4.7 for illustration), where different loading conditions are applicable. Hence the FE model used is the same as presented in the previous paragraph, Figure 4.6. And the relevant definition of load cases is given above in in Table 4.2.

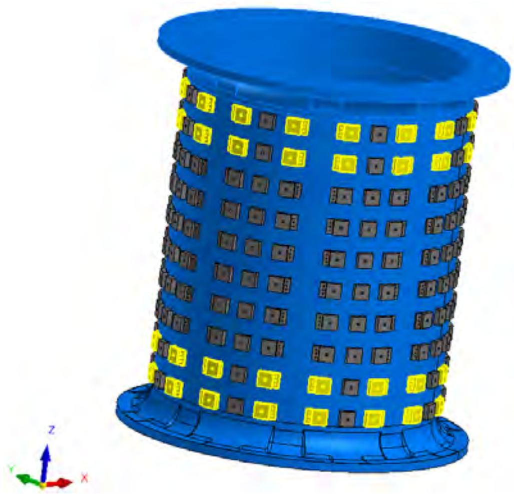

Figure 4.7 – HFS-side adapters, two upper and lower rows

Resulting contour plots of the fictive elastic von Mises stress for the two analysed load cases are given in annex 4, pages 18 and 19. More severe situation is for load case number 1, where the maximum stress value reached is 400 MPa and thus it exceeds the assumed yield strength of the material. To reduce the peak values of stress, design modifications of the adapter should be considered. We suggest to focus mainly on the zone, where the change of height of the adapter is designed, because this sudden change in the material thickness acts as significant structural stress concentrator which is eventually superimposed with local effects of stress concentrations in notches existing nearby.

4.1.2 Divertor adapters

This type of adapters which shall be joined to the vessel wall in area of the forged rings (see also Figure 4.8) will serve as mounting points for the support system of divertor. FE model used for the structural analysis is shown in Figure 4.9. There are again two load cases considered for this adapter type, which are defined below in Table 4.3.

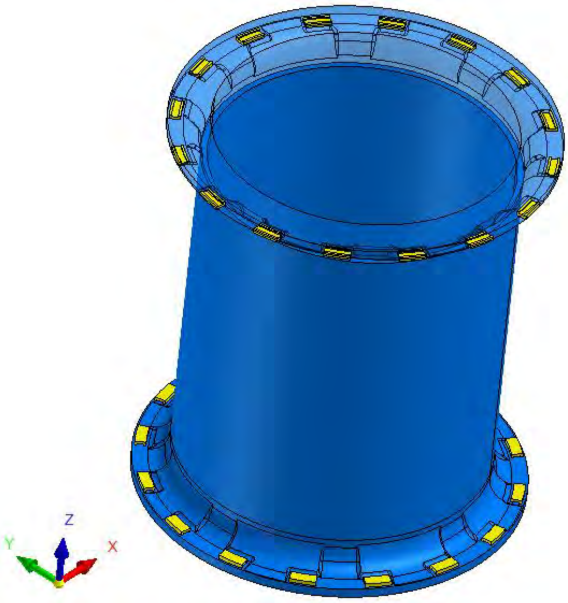

Figure 4.8 – Divertor adapters

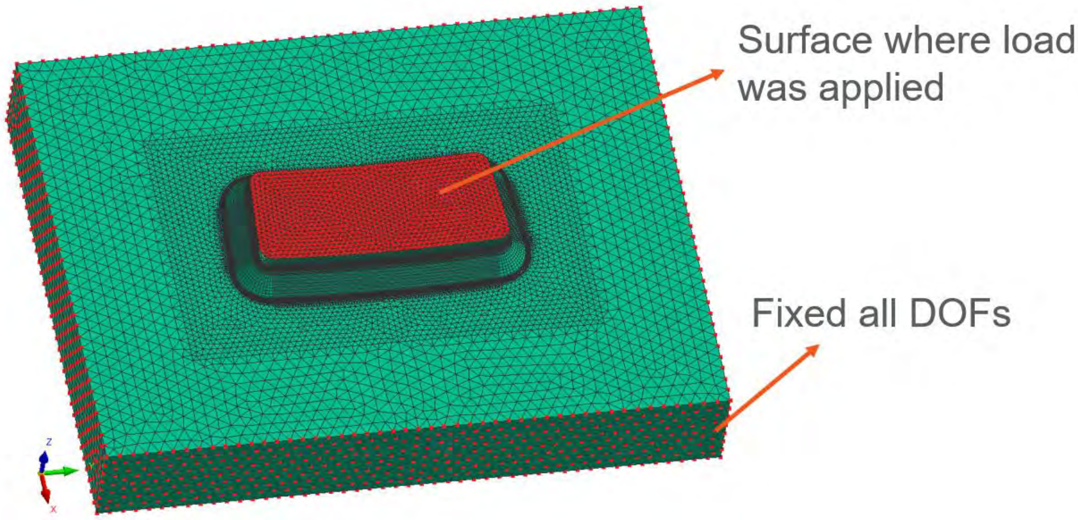

Figure 4.9 – FE model for divertor adapter analysis

Table 4.3 – Pre-scribed/defined load cases for divertor adapters

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The resulting contour plots of fictive elastic von Mises stress are presented in annex 4, pages 22 and 23. Slightly worse situation is observed for load case number 1, where the maximum stress value reached is 146 MPa and it is located in weld root notch. It can be concluded that the stresses are generally rather low and sufficient safety margin versus the yield strength of the material exists.

4.1.3 Combined adapters

The combined adapters are to be joined to the vessel wall in area of annuluses (see Figure 4.10) and are intended as common attachment point for supports of divertor and also of passive stabilization system.

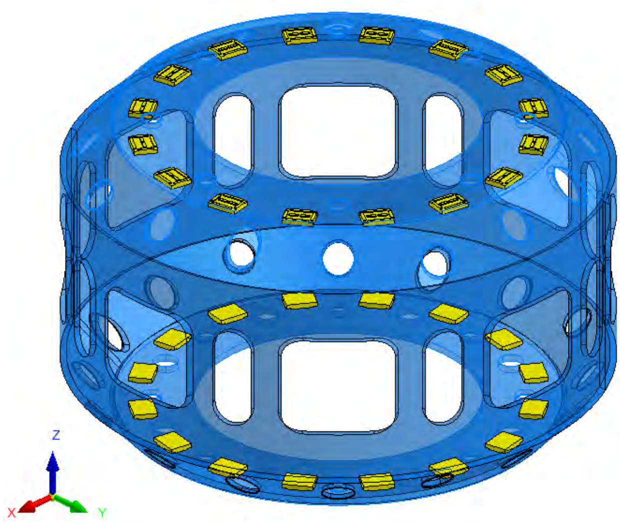

Figure 4.10 – Combined adapters

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Because the loading level expected for this adapter is rather high and its dimensions are quite big (especially in terms of dimensions of top surface of the adapter) the concept of connection proposed in this case is partly different compared to the other adapter types. There is again supposed to be done weld around complete circumference of the adapter of similar dimensions as for the other adapters. But additionally, there is suggested to reinforce yet the central portions of this adapter. This was proposed to be done using cylindrical pin with diameter of 25 mm and height similar to height of the adapter itself. The pin will be firstly welded to the vessel wall with similar type of weld as assumed to be used on the adapter circumference (1/2 Y shape weld with bevel depth of 6 mm covered by fillet weld of a6 size). In the adapter a hole will be done enabling to place the adapter on the vessel wall and centre it around the pin. On the edge of the hole, weld bevel preparation will be done in shape of 1/2 V, opening angle 45°, depth corresponding to the adapter upper plate thickness (15 mm) and considering also root gap of 2 mm. So, after positioning the adapter over the pin, the adapter will be welded to the vessel wall and afterward the top plate of the adapter will be also joined to the pin by the 1/2 V-shape weld. This concept is also shown in Figure 4.11 illustrating the configuration of FE model for this adapter type analysis.

The load cases considered for this adapter are defined below in Figure 4.10, and they correspond to summation of loading assumed to originate from both divertor and passive stabilization system effects.

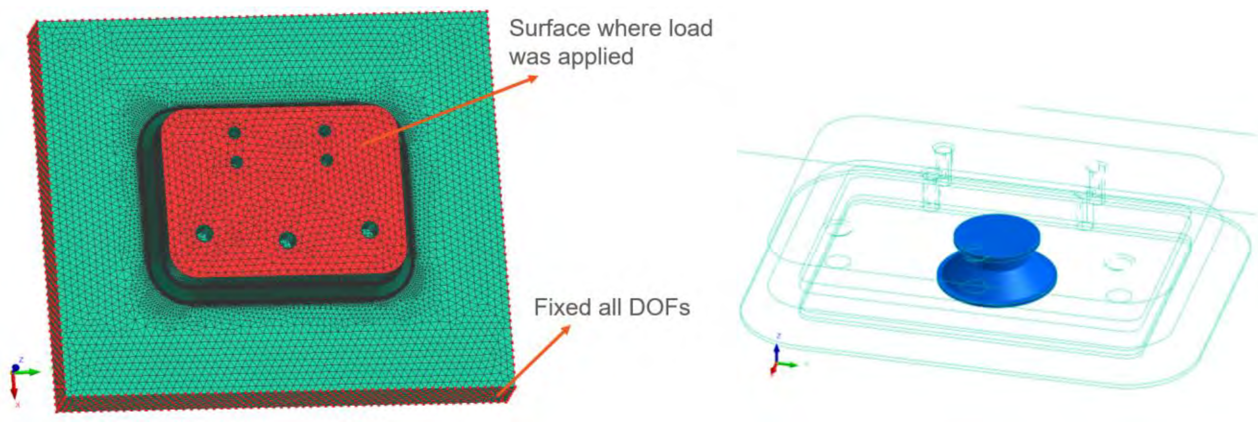

Figure 4.11 – FE model of combined adapter (left) and detail of pin reinforcing the centre of the adapter (right)

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Table 4.4 – Pre-scribed load cases for combined adapters

Resulting contour plots of fictive elastic von Mises stress corresponding to this scenario are given in annex 4, pages 26 and 27. More critical situation is observed for load case number 1, where the maximum stress value reached is 341 MPa and it is located in root notch of weld between the adapter plate and the restraining pin. Hence the assumed yield strength of the material is not really exceeded, but the safety margin is rather low. In can be recommended to apply local design changes to further reduce the peak stresses. For instance, by increasing diameter of the supporting pin or by increasing number of such supporting elements, the leverage effects of loading leading to local stress concentration in the critical transition area should decrease.

4.1.4 Passive stabilization system adapters

In this sub-section we deal with adapters which will serve as mounting points of passive stabilization system and are to be joined to the vessel wall in the area of outer cylindrical shell (see Figure 4.12). The are 2 sub-types of these adapter referred as 2A and 1A/1B, which are quite similar in shape, but differ in general dimensions, with type 2A being larger whereas type 1A/1B being smaller.

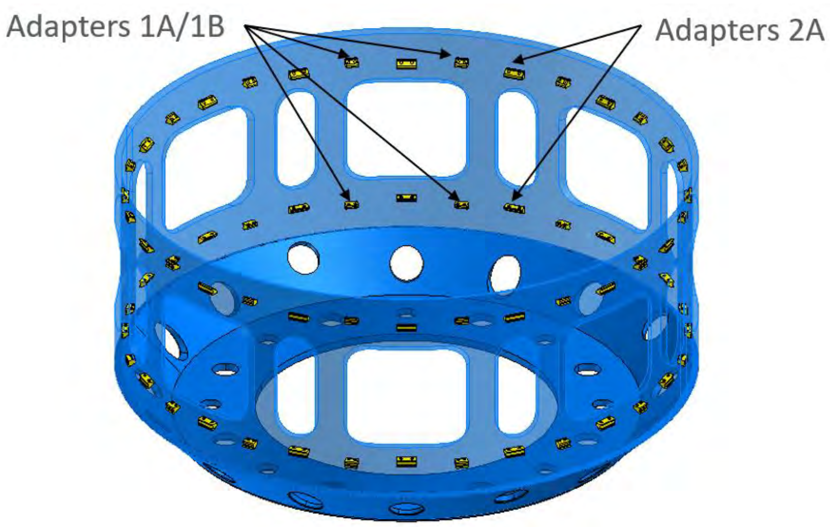

Figure 4.12 – Adapters of passive stabilization system 2A and 1A/1B

Adapters 2A

The FE model used for analysis for this type of adapter is depicted in Figure 4.13 and corresponding load cases are defined in Table 4.5.

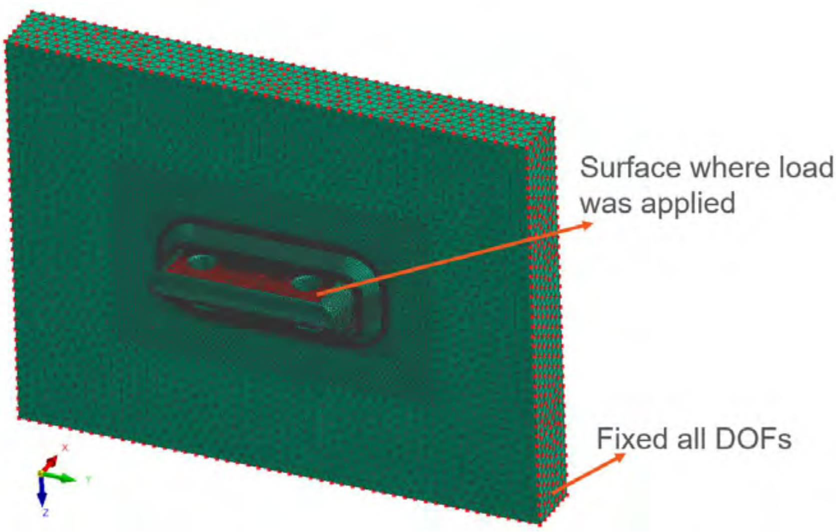

Figure 4.13 – FE model of passive stabilization system adapter 2A

Table 4.5 – Pre-scribed/defined load cases for passive stabilization system adapters 2A

Results of this analysis in terms of contour plots of fictive elastic von Mises stress are given in annex 4, pages 30 and 31. Significantly worse situation is observed for load case number 1, where the maximum stress value reached is 515 MPa (located in weld tow notch) and hence it clearly exceeds the assumed level of yield strength of the material. The problem of high stress occurrence is however not limited only to the weld joint area and the corresponding technological notches. Inacceptable values of stress are reached also in some areas the body of the adapter itself. In must be therefore stated that the adapter is generally undersized and in this case, a wider redesign of the adapter will be needed for the considered loading levels.

Adapters 1A/1B

The FE model used for analysis of the 1A/AB adapter type is depicted in Figure 4.14 and corresponding load cases are defined in Table 4.6.

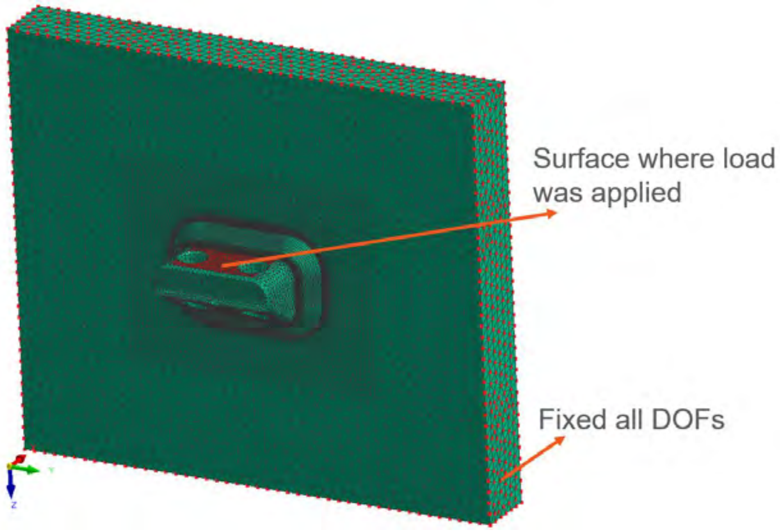

Figure 4.14 – FE model of passive stabilization system adapter 1A/1B

Table 4.6 – Pre-scribed/defined load cases for passive stabilization system adapters 1A/1B

Results of this analysis in terms of contour plots of fictive elastic von Mises stress are given in annex 4, pages 34 and 35. Significantly worse situation is observed for load case number 1, where the maximum stress value reached is 1137 MPa (located in weld tow notch) and hence it highly exceeds the assumed level of yield strength of the material. The problem of very high stress occurrence is however common to both of the studied load cases and it is not limited only to the weld joint area and the corresponding technological notches. Very high values of stress are reached in large areas of the entire adapter body. In must be therefore stated that the adapter is strongly undersized, and a general redesign is required for the considered loading levels.

4.1.5 Support columns adapters

This type of adapters will be joined to the vessel wall in the area of the bottom annulus, then these adapters will serve as mounting points of the entire vessel to support columns and via them the vessel will be connected to the support structure of the tokamak. The strategy of welding the support column adapters is different compared to all the other adapters and actually it was already described above in section 2.2.1, where the position of these adapters was illustrated in Figure 2.14 and the suggested types and sizes of weld joints in Figure 2.16.

The model used for structural analysis of this adapter is depicted in Figure 4.15 and the corresponding load cases are defined in Table 4.7. In this case the magnitude of the loads assumed was defined as summation of loading from 2 loading scenarios defined in the input documentation. Further it is to be mentioned that there was required to apply the loads into the positions of holes for pins, where the adapter will be joined to the support column. On the other hand, the initially defined place of action of the loading was at the level of wall of the vessel. Therefore, to transfer the loading effect accordingly a structure of rigid body elements (RBEs) was constructed (as also shown in Figure 4.15) and the loading are applied into the master node of the RBEs.

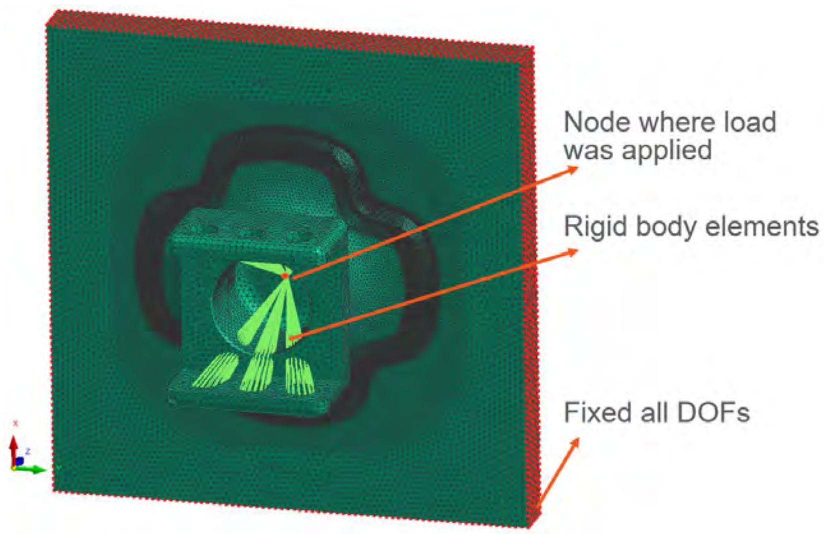

Figure 4.15 – FE model of support column adapter

Table 4.7 – Pre-scribed/defined load cases for support column adapters

The resulting contour plots of the fictive elastic von Mises stress are given in annex 4, pages 38 and 39. Slightly worse situation is observed for load case number 1, where the maximum stress value reached is 234 MPa and it is located in root area of outer weld. Hence, the stress level is generally rather low and sufficient safety margin versus the yield strength of the material exists.

4.2 Heating and cooling pipelines

There is to be installed a system of piping on the internal wall of the vacuum vessel, which will serve for thermal management, i.e. for heating or cooling of the vessel during different service or emergency scenarios. The tentative design proposal for location of the piping is illustrated in Figure 4.16. The preliminary assumption regarding the tube dimension to be selected was considering 12 mm internal diameter and 2 mm wall thickness. The internal diameter selection is to be understood as minimum requirement in terms of enabling sufficient flow rate of the heating / cooling medium and generally sufficient heat transfer capacity of the entire system.

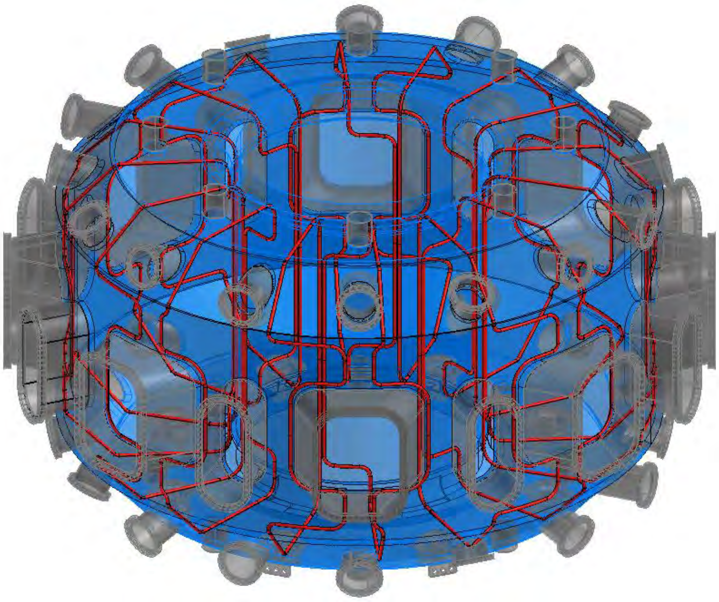

Figure 4.16 – Preliminary proposal for design of piping of heating and cooling system

For selection of the final design of piping and type of joining of the pipes to the vessel wall, there are several factors of high importance:

- Connection of the pipes have to exhibit sufficient integrity and strength to withstand the expected mechanical loading of the pipeline and guarantee firm fixation of the entire pipeline system.
- There must be sufficient capacity to transfer heat from material of the pipes (affected directly by the internal medium) to the vessel wall during heating or vice versa during cooling.
- There may not be formed any enclosed or narrow spaces, which are impossible or difficult to evacuate.
- Minimum possible space should be occupied by the complete system of the piping installation, especially into lateral direction of the pipes, to avoid interaction with other equipment to be installed inside the vessel.
- Selection of similar material for the pipes and weld metal to the material of the vessel wall itself would be highly beneficial in terms of minimizing the thermo-mechanical loading of the piping and joints (for different materials with different thermal expansion there will be imposed significant stresses during the elevated operation temperature).

With respect to the above mentioned there was proposed a solution, where the tubes will be welded to the vessel wall, according to the schematic depiction in Figure 4.17. It means that the pipe shall be welded to the wall by fillet weld from both sides with defined gap size between the tube and the wall surface. To provide sufficient capacity for heat transfer from tubes to the vessel the relatively large weld size of a6 is suggested. In longitudinal direction the welds will be however not continuous, but with regular spacing, to enable evacuation of the zones below the pipes. It is to be expected that in some areas certain portions of the weld will be omitted also for other practical reason, for instance when the pipe will be too close to other equipment of in locations with problematic access to perform the welding.

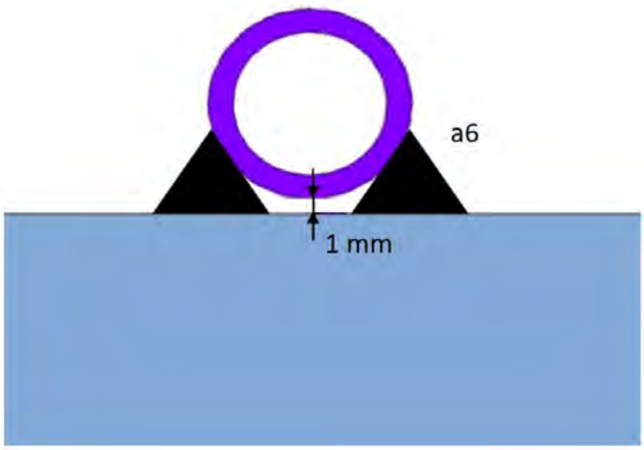

Figure 4.17 – Schematic depiction of joining pipeline to vessel wall by fillet welds

To evaluate the strength of this joining approach, structural analysis was performed for the model covering straight longitudinal segment of the tube with an appropriate section of plate representing the vessel wall and with corresponding number of weld and spacing sections. There were analysed 2 scenarios regarding specific selection of length of the weld segments versus length of spaces where welds are missing. In the first scenario, the length of the weld segments was 80 mm and the length of spaces 70 mm, while in the second one the length of the weld segments was 60 mm and length of the space 10 mm (see also Figure 4.18 with general views of the corresponding FE models). Boundary conditions were set in equivalent way for both of the model scenarios, where on the frontal section planes of the model (with respect to the pipe segment direction) boundary conditions of symmetry were applied and on the lateral section planes all degrees of freedom were fixed (see Figure 4.19 for illustration). There are 2 load cases determined for the unit pipe segment as defined in Table 4.8. The loads are distributed evenly over the internal surface of the pipe.

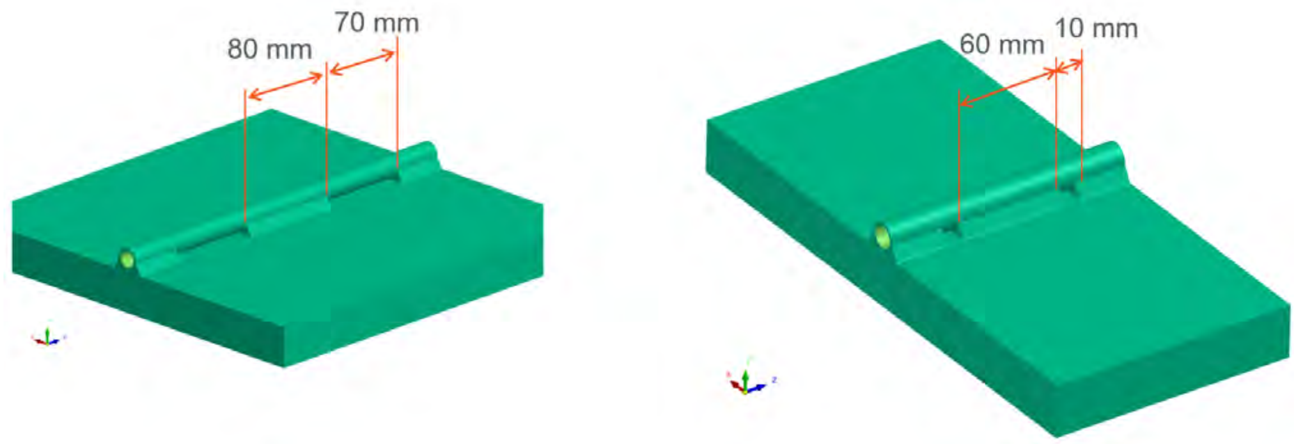

Figure 4.18 – General configuration of models for structural analysis of pipe connections

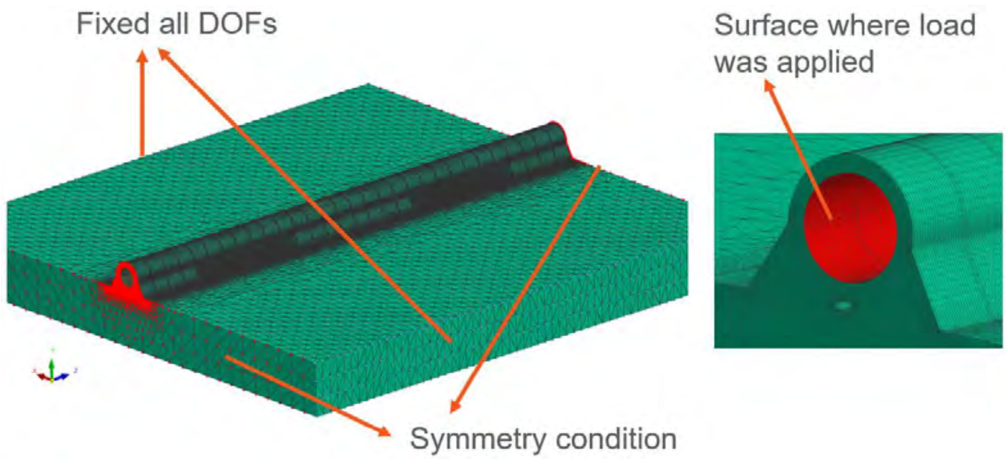

Figure 4.19 – Definition of constraints and area of loads application for the structural analysis of piping segment

Table 4.8 – Pre-scribed/defined load cases for piping segment

Results of these structural analyses in terms of contour plots of total displacements and fictive equivalent von Mises stresses are given in annex 4, on pages 43 to 46 for scenario 1 and on pages 48 to 51 for scenario 2. One can see that because the welds are quite massive, the level of stress affecting complete cross-section of the welds is generally very low for both of these scenarios. But especially for scenario 1, where relatively long segments of the pipe unsupported by the welds are considered, we can then observe remarkable peak values of stress concentrated into the end areas of the weld joints. From this point of view, it is thus advisable to limit the length of the non-welded segments of pipe as much as possible, which will be also beneficial in terms of increasing the heat transfer capacity between the pipes and the vessel wall.

In terms of details of welding technology for this weld, partly challenging is the aspect of selecting the welding parameters in terms of suitable heat input level. This is because on one hand the tube wall is relatively thin, during the welding process it will have rather low capacity to transfer heat and thus the heat input of the process has to be limited to prevent penetration of the molten zone through the full wall thickness. But on the other hand, the vessel wall is of very high thickness and so with the high heat transfer capacity and therefore the heat input of the welding process must be high enough to avoid defects of insufficient fusion. With respect to this compromising situation, it is recommended to perform the welding using the TIG method and a preliminary proposal of welding parameters as per Table 4.9 was given. It is considered that to complete the entire weld joint of specified size a6, there will be needed about 5 weld passes with expected layout of deposition as per Figure 4.20.

Table 4.9 – Suggested welding parameters for joining of heating pipes to the vessel wall

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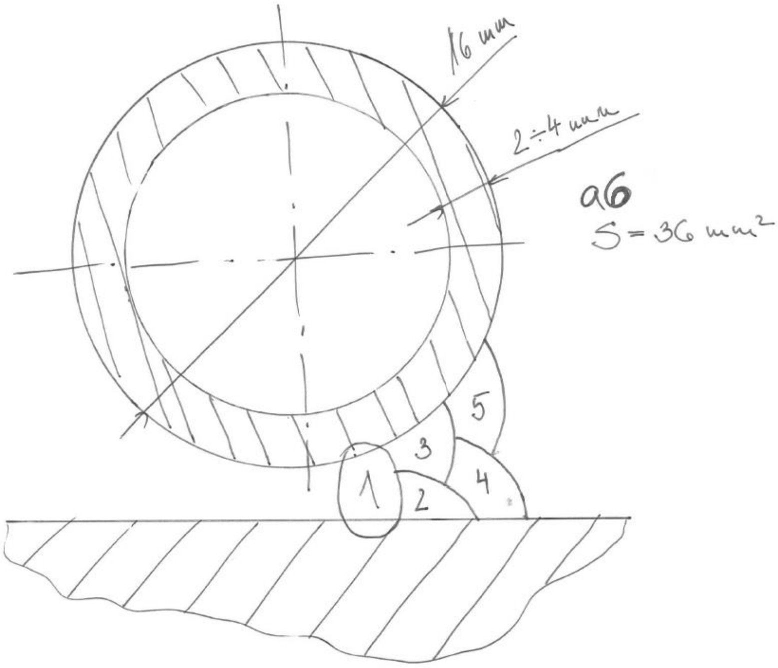

Figure 4.20 – Weld for connection of heating pipes to vessel wall – schematics of weld passes deposition layout

Still there persist some doubts about practical feasibility of the welding process with respect to the above mentioned risk of full fusion of the tube wall. In other words, the question is if the initially intended pipe wall thickness of 2 mm is not too low, or what should be the minimum thickness to select to avoid the full fusion? To get better insight on this problem there was conducted an analysis of the heat transfer using a local sub-model of the pipe-wall welding scenario, where the power input of the process is represented by equivalent moving heat source. There were studied the generated temperature fields mainly in terms of penetration of maximum temperatures into the tube wall. It must be emphasized that the analysis approach applied here does not represent exactly all the physical effect occurring during a welding process in electric arc or in molten zone of the weld. The analysis is done based on modelling of heat transfer in solid material and considering the total heat input corresponding to preliminary estimate of the welding process parameters. It must be therefore understood that the results are not 100% reliable in terms of prediction of performance of the real welding process.

The investigation was firstly done for the scenario, where the pipe and deposited material are considered to be of equivalent material grade as the vessel wall material, it means Inconel alloy 625. The analysis is done using dedicated 3D sub-model, where the mesh is representing a segment of the vessel wall, segment of the pipe and weld between the pipe and wall (on one side only). In Figure 4.21 there is shown cross-section of the FE mesh of this model for the base-line variant with pipe wall thickness

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In this context, the name "Inconel 625" shall be understood as any alloy with chemical composition according DIN 17744/17750, UNS N06625/UNS N26625 or ASTM B443. The reason for giving the name is that this is a commonly used industry habit. Irrespective of the trade name of the alloy, manufacturer or registered trademark etc., the Contracting Authority/Buyer (Institute of Plasma Physics of the CAS) requires to use alloy with specific chemical composition, see Technical Specification, section 4.1.2.

of 2 mm. There is evident also the considered structure of the material deposit increments as per the individual passes of the weld. In Figure 4.22 there is then given the contour plot from the corresponding analysis showing the temperature field in a selected time instant during deposition of the first pass, which illustrates instantaneous effect of the heat source.

This type of analysis was however done in 3 different variants considering different value of the pipe wall thickness (more exactly 2, 3 and 4 mm), while keeping all the other dimensional parameters and considering identical net heat input corresponding to the proposed welding parameters (750 J/mm) and welding speed (70 mm/min). The results are then compared in Figure 4.23 in form of contour plots showing the maximum temperatures reached during the whole process history (deposition of all 5 beads). The legend of the contour plot is set to highlight the level of solidus (1290°C) and liquidus (1350°C) temperature assumed for Inconel 625, so the figure can be understood as representation of penetration of the fusion zone. One can see that for the variant with 2 mm pipe wall thickness the penetration is rather high and therefore the full fusion of the pipe wall is very probable. For the 3 ad 4 mm wall thickness the full fusion should not occur.

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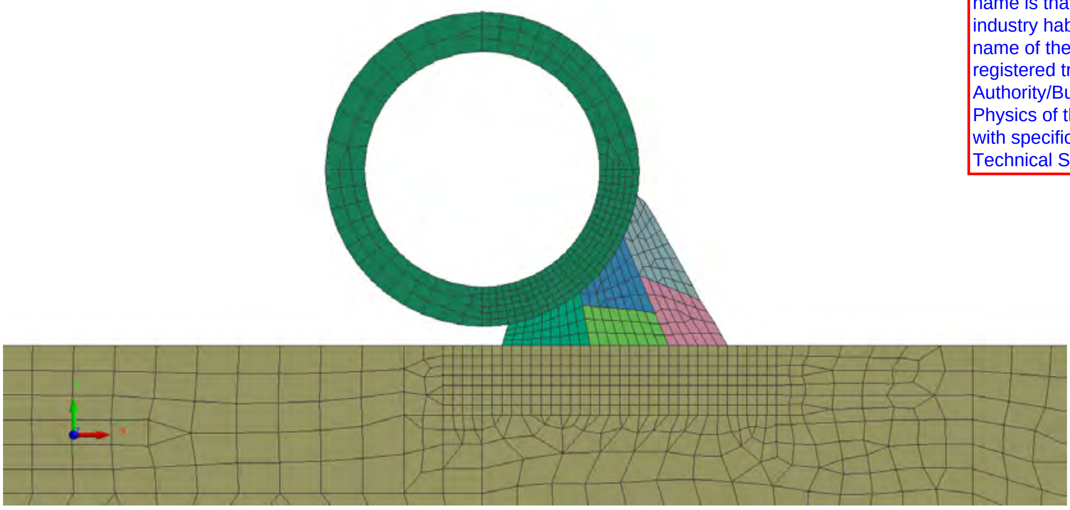

Figure 4.21 – Cross-section of FE mesh used for investigation of thermal fields during the pipe welding (variant for pipe wall thickness of 2 mm)

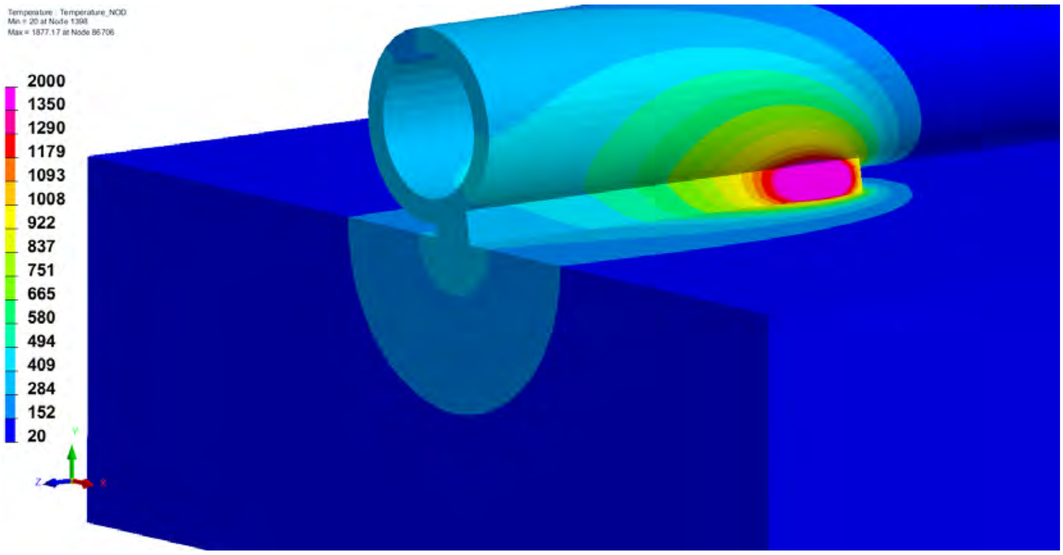

Figure 4.22 – Thermal field [°C] in selected time instant during deposition of the first welding pass (variant for pipe wall thickness of 2 mm)

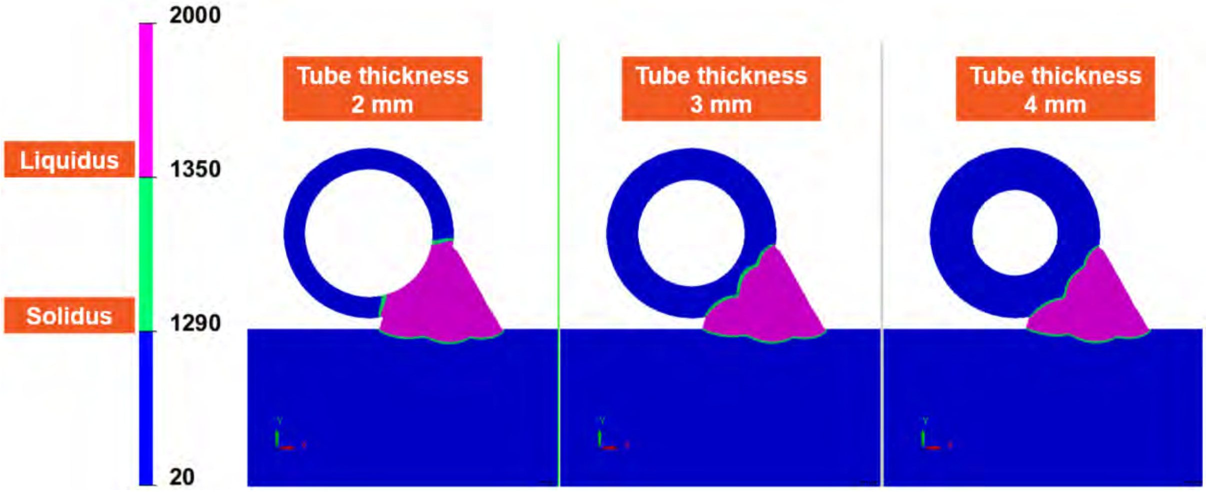

Figure 4.23 – Fields of maximum temperature [°C] reached during the entire process, different wall thickness of pipes made of Inconel 625

Further, this type of analysis was also done for one more scenario, where it was considered that the pipe and weld material would instead of Inconel 625 correspond to the stainless steel grade 316L. The interest for such potential solution is motivated by the fact that steel 316L has better thermal conductivity compared to Inconel 625 and more suitable pipe dimensions are available on the market. Therefore, the pipeline system and the connection welds would in such case provide better performance during operation of the fusion reactor in terms of transferring heat between the pipes and vessel wall. (On the other hand, one has to consider the risk of thermal strains and

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stresses induced at the operating temperature due to different thermal expansion of the mentioned material grades). Also, the relatively higher thermal conductivity of the 316L steel grade was considered as potentially beneficial factor to reduce the risk of full fusion through the pipe wall during the stage of welding the pipes to the vessel wall.

For the scenario of modified material properties of the pipe and weld, the analysis was already done only for the variant of 3 mm wall thickness. The primary intention was to do this analysis with consideration of identical power input as it was described above in case of the analyses considering all components of the system made of Inconel 625. However, it turned out that in this scenario, the power input is then not high enough to provide sufficient heating of the weld zone, especially on the side towards the vessel wall material domain. Therefore, the analysis was updated for assumption of partly higher net power input (900 J/mm), while considering still the same welding speed (70 mm/min).

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The results in terms and of contour plot of maximum temperatures reached are presented in Figure 4.24 and they are directly compared to corresponding situation from Figure 4.23 (i.e. all components made of Inconel 625, pipe wall thickness of 3 mm), where the focus is done on displaying of the maximum spread of the relevant levels of temperature corresponding to solidus and liquidus of the materials towards the domain of the pipe wall. It can be stated that there is not evident any significant difference between the two compared scenarios.

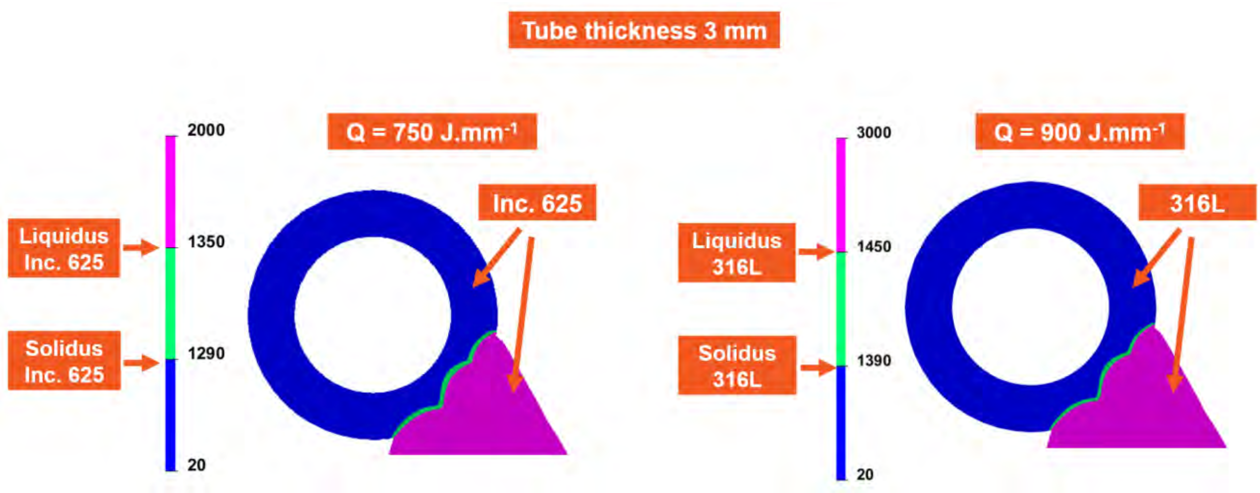

Figure 4.24 – Fields of maximum temperature [°C] reached during the entire process, Inconel 625 vs. steel 316L

At this place it is to be repeated that previously presented results of thermal field analyses have to be understood as very approximate. To fully confirm the feasibility of the process in terms of avoidance of the pipe wall fusion, there will be necessary to perform practical welding experiments. However, the presented simulation results should enable to significantly reduce the number such practical experimental scenarios.

5 NUMERICAL SIMULATION OF THE SELECTED WELDING PROCEDURE – PREDICTION OF DISTORTIONS

In order to validate the feasibility of the manufacturing process of the vacuum vessel (with respect to welding induced distortions arising during the fabrication), the major stages of the manufacturing procedure as suggested above in section 2.2 were subject to the numerical simulation. More exactly we speak about non-stationary analyses of the thermal fields in the material induced by power input of the process followed by analysis of thermo-mechanical response of the material taking into account also the changes of material properties vs. temperature. These analyses were done using finite element method (FEM) based software SYSWELD, which is well renowned and fully industrially validated tool for this type of simulation.

The analyses were split into several stages as it corresponds to the suggested manufacturing process. Thus there were done especially simulations of the welding process of the inner and outer sub-assemblies of the vessel, where the important point to see was, if it will be possible to meet very stringent tolerance requirements for both of the parts of the vessel, which is also critical for enabling the final assembly of the entire VV assembly from these main sub-assemblies. The operation of the final vessel assembly and joining using EBW process was also a subject to a corresponding simulation stage.

Hence the numerical modelling as described below does not necessarily cover all the manufacturing operations or all the welds which will be done in practice. For instance, there are typically not simulated operation of welding assembly of individual basic components used later in the higher assemblies of the VV, which are of simple geometrical shape (planar, cylindrical etc.). This is because that even if some significant distortions would appear for these cases, they will be quite easily repaired by mechanical straightening. Also the simulation typically neglects the welds, where it is not expected that they could significantly contribute to the overall welding distortions (typically welds with relatively low quantity of deposited material etc.)

More details about the structure of the FE models used for these simulations will be given below in this chapter. However, generally it can be mentioned that for the FE mesh construction, the geometrical symmetries of the VV were considered. The vessel design is axisymmetric toroidal shell with certain pattern of repetition of different types of ports or adapters on it. Hence the FE models are constructed for a sector covering 45° in circumferential direction and ½ of the entire VV height. Naturally the corresponding symmetry boundary conditions are then applied for execution of the simulations. The FE mesh is built using exclusively solid elements and there are applied high mesh refinements in the areas of weld joints, which is necessary to properly describe the physical phenomena in these zones in terms of capturing the high time and space gradients of different quantities.

The VV is a very complex assembly with high number of weld joins (moreover we speak about multi-pass welds, often with high number of passes), therefore the numerical model will have quite a high number of elements and nodes, and thus the execution of non-stationary analysis of the corresponding process tends to have very high requirements on computation resources and time. To keep these requirements at a practically acceptable level, the simulation approach referred usually as imposed thermal cycle (ITC) method is applied. In this approach the strictly localized effects of moving heat source are substituted by applying the heat input instantaneously into a larger longitudinal segments of a single weld pass, as illustrated on page 4 of annex 3. The thermal cycle applied has to be representative for the given weld joint and weld pass and is obtained as result of dedicated calibration procedure for the specific welding parameters. Anyway, the key aspect related to usage of the ITC method is that it allows to optimize the meshing of weld joints areas and also the global scheme of time increments of the analysis and consequently leads to significant reduction of the total resolution times. At the same time this methodology is fully industrially validated and presents no qualitative compromise in terms of prediction of the residual distortions.

Throughout this chapter, numerous references to annex 3 will be mentioned, which is presentation in PPT format containing mainly depictions of the results from the numerical analyses of distortions. This is mainly because the PPT format is more suitable also in terms of comprehensibility and recognition of details in such type of graphical depictions. Therefore, only relatively low number of the pictures will be given or reproduced also directly in this report.

5.1 Analysis of the inner sub-assembly welding

The inner sub-assembly, as already described above in section 2.2.2, is to be composed of the inner cylindrical shell, two pieces of the forged rings and of adapters welded to inner surface of this portion of the main shell. In terms of the analysis the modelling will cover the circumferential welds between inner cylindrical shell and forged rings (which are naturally quite massive) and the welds of the first wall adapters (which are not really subtle and moreover the number of these adapters and weld is high) joined to the inner cylindrical shell.

The overview of FE model of the inner sub-assembly (including the considered symmetry conditions) is shown in Figure 5.1. Some additional information, including detailed mesh views of some key areas of the model can be found on pages 7 to 9 of annex 3.

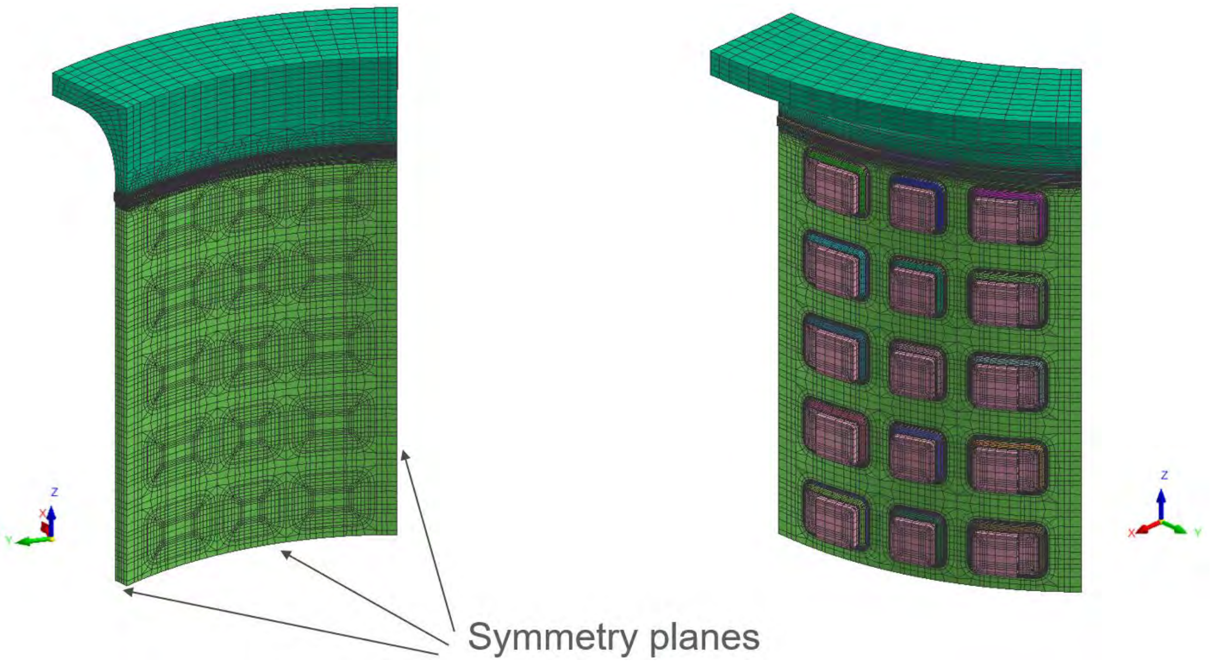

Figure 5.1 – FE mesh of the inner sub-assembly – general view

Results from this analysis are documented in annex 3 on pages 12 to 21 through the two main stages of this sub-assembly manufacturing, i.e. after completing the circumferential welds between the inner cylindrical shell and the forged rings and for the final state after welding also the adapter. Here we will sum-up the situation directly for the final state.

The dominant deformation mode of the inner sub-assembly is shrinking in axial direction of the vessel. This is caused mainly by shrinking of the circumferential weld between the inner cylindrical shell and the forged ring, where directly after finishing this weld we observe typical value about 1.2 mm. (The field of displacements is slightly variable vs. the circumferential direction of the vessel, with typical magnitude of the variation about ± 0.2 mm, which is caused by the effects of welding sequence defined for the circumferential direction. We expect that similar level of variations, i.e. in the order of some tenths of a millimetre, will be possible to observe around the circumference of the vessel also in practice). In the final state of the sub-assembly, it means after there are welded also all the adapters, the value of the axial shrinkage yet partly increments to typical value about 1.6 mm, see also Figure 5.3. Here we have to realize that the mentioned values correspond to the “one half” FE model with symmetry conditions also in the axial direction. For the full vessel the axial shrinkage value will thus total about 3.2 mm.

Another deformation mode, that can be observed are displacements in radial direction, where mainly in the area of the inner cylindrical shell occurs certain intrusion of the VV wall towards the axis of rotation of the vessel. After the deposition of the circumferential welds remains this effect still very limited with maximum values of the axial displacement about -0.2 mm, which are located just near the circumferential welds. For the final state after welding the adapters, this displacement component further increments, see Figure 5.4. Some kind of local intrusion of the vessel wall (towards the vessel axis) occurs under each of the adapters with typical value of the axial displacement reaching about -0.5 or -0.6 mm. The resulting effect after welding all adapters is kind of integral and especially for the first row of the adapters next to the circumferential weld it interacts with the effects of this weld also. Therefore, in the area of the first row of the adapters the extreme value of the axial displacements is about -0.9 mm.

On the other hand, the area of free edge of the forged ring (where joining with annulus shall be done later in the process) remains with practically no effects of radial or angular distortions.

Regarding the circumferential component of displacements, it can be stated that generally for the entire inner sub-assembly, no practically significant values were observed.

There was also done certain sensitivity analysis regarding effect of the welding sequence selected for joining of the adapters to the vessel wall on the final distortions of the sub-assembly. However, the conclusion is that this effect is rather negligible. For the different sequences there can be seen some small local discrepancies of final radial displacement, however the relative differences, which can be reached for the individual adapters are in the range of about 0.05 to 0.1 mm.

The observed magnitude of the distortions is not small, but the deformation modes of the inner sub-assembly are quite simple, enabling relatively easy compensation during the manufacturing process. This will succeed by application of suitable material allowance for the initial axial dimension of the inner cylindrical shell component and further by sufficient allowance for the height of the adapters. In other words, when the right size of allowances will be applied, the simulation confirms the suggested welding procedure of the inner sub-assembly to be feasible.

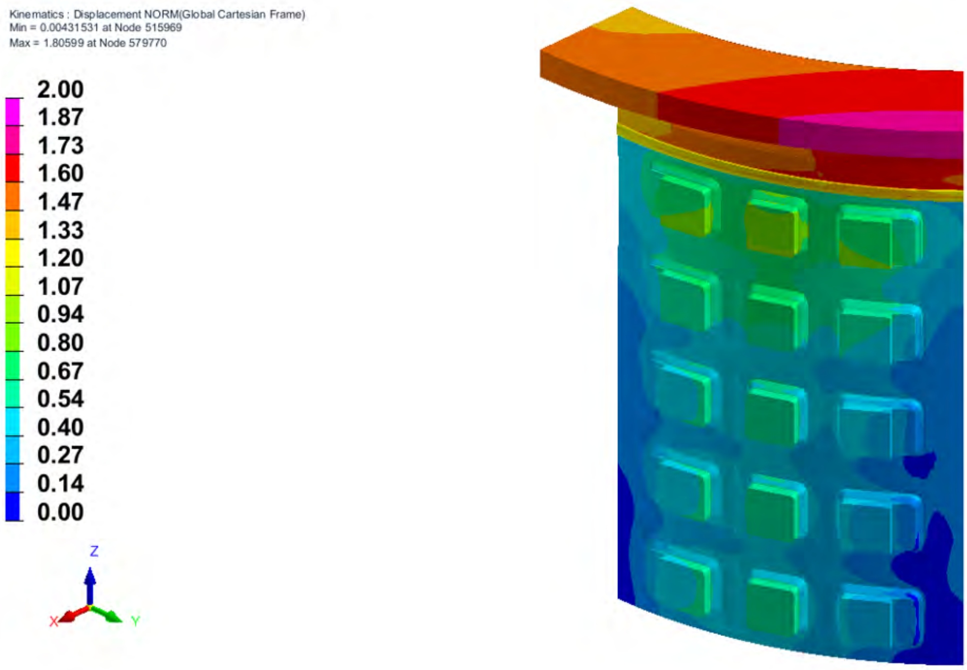

Figure 5.2 – Total displacement [mm] – final state for the inner sub-assembly

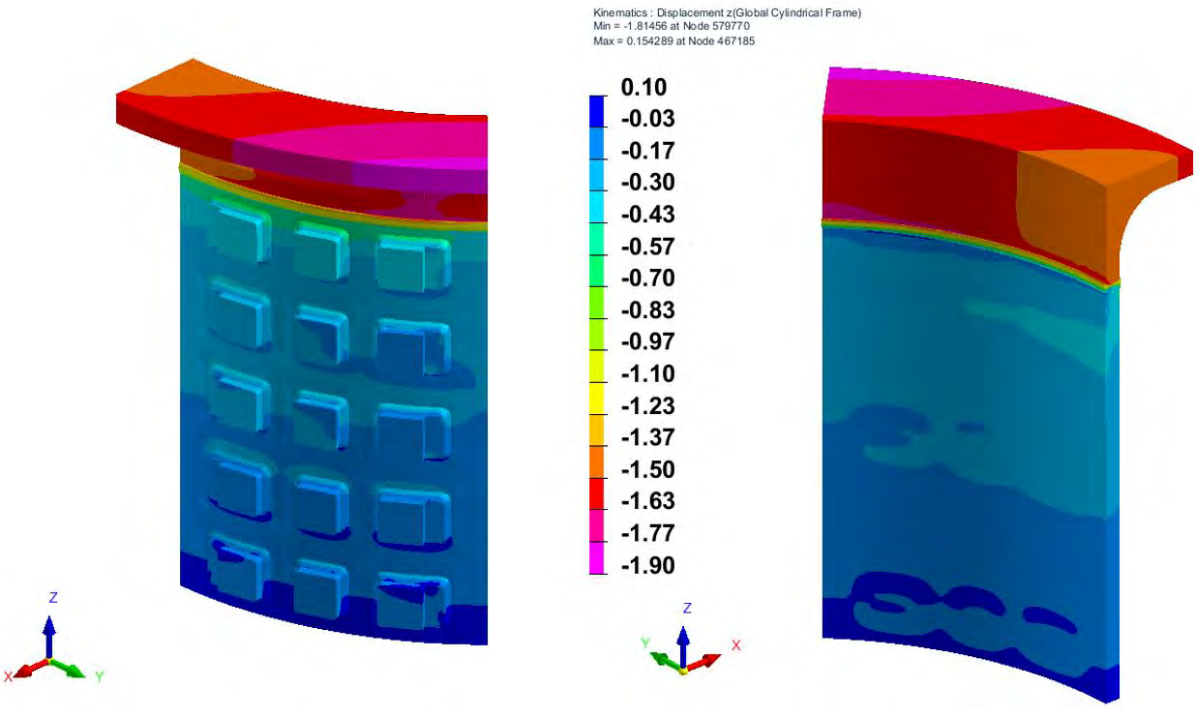

Figure 5.3 – Axial displacement component [mm] – final state for the inner sub-assembly

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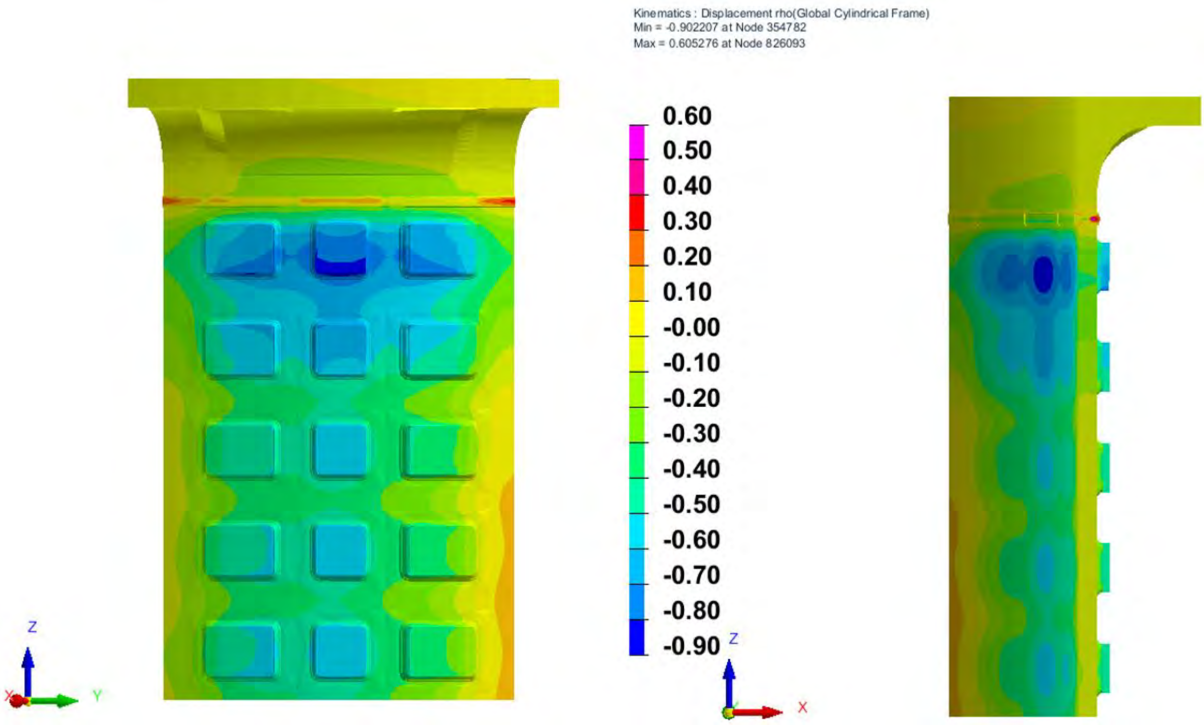

Figure 5.4 – Radial displacement component [mm] – final state for the inner sub-assembly

5.2 Analysis of the support column adapter welding

The welding of the support column adapters is considered as another potentially problematic operation in terms of distortions, therefore it is also subject to the numerical prediction of welding induced distortions.

Details about the suggested manufacturing and welding procedure were described above in section 2.2. The adapters are supposed to be welded to the standalone component of annulus, hence the arising sub-assembly has relatively low stiffness in this manufacturing phase and it is needed that after the welding it will meet dimensional tolerances enabling later integration of this sub-assembly into the outer sub-assembly of the vessel. There is considered application of conventional welding process (MIG) and the welds for connecting this adapter will be very massive. More exactly there is considered application of 1/2 V 30 mm groove preparation and MIG process welding from inner side followed by filet a7 MIG weld applied from the external side.

The mesh of FE model for this analysis is presented in Figure 5.5, it corresponds again to sector of the structure of 45°, where conditions of symmetry will be defined on the section planes during the analysis.

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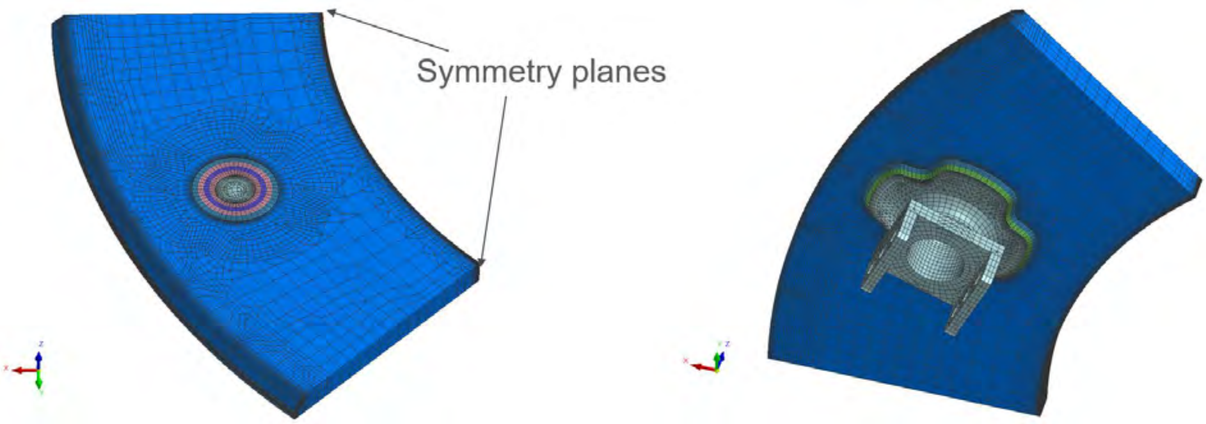

Figure 5.5 – FE mesh of the model for the support column adapter welding analysis – general view

Regarding this part of analysis, see also annex 3, pages 22 to 28. The resulting distortion mode is coming from certain counter-balance of effects of the 1/2 V weld done from internal side (which is having majority of deposited material volume offset from the annulus mid-surface towards its internal surface) versus the fillet weld done on the external surface and thus imposing also some shrinkage effect to opposite direction (compared to the 1/2 V weld). Anyway, after finishing all the welding operations, there can be observed distortion of the annulus sheet turning it into slightly conical shape with Z (axial) deviation between the internal and external edge of around -1 mm, see also Figure 5.7.

Also, the shrinkage of the weld metal causes some distortions, which can be observed as circumferential shrinking of the whole anulus and thus resulting into radial intrusions of its edges towards the centre of the coordinate system, see Figure 5.7. On the external edge of the annulus sheet the extreme of the radial distortion is close to the adapter position and reaches about -0.5 mm. On the internal circumference the extreme values are about -0.2 mm.

Generally, we see the magnitude of the arising distortions for this sub-assembly as very limited, a positive aspect is also that the distortions are quite uniform in circumferential direction of the anulus, hence there occurs no significant localized deviation around position of the adapter. The distortions in radial direction are from practical point of view unimportant and can be easily compensated by small allowance applied on the edges of the annulus component. The deformation towards the axial direction shall be eventually repaired by mechanical straightening.

For the joining of the support column adapter, there were also suggestions to perform the welding from inner side alternatively by EBW. However, based on the above results this option seems not really attractive enough (we expect much higher cost and complicated logistics in case of EBW application) while the distortions are not really critical for the purely MIG process.

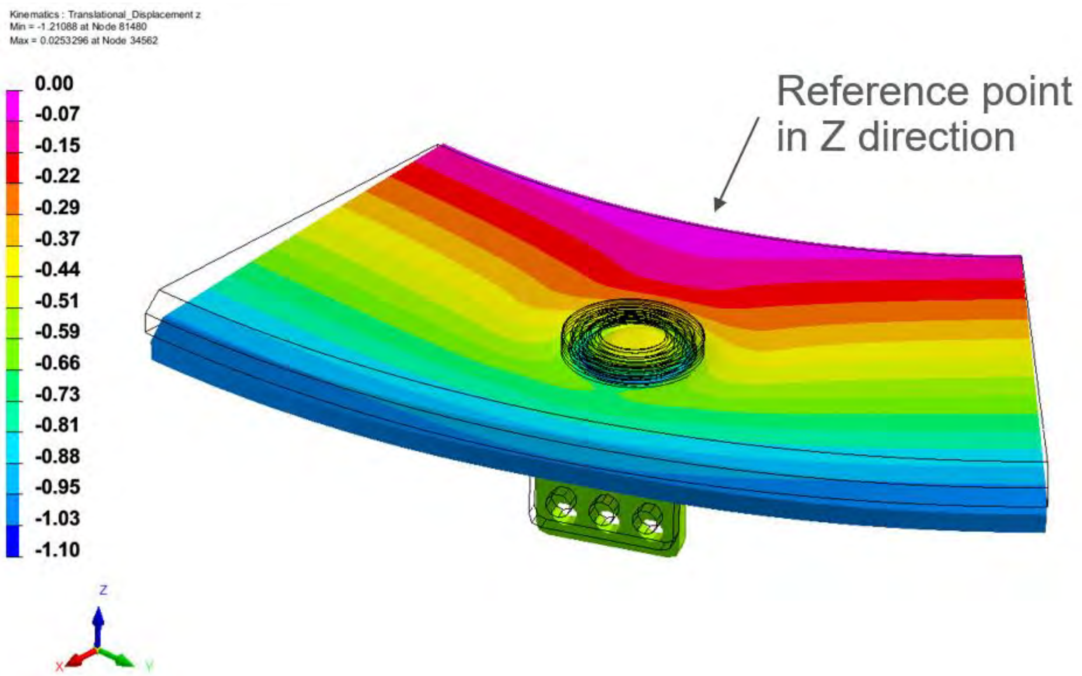

Figure 5.6 – Axial displacement component [mm] – final state for the sub-assembly

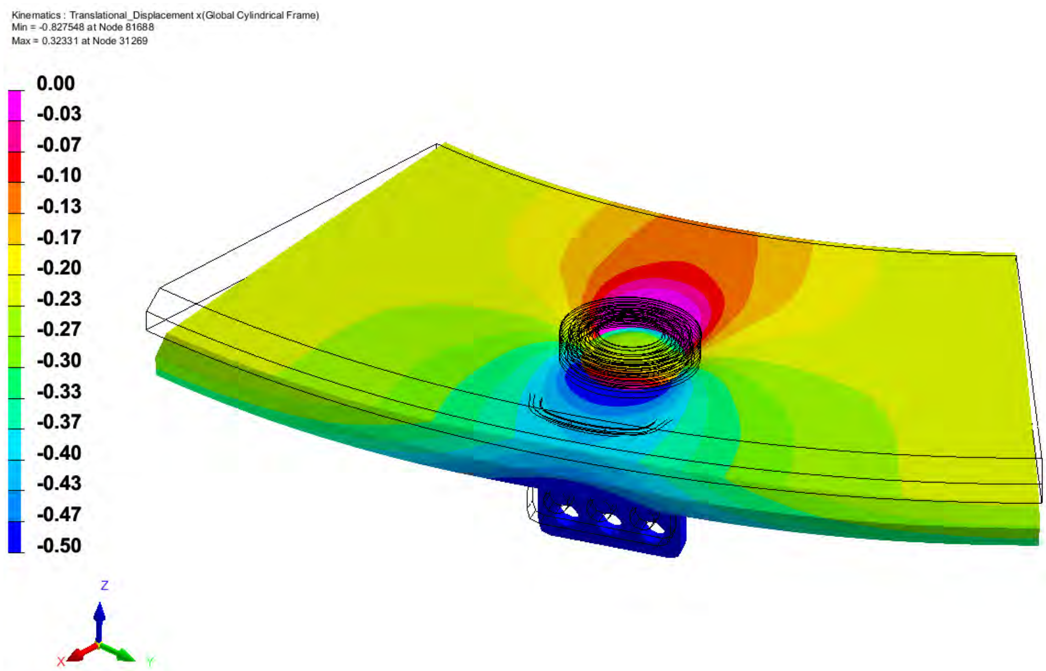

Figure 5.7 – Radial displacement component [mm] – final state for the sub-assembly

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5.3 Analysis of the outer sub-assembly welding

The outer sub-assembly, as it was already described in section 2.2.2, is to be composed from the outer cylindrical shell, annuluses and cones and further from different types of ports and adapters welded to the corresponding segment of the main shell.

The numerical analysis is used here to study the process of the outer sub-assembly welding through its different stages, like welding the circumferential welds on components of the main shell and then further during the installation and welding of ports. The overview of the FE model of the outer sub-assembly is shown in Figure 5.8. It is again a model corresponding to angular sector of the vessel of 45° and 1/2 in height, where conditions of symmetry are applied on the section planes.

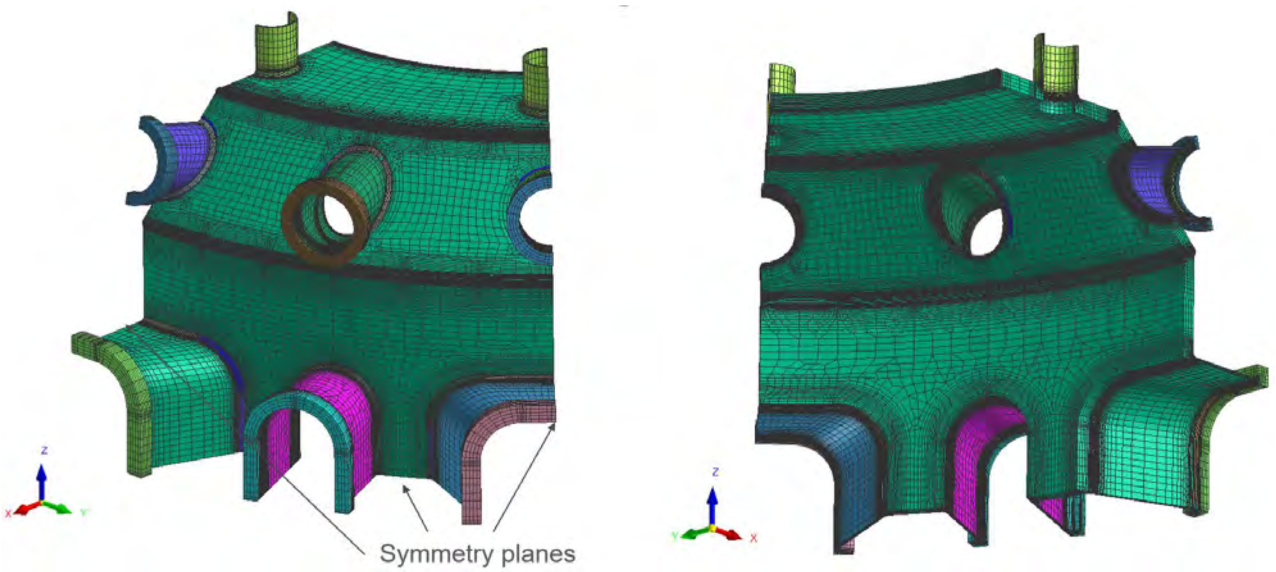

Figure 5.8 – FE mesh of the model for the outer sub-assembly – general view

In case of the outer sub-assembly, there were assessed 3 variants of the numerical analyses denoted as A0, A and B, which were evaluating certain modifications of the proposed process configuration. The corresponding conditions and results from all of these variants are presented in detail in annex 3.

The variant denoted as A0 is documented in annex 3 on pages 29 to 39 and it is focussed only on the stage of welding components of the main shell. It considers configuration of symmetrical X-shape welds on the interfaces of the outer cylindrical shell with cones and between cones and annuluses. The aim was mainly to investigate the typical distortion modes and magnitudes which will occur in situation when the individual components are not constrained by any tools or stiffeners or other tools during the welding process. It was shown that in such situation, there occur quite intensive distortions of the main shell, mainly in area of annuluses, which are moving inwards the vessel domain. The resulting magnitude of distortion would not be acceptable in practice. Consequently, and based also on this analysis results, there was recommended the usage of reinforcements, which are to be inserted in the outer sub-assembly during the vessel manufacturing.

The analysis variant denoted as A corresponds fully to the current proposal of the manufacturing procedure, as it is described in this document (section 2.2). Execution and results of this analysis variant will be discussed in more detail below in this section of the report. However, in brief we can state that the results indicate level of distortions which is not negligible, but which can be kept under control or compensated in practice with suitable precautions (as described in chapter 3). The maximum distortions, which from practical point of view can be potentially problematic, still occur in area of annuluses and into large extent arise already during the stage of welding the circumferential welds joining components of the main shell of the vessel. But due to usage of reinforcements the final level of the deformation is strongly limited.

The analysis variant denoted as B was consequently performed as an additional attempt to further reduce the mentioned distortions of the main shell in area of annuluses. For that purpose, there was suggested modified configuration of the circumferential welds between components of main shell of the vessel. Instead of the symmetrical X-shape welds considered in analysis variants A0 and A, there was suggested modified shape of the weld bevels leading to non-symmetric distribution of deposited material of the individual weld joints. The details of the configuration and corresponding results for variant B can be found in annex 3 on pages 76 to 102. However, it had to be concluded that such process modification would not be beneficial, because in area of annuluses the distortion magnitude was not really reduced, while in some other areas, like on the outer cylindrical shell, the deformations were augmented quite significantly.

Let us now focus in more detail on description of the execution and results of the analysis variant A, because as already mentioned, it is the representative one for the current proposal of the outer sub-assembly manufacturing process defined in this report. See also annex 3, pages 40 to 75, where more details regarding this analysis variant are given, mainly in terms of more numerous results depictions.

In Figure 5.9 and Figure 5.10 we can see deformations of the outer sub-assembly after the main shell components are joined by the circumferential welds. In this stage of the outer sub-assembly welding the most intensive distortions occur in the zone of annulus, which is getting deformed into slightly conical shape. In terms of axial component of displacement, the edge of annulus welded with cone is intruding in the direction inwards the vessel by about 2.5 mm, while the free internal edge of annulus is moving by about 0.6 mm outwards. There can be also observed certain level of displacement in radial direction. Close to the weld of the outer cylindrical shell with cone there is radial intrusion slightly below 1 mm, in the zone of weld of cone with annulus, it reaches up to around 1.5 mm. Even though this is not directly visible in the figures, it is to be reminded that these results correspond to situation when the reinforcements are installed in the subassembly (they are modelled by equivalent elastic conditions).

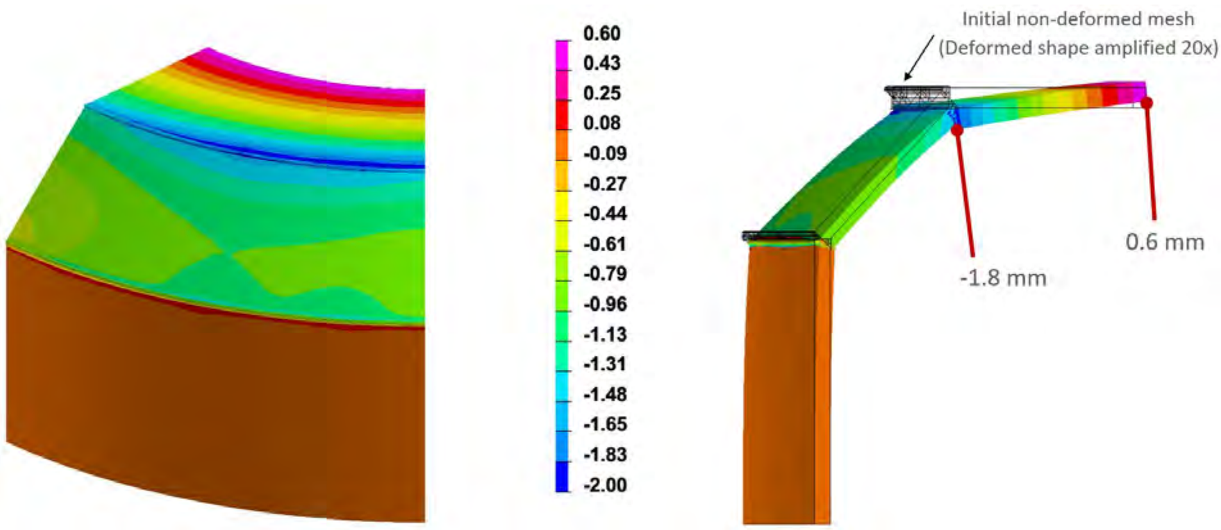

Figure 5.9 – Axial displacement component [mm] – after finishing the circumferential welds

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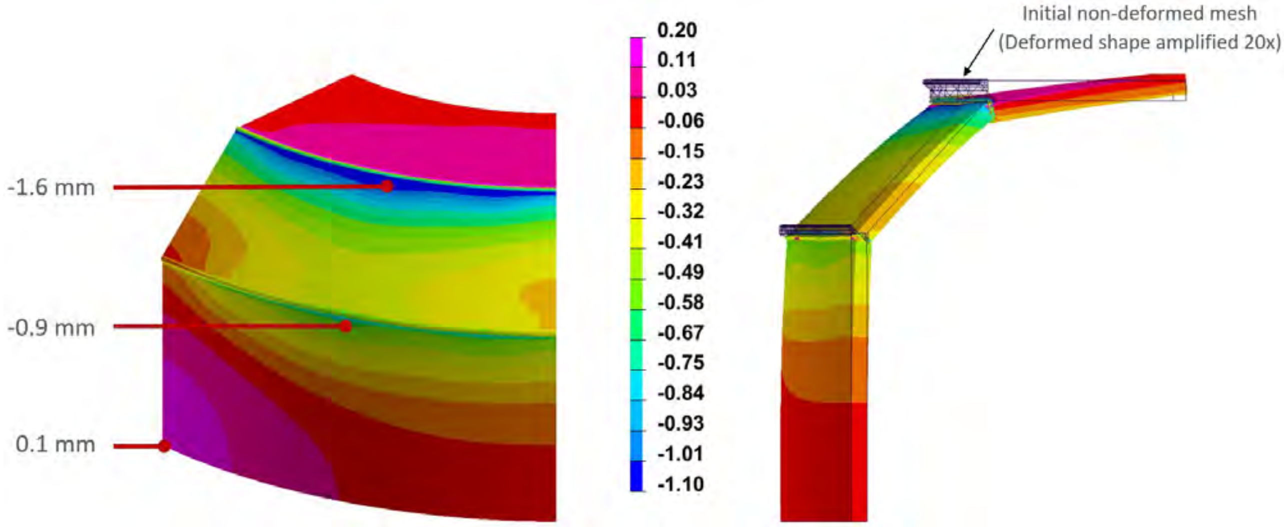

Figure 5.10 – Radial displacement component [mm] – after finishing the circumferential welds

Consequently, the analysis continues with representing the effects of opening holes in the main shell and deposition of welds on the ports. The corresponding resulting deformations are presented in Figure 5.11 (axial component) and Figure 5.12 (radial component) and they are useful for understanding of distortion of the main shell in the final state of the outer sub-assembly. (In fact, these results are not relevant for the domains of ports. The reasons for that are explained in the next sub-section and there will be also given additional results which in the contrary are representative for ports).

The most critical situation is observed for the main shell are distortions in area of conus and annulus. The zone of weld between conus and annulus is being intruded inside the vessel, while the free internal edge of annulus is moving outwards. Similarly, we can observe distortion of the annulus sheet turning into conical shape with final axial distortions on outer edge about -2.6 mm and on inner edge about 1 mm. This type of distortion mode was existing here already after welding the circumferential welds on the main shell, but the magnitudes were lower (in interval of -2 to +0.6 mm), hence it can be seen that machining of holes and welding of the ports is further increasing the magnitudes.

There is also certain level of residual radial distortions, which can be observed mainly in area of the outer cylindrical shell and conus, see Figure 5.10. The field is relatively complex and variable through different zones of the surface of the mentioned components, firstly because of effect of welding sequence considered for the circumferential welds and secondly based on proximity and effect of welds of the different ports. Generally, the values lie in interval between -1 mm to +0.5 mm.

The presented results therefor correspond to the state of outer sub-assembly in which it will be later fitted to the inner sub-assembly and both will be joined together by EBW operation. And it should be reminded again that this is the situation, when the reinforcements are still installed inside the inner subassembly and thus limit the actual magnitude of distortions of the main shell. In practice, for some critical locations these distortions will need to be optimised and compensated first, to enable successful execution of the final assembly with the inner sub-assembly.

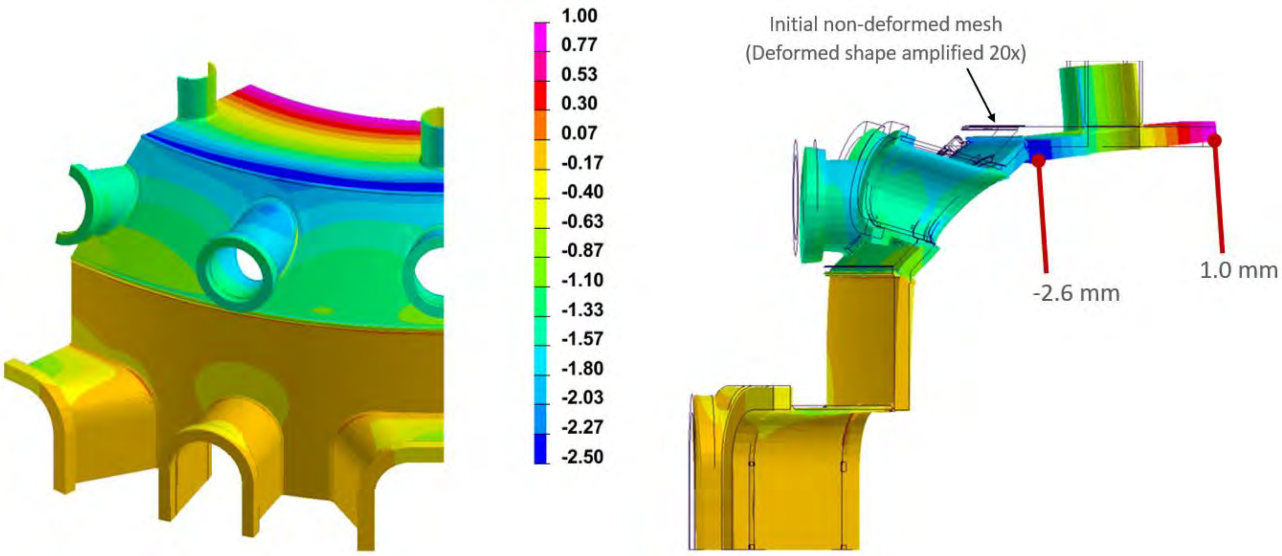

Figure 5.11 – Axial displacement component [mm] – final state for the outer sub-assembly

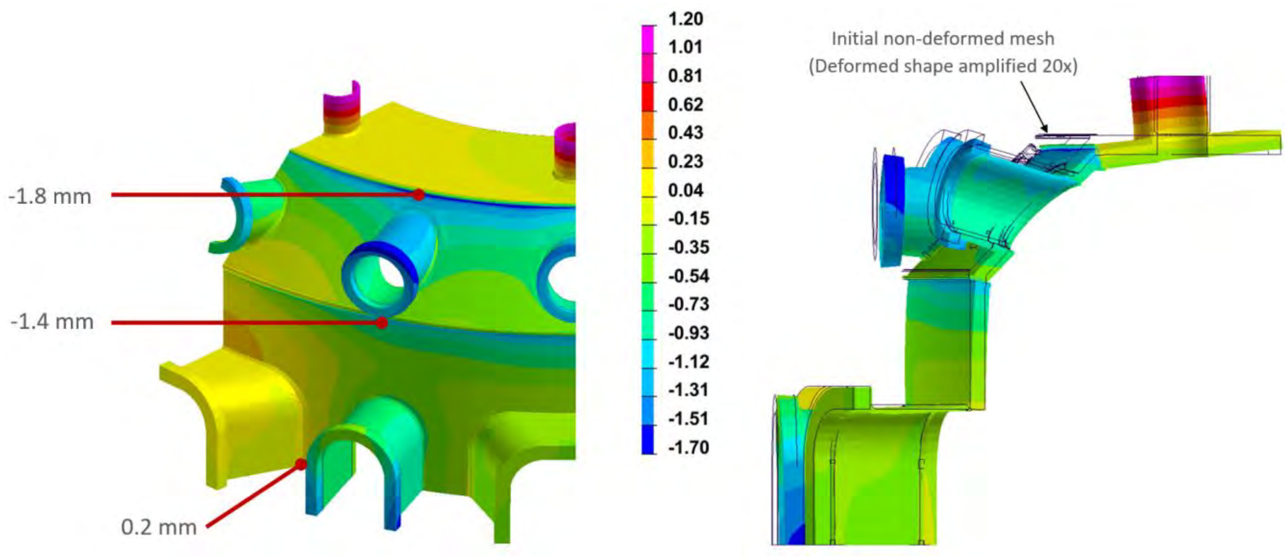

Figure 5.12 – Radial displacement component [mm] – final state for the outer sub-assembly

5.4 Analysis of distortions of the ports

As it was already mentioned, the results presented above in section 5.3 are useful to understand the overall distortion of the main shell cumulated during the entire process of the outer sub-assembly welding. On the other hand, they are not really relevant for evaluation of distortions induced in areas of the ports. This is because during the analysis documented in the previous section the history of displacements is continuous through the complete time range of the modelling. Therefore, the domains of mesh corresponding to material of ports will experience significant increments of distortions already during the stage of welding the circumferential welds of the main shell and afterwards further evolution of the displacements occur due to the operations of welding the ports itself. However, this does not really correspond to the situation in practice, where the main shell will be welded first and even if some distortions occur during that, the ports will be consequently positioned and pre-fixed on it rather with the desired and correct initial position and orientation prior to their welding. And thus, only the distortion increments generated afterwards during the port welds deposition are important from this aspect. Therefore, an independent analysis was performed to investigate exactly this part of the effect.

The FE mesh used is of the same configuration as presented above in Figure 5.8, but deposition of the circumferential welds is not simulated. Therefore, the model is still in undeformed shape when simulation of the port welding starts and the displacement history will cover only the ports welding stage effects. There are presented the general views of the model with contour plots of axial (Figure 5.13), radial (Figure 5.14) and circumferential (Figure 5.15) components of the displacement vector. But one should also inspect annex 3, pages 103 to 116, where additional depiction with more detailed analysis of the displacement fields are given.

Based on these figures, we can firstly understand, what is the contribution of the simulated welding operations to the distortions of the main shell of the assembly. We find it as relatively limited. The most visible distortions for the main shell occur in radial direction and are located next to the MN port. The extreme value is here about -0.9 mm (direction towards the centre of the vessel). Another effect to be considered is increment of axial distortions on internal free edge of annulus, which reaches value of 0.3 mm.

Distortions of the different ports and their flanges have quite complex character but are usually within the total value about 1 mm. The extreme value then occurs on the flange of the MN port with value of -1.7 mm in radial direction. Generally, we consider the observed distortions of the port bodies as non-significant. They correspond mainly to local deflection of the port shells (which are not critical from practical point of view) and of the flanges (these are to be considered but can be compensated quite easily by application of suitable material allowance to the flanges). On the other hand, we do not observe any significant global deviations of the ports like angular distortions of their axes.

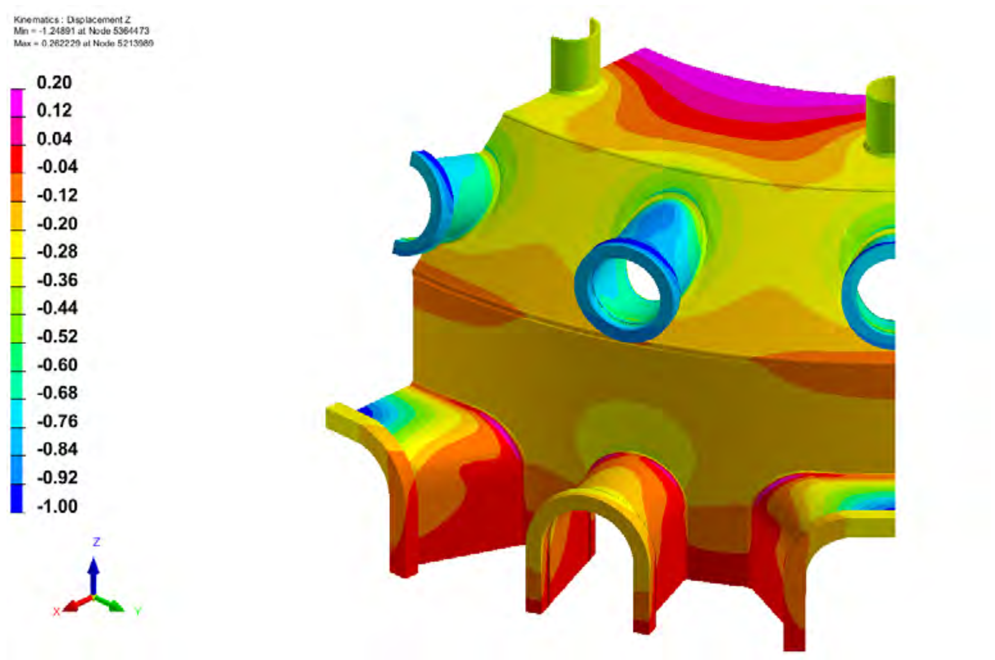

Figure 5.13 – Axial displacement component [mm] – isolated effect for areas of ports

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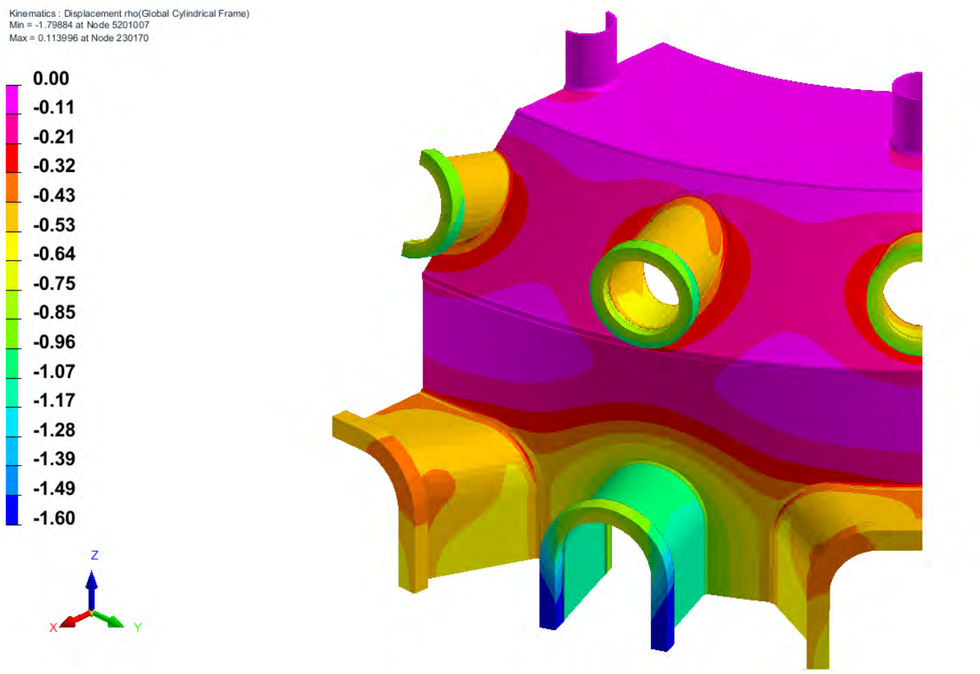

Figure 5.14 – Radial displacement component [mm] – isolated effect for areas of ports

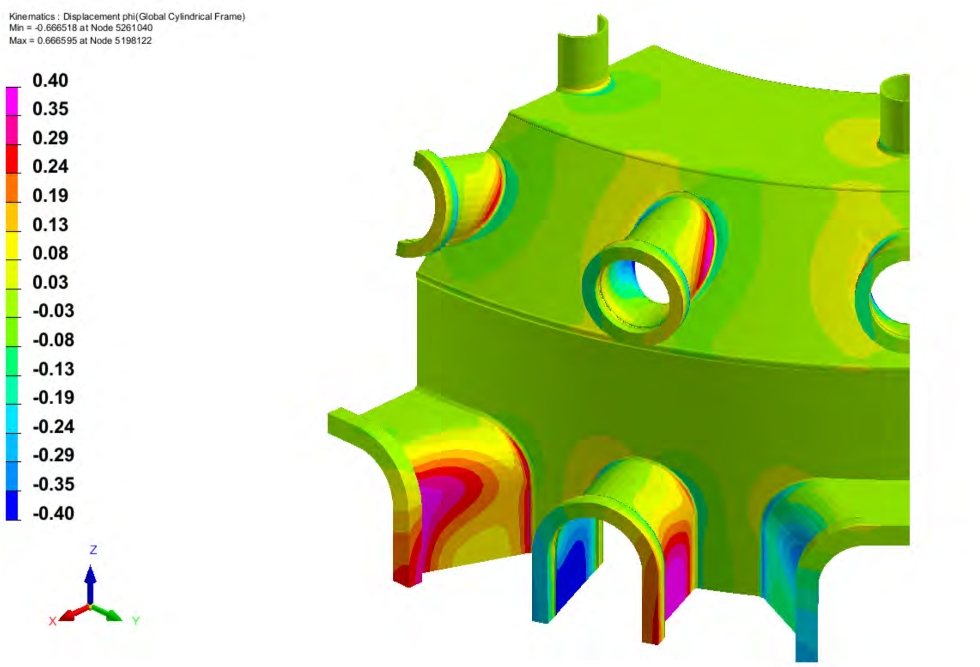

Figure 5.15 – Circumferential displacement component [mm] – isolated effect for areas of ports

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5.5 Analysis of the EBW joining of the inner and outer sub-assemblies

In this part of analysis, there is studied the increment of distortions which shall be induced by the operation of electron beam welding of the outer and inner sub-assemblies along the edge of the annulus and the forged ring.

This is done as quite stand-alone simulation (without a direct transfer of the results from the inner and outer sub-assembly simulations), because in practice for this final joining operation both the major sub-assemblies will have to be well fitted and their distortions compensated. However, the effect of removing stiffeners (and thus corresponding residual stress rebalancing), which are kept in the outer sub-assembly until the EBW joining operation is completed, is represented here by application of inverse values of appropriate reaction forces from the previously performed welding simulation of the outer sub-assembly (variant A).

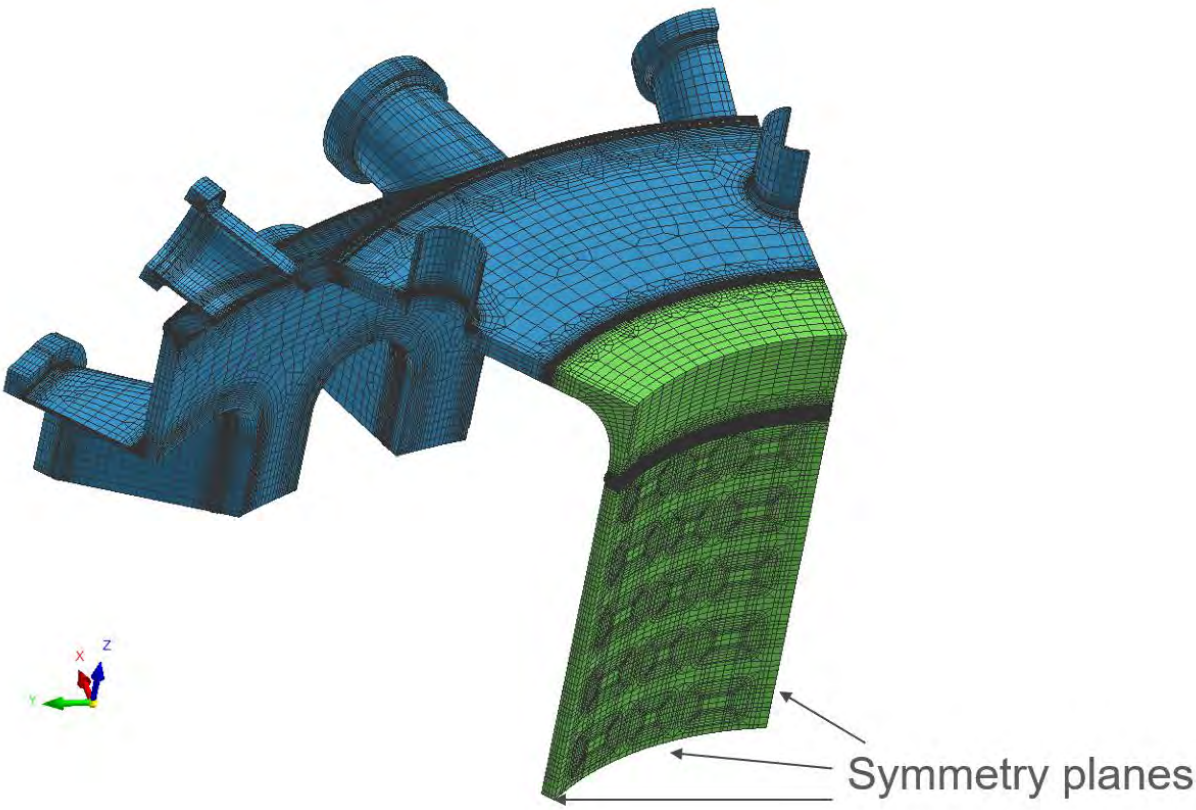

Figure 5.16 – FE mesh of the model for the EBW process modelling – general view

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Based on the results of the analysis we can evaluate the magnitude of distortions coming from the EBW process as very low.

The transversal shrinkage of the weld results into relatively small angular deformations pronounced mainly into the area of annulus on one side and of the forged ring on the other side. Decomposing this effect into components of distortions expressed in cylindrical system, we can speak about radial displacement (see Figure 5.13) of about -0.25 mm on the outer edge of annulus and 0.15 mm on the inner edge of forged ring. There can be also seen axial displacement (see Figure 5.12) of less than -0.2 mm in the anulus area.

The values mentioned above correspond to situation just after completing the EBW operation. In annex 3, pages 117 to 127 additional depictions of this analysis results are given. There is also presented the state after cancelling effect of the stiffeners (inserted inside the outer sub-assembly), when the distortions yet partially change, however the magnitude of this change is again very small and from practical point of view negligible.

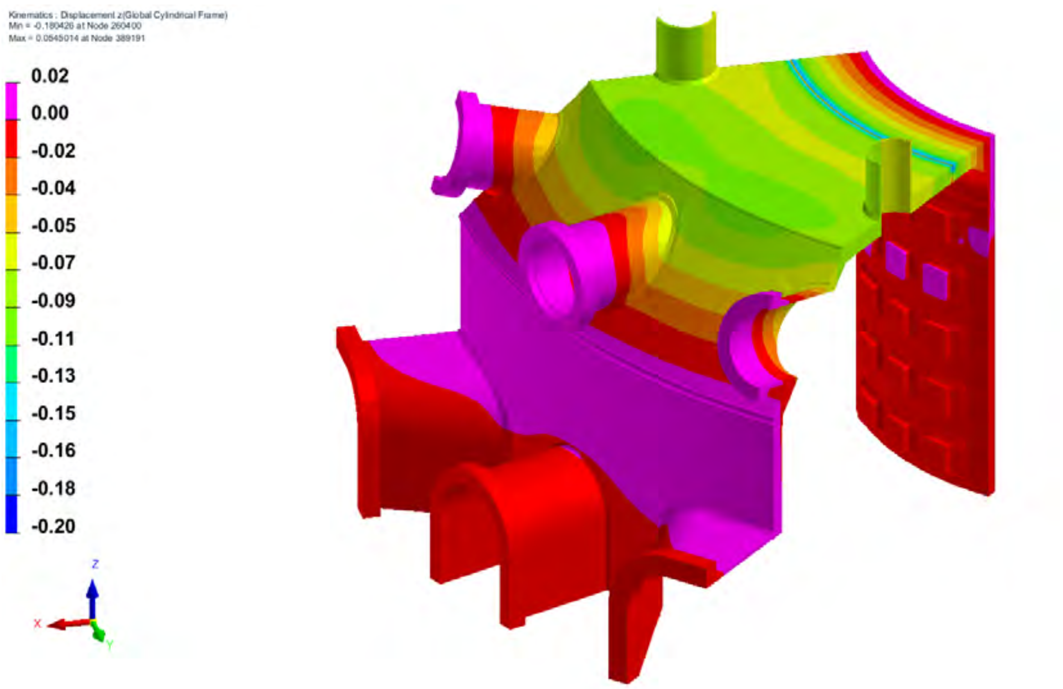

Figure 5.12 – Axial displacement component [mm] – increment caused by EBW

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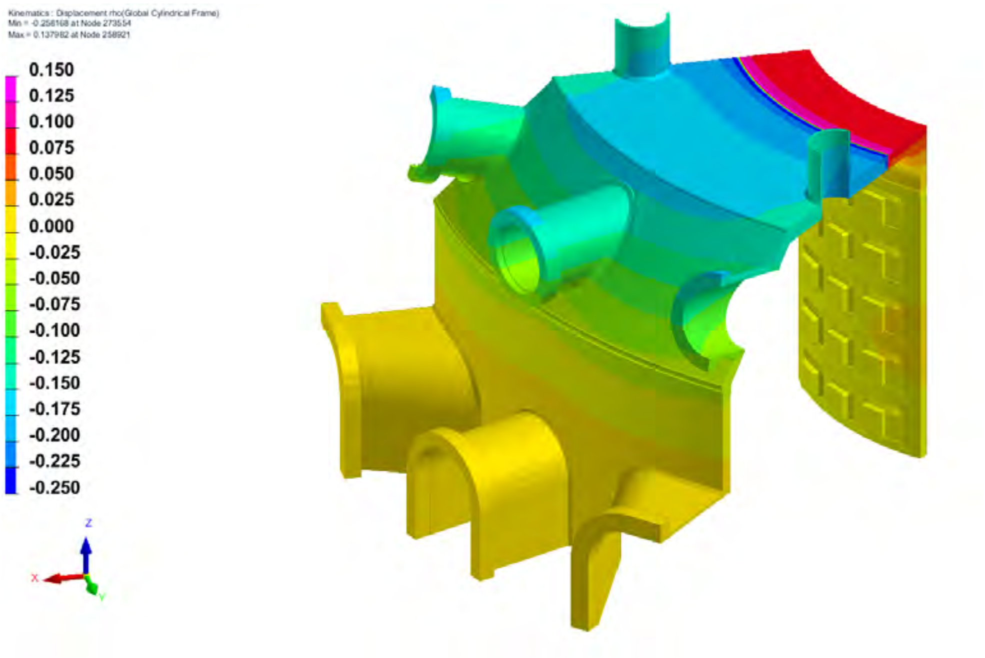

Figure 5.13 – Radial displacement component [mm] – increment caused by EBW

6 LIST OF THE MINIMUM REQUIREMENTS FOR QUALITY ASSURANCE AND WELDING CERTIFICATION

This chapter gives a list of necessary documents and industrial standards which are applicable to the manufacturing process of the VV as well as for quality assurance of the finished product. The list is divided into several sections, according to the scope of the individual documents.

6.1 Material certificates

EN ISO 10204 - type 3.1 - Metallic Products - Types of Inspection Documents

Inspection certificate for supplied material. It is a declaration of conformity with the material order. It includes information like dimensions, sizes, weight, chemical composition, mechanical strength, heat treatment status etc. obtained on the basis of the specified inspection.

6.2 Standards for welding

EN ISO 13445 - Unfired pressure vessels

The manufacturer is required to declare that the technical, design and supporting documentation is in accordance with the requirements of this standard. Unexpected factors may occur that require a change in design or special precautions during manufacturing. Any of such changes must be handled with the same level of severity as for the original design assessment.

EN ISO 3834-2 - Quality requirements for fusion welding of metallic materials

These regulations clearly define the manufacturer's link to the certified quality system in welding, according to the standards of the EN ISO 3834-2, 3, 4 series. If the manufacturer holds a certificate according to ISO 9001: 2008, it is then necessary to meet higher quality requirements according to EN ISO 3834-2. Definition of the quality requirements on welding processes is very important, because the quality of these processes cannot be easily verified. For this reason, welding belongs to the category of special processes, as defined by the ISO 9001: 2008 standard. Achieving the quality of the final product or its parts cannot be ensured only by final quality control, but it must be gradually brought into the product at each step of its manufacturing and must subsequently become a part of it. By control it is not possible to create the quality, but only to prove it. No non-destructive testing can replace this activity. The control activities must be set from the moment the product request arises, i.e. during the review of the contract and subsequently the design phase, through the selection of suitable basic and additional material, meeting the boundary conditions of the task, further through the production phase, inspection activities, etc. The company's certification according to the standards of the EN ISO 3834-2,3,4 series declares the assessment of the manufacturer's competence, in connection with a specific product code as for example 2000 Mbl., DIN 18800, DIN / ČSN 15085, DIN EN 1090-1,2,3 etc.

EN ISO 15614-1 - Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

Arc welding of nickel and nickel alloys by method 131. This standard defines the conditions for performing welding procedure tests and the scope of qualification for welding procedures for all practical welding operations. Tests on welded specimens must be performed in accordance with this standard.

EN ISO 15609-1 - Specification and qualification of welding procedures for metallic materials - Welding procedure specification - Part 1: Arc welding

This standard specifies requirements for the content of welding procedure specifications for arc welding methods completed with information on welding parameters, welding materials and working instructions.

EN ISO 9606-1 - Qualification testing of welders - Fusion welding - Part 1: Steels

A set of technical rules for systematic testing of welders allowing uniform qualifications that are independent of product type, testing location and testing authority or organization. During the welder's tests, emphasis is given to approving the welder's ability to manually manipulate the electrode or welding torch and thereby create a weld of acceptable quality and required parameters.

6.3 Standards for non-destructive testing

EN ISO 5817 Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections

Simplified selection of fusion weld defects based on the designation given in ISO 6520-1. The purpose of the standard is to define the dimensions of typical defects which can be expected in normal production. The quality level must be prescribed before the start of production, preferably at the inquiry or offering stage. Additional details may be prescribed for special purposes.

EN ISO 3452-1 - Non-destructive testing - Penetrant testing

Capillary testing used to detect discontinuities on the test surface, such as cracks, folds, scratches, pores and cold joints that are open on the surface of the test material. The test is mainly used for metallic materials.

EN ISO 17636-1 - Non-destructive testing of welds - Radiographic testing – Part 1: X- and gamma-ray techniques with film

The standard specifies the basic techniques of radiography with the intention of obtaining satisfactory and repeatable results during control of fusion welds using industrial radiographic films.

EN ISO 17640 - Non-destructive testing of welds - Ultrasonic testing - Techniques, testing levels, and assessment

This standard specifies techniques, classes of testing and evaluation of defects in fusion welds of metallic materials via manual ultrasonic testing. It is applicable for materials with a thickness of 8 mm and higher, which show low attenuation of ultrasonic waves. The standard is primarily intended for testing welds with full penetration, in which the welding and base material is ferritic.

EN ISO 11666 - Non-destructive testing of welds - Ultrasonic testing - Acceptance levels

The standard specifies degrees of acceptance 2 and 3 (abbreviated AL 2 and AL 3) for testing full penetration welded joints in ferritic steels with thicknesses from 8 mm to 100 mm. These degrees of acceptability are used in ultrasonic testing according to EN ISO 17640.

6.4 Leakage testing

EN ISO 1779 - Non-destructive testing - Leak testing - Criteria for method and technique selection

Standard leak test. It is performed from the outer side of the vessel by blowing helium, while there is vacuum in the vessel. The penetration of helium into the vacuum space of the vessel, which is connected to the helium detector, is monitored. The blow inspection is done for all welds and joints. The test is suitable for all materials (stainless steel, ferritic steel etc.) and all types of surfaces (polished, blasted, painted etc.). There is however certain possibility to overlook some local leaks. For each leak we must consider also the total leak of the vessel (device). The examined vessel is evacuated and closed. The increase in total pressure over time is measured. It is necessary to take into account the degassing of the inner surface of the material. This is a supplement to the test of individual leaks with a general view of the total volume of the vessel.

7 SUMMARY

The aim of this study was to propose and analyse welding technology of the vacuum vessel and to enable the future manufacturer to assess critical points of the design and manufacturing process. The extent of the study fully corresponds to specified scope requested by ÚFP AV ČR and individual chapters of the report describe results of numerical analyses and derived suggestions for several separate tasks related to manufacturing aspects of the vacuum vessel. In chapter 2, there is given complete description of the suggested manufacturing process of the vacuum vessel. Chapter 3 is dedicated to proposal of precautions for limiting or resolving the issue of welding induced distortions during the vessel manufacturing. In chapter 4, there is done more detailed analysis regarding joining of adapters and heating and cooling tubes to the internal wall of the vessel. Significant effort was made with numerical predictions of the welding induced distortions and this activity and corresponding results are presented in chapter 5. Finally, chapter 6 is dedicated to certification procedures and quality assurance process.

As one of the critical points of the entire manufacturing procedure there is foreseen the effect of occurrence of the welding induced distortions. These can cause very serious problems in terms of feasibility of the manufacturing procedure and possibility of successful completing the entire assembly, but also in terms of the possibility to achieve the necessary dimensional accuracy of the final product. For these reasons, significant efforts were spent with numerical predictions of the welding induced distortions for the suggested manufacturing procedure. Results of the analyses show that the distortion level is not negligible. Nevertheless, there can be concluded that when the inherent distortion modes and the typical distortion magnitudes in different stages of the process are understood, it will be possible to master the entire assembly successfully. Based on the simulation results, there were also proposed measures against the arising deformations via usage of reinforcements temporarily installed during the assembly process. Due to the very complex design of the vacuum vessel, this type of precaution enables only partial improvement, and some residual deformations should be expected. Therefore, the key point of the suggested strategy to achieve the required tolerances of the assembly is suitable initial fit-up and pre-positioning of the parts and addition of appropriate quantity of material allowance for selected locations, which will compensate the arising deformation.

At this point it must be highlighted that the study was prepared based on specified inputs existing in certain stage of design process, when many design changes were still considered or under implementation. Recommendations, proposals and considerations regarding the process execution and parameters must be understood with certain uncertainty and there are to be expected partial adjustments regarding the specific situation and available equipment as per selection of the future manufacturer. This also affects the applicability of results of the numerical simulation, where the absolute magnitudes of the predicted distortions are depending on the considered inputs. One of the key parameters is the net power input of the process defined for the purpose of the study elaboration. The power input considered was estimated, because in the given time period no clear evidence based on execution of qualification or other practical welding tests was available.

It is to be understood that the final selection and execution of the welding procedures will also be dependent on the selected final manufacturer of the vessel and the available equipment, experience and the necessary personnel qualification. In this context we would like to mention that we are aware that the MIG welding method can be relatively prone to defects of incomplete fusion, which can locally occur alongside the weld. Regarding this specific aspect the TIG method is generally seen as more robust in terms of quality and therefore more widely recommended for applications of vacuum vessel production. Unfortunately, for welding of vacuum vessel of COMPASS-U with its very complex design and quite large dimensions, we do not consider application of a purely TIG based process to be realistic. It is firstly due to low productivity of the TIG method and secondly due to significantly higher heat input causing consequently much higher distortions. For these reasons the general preference to usage of MIG process was given. At the same time, it must be emphasized that application of this method for the given purpose will require high care to be paid and appropriate precautions to be applied to eliminate the mentioned risk of incomplete fusion. The typical recommendations we can mention are: suitable configuration of weld bevels and root gaps, high care of the welders during all the operations including correct control of the welding torch, careful cleaning of the base material as well as deposited filler material before welding of successive beads, selection of suitable type of welding consumable, correct selection of welding parameters optimally including usage of hot-start feature etc.

With respect to all the above mentioned aspects, it is to be emphasized that for the future real manufacturing phase the final material parameters and later implemented design and process changes should be considered and analysed very carefully. It is also highly recommended to repeat validation of the process using the numerical simulation of distortions, where the input data will be updated accordingly to reflect properly the final design and process conditions. The study was performed as feasibility study to support future tender participant decision. There can be potentially reached improvement of residual distortions in some of the problematic areas, like for instance for the main shell of the outer sub-assembly, by performing of some additional optimization iterations of numerical simulation, which was not possible to do within the limited extent of this study.

● LIST OF ANNEXES

Annex 1 – Material certificate of Arcelor Mittal – PDF document

Annex 2 – Material Certificate of Boehler – PDF document

Annex 3 – Numerical analysis of welding induced distortions of the vacuum vessel – PPT document

Annex 4 – Analysis of static loading of joints of adapters – PPT document