Manufacture of the Plasma Vessel for WENDELSTEIN 7-X

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Abstract

The plasma vessel is one of the main components of the cryostat for the WENDELSTEIN 7-X stellerator which is presently beeing assembled at the Greifswald IPP branch. The order for the manufacture of the plasma vessel was placed with the company MAN DWE GmbH Deggendorf. Delivery of the first out of altogether ten half-modules of the plasma vessel is scheduled for October 2003. This paper describes the general idea for the design and manucature of the plasma vessel.

Introduction

WENDELSTEIN 7-X is a helical advanced stellarator which is presently under construction at the Greifswald branch of IPP. A set of 70 superconducting coils arranged in five modules provide a twisted shaped magnetic cage for the plasma and allow for steady state operation. Operation of the magnet system at cryogenic temperatures requires a cryostat which provides the thermal protection and gives access to the plasma. The main components of the cryostat are the plasma vessel, the outer vessel, the ports, and the thermal protection.
The German company, MAN DWE GmbH Deggendorf, is responsible for manufacture of the plasma vessel, the outer vessel and the thermal insulation.

1. Design of the plasma vessel

The plasma vessel encloses the plasma and constitutes a barrier between the plasma and the insulation vacuum compartment for the superconducting coils. Due to the spatial restrictions, the wall of the plasma vessel has to comply with the complicated plasma form. For symmetry reasons, the plasma vessel is divided into 10 similar half-modules.
The cross section of the plasma vessel alters within a half module from triangular- to bean-shaped. Adjacent half-modules are axial symmetric concerning the significant toroidal radius, and thus the cross section of the succeeding half-module alters back from bean-shaped to triangular. Each half-module of the plasma vessel had to be divided into two sectors in order to position the innermost coil of the magnetic system over the vessel. The plasma vessel has an average diameter of 11 m. In the bean-shaped cross section, the vessel has a height of approx. 2.5 m and a width of approx. 1.3 m; and in the triangular-shaped cross section it has a height of 1.5 m and a width of 2.1 m.
The surface of the plasma vessel is a free-formed area**.** An inner and outer enveloping area was determined as design space for the wall of the vessel by means of a 3D-model provided as a CAD-set. Depending on the tolerance zones, the distance between the inner and outer enveloping area had to be reduced to 45 mm respectively 30 mm in order to allow for sufficient space between the wall of the vessel and the cold magnet coils and the hot plasma.

Apart from the manufacturing tolerances for the wall of the vessel, the design space also includes the necessary room to route and weld heating and cooling pipes. As a result of the stability calculations, a minimum wall thickness of 17 mm was defined.
Stainless steel 1.4429 was selected as material for the wall of the vessel. Its cobalt content, however, must not exceed 500 ppm and the relative permeability must be less than 1.01. Only in the welding seams, a relative permeability of 1.05 is permitted.

299 ports connect the interior of the plasma vessel with the outer vessel. These ports facilitate the monitoring and heating of the plasma as well as the supplying of the components inside the vessel. The cross sections of the port pipes are round, oval and rectangular. The ports have a diameter of 100 to 400 mm respectively 400 x 1000 mm². The plasma vessel has the necessary openings for these ports.

Sector-, half module and module connections are required for the assemly of the plasma vessel torus. The sector connection is regarded as essential because the geometry of the innermost non-planar magent coil averts its positioning over the plasma vessel neither from the bean-shaped nor from the triangular plane. The position of the sector connection is at a toroidal angle of 27° and has a plane shape. The half module disconnection is in the bean-shaped cross section at a toroidal angle of 36° and is plane, too.

Because the outermost non-planar coil of the module extends across the end of the relevant module over the neighbouring one the module connection has must therefore be designed as non-planar. In addition the module connection has to be designed with non-planar 140 mm wide intermediate ring in order to compensate for the inaccuracies that occur during the assembly works.

The plasma vessel module is vertically supported by two legs at the inner side of the torus and another support at the outer side.

In the evacuated state the plasma vessel must allow for bake-out at 150°C. During plasma operation, however, a direct cooling of the wall of the plasma vessel is required. The heating respectively the cooling of the wall is effected by nine poloidalturns of an tube with the dimensions $\varnothing 12 \times 2$ mm welded at the outside of the vessel. For redundancy reasons, each half module has two poloidal cooling cycles with two parallel cooling pipes each. The distance of the heating respectively cooling pipes amounts maximally to approx. 400 mm between similar cycles respectively to approx. 100 mm between redundant cycles. The required heat transfer from the heating respectively cooling water to the vessel is ensured by double-sided filled welds for 90% of the total length of pipes. For vacuum reasons, the filled welds are performed as reciprocally discontinued seams. The length of cycle per half module runs to approx. 65 m.
Brackets at the inner side of the plasma vessel are designed for the fastening of in-vessel components e.g. targets, baffles and control coils.

During the assembly, the half modules have to be laterally positioned and vertically supported when the coils are strung. Bearing flanges, which will have to be removed after the completion of assembly works, are mounted at the half module and module disconnections inside the vessel to facilitate the relevant assembly works.

2. Order management and manufacture

The order for the manufacture of the plasma vessel was placed with MAN DWE GmbH in December 2000. In compliance with a quality management plan, a test and inspection plan for general manufacturing and test instructions was elaborated.
The manufacturing and sequential test plans describe each of the manufacturing steps, tests and inspections for the manufacture of each semi-module sector including all the built-in parts and external mounted parts.

Specific steps of productions and tests during manufacture were additionally defined in descriptions respectively manufacture and work instructions.

For reasons of compatibilty and a definite transfer of data, MAN DWE and the IPP-branch use both the CAD-system CADDS5.
MAN DWE carried out extensive studies and tests in order to ensure the manufacture of the complicated shaped geometry of the plasma vessel within the tight tolerance zones.
A model to a scale of 1:5 was made in order for a quick visualizing of processes.
In order to manufacture the shape of the vessel, MAN DWE decided for edge-bent rings which are assembled as a torus. A study determined the optimal width of the rings so to use the space available between the inner and outer enveloping area as best as possible for the design of the 17 mm thick steel shell. In doing so, the scope of welding works had to be minimized particularly with regard to shrinkage and the CAD-edge model had to be kept within the tolerance zones. The results were rings with a torodial division of 1.8° resulting in 200 rings for the complete torus. Due to production-orientated reasons, each ring is assembled of 4 poloid segments.

Edge-bending templates were made in order to verify the outline-accuracy of the individual segments in a simple and effective way when bending. During the assembly of the segments as well as during the welding of the poloidal seams, the accuracy of the entire outline of a ring was guaranteed by circumferential templates which were specially made for this purpose**.**
Correct lining-up, positioning and tacking of the individual rings was achieved by a measuring dividers and a special table. All segements of the plasma vessel and the single components of the edge-bending and circumferential templates are marked with an identification number in one single operation already during the water jet cutting.

After the determination of the manufacturing process, three sample rings of a half module sector were fabricated. Two more rings, which fullfilled the specified tolerances, were built after the modification of the process. These results made it possible to manufacture segments which lie in the tolerance zone of 45 mm. For the segments with particular tight tolerances, die-forged parts had to be manufactured by hot-forming. 150 segments out of the required 820 for the complete torus were manufactured as forged parts.

The sample rings were used to investigate the welding shrink of Y and X-seams. Both seam types were welded by means of the TIG-cold rode technique. This special technique facilitated the simultaneous double-sided welding of the X-seam. An average welding shrinkage of 1.9 mm for the Y-seam and 2.0 mm for the X-seam could be realised. The decision was made in favour of the X-seam since it does not require any costly smoothing.

With regard to their dimensions and complex form, the surveying of the test parts was carried out with a lasertracker.

The pre-tests represented the basis for the manufacturing process which could be initialized with the cutting of the sector rings and the preparation of the welding edges through water jet cutting. Then, the sectors were edge-bent respectively hot formed and the welding seam preparation was attached. The assembly of each 4 segments in a ring and the welding of the straight seam were carried out afterwards. The 1.8° - sector rings were then milled and the welding edges for the poloidal circumferential joints were prepared. For the primary body of the 9°half module sector**,** 5 sector rings were assembled and welded with circumferential joints. For the primary shell of the 27° half module sector three 9°-sectors were assembled and poloidally welded.

An integral helium-leak-test of the half module sector was carried out to proof the specified leak tightness of the welding seams. For this, the ends of the sectors were closed with sheet covers. With this method, the integral leakrate of 10^{-7} mbar×l×$s^{-1.}$ could be verified. The cutting of the holes for the ports was carried out with a 3D-water jet cutting plant**.** The 3D-CAD-data could be directly taken for the programming. The test-sector of the three 1.8° rings could be utilized to test the accuracy for the port hole cutting. The shape and position of the holes was then surveyed with a lasertracker and confirmed the compliance of the high demands for dimension accuracy.

For the neighbouring 9° half module sectors, which were still welded together, cutting of the port holes of the non-planar adjusting ring for the module connection as well as the tailoring of the sectors was performed by the water jet cutting technique**.**

The pre-fabrication of the bearings for the three supporting legs was carried out in parallel to the manufacture of the plasma vessel. Pipe lengths of 9 m were used for the heating and cooling pipes in order to keep the number of orbital weldings as small as possible. Each pipe was integrally leak tested before it was mounted on the outside of the plasma vessel. One pipe showed a clearly defined leak and had to be removed. The routing of the heating and cooling pipes was marked on the surface of the vessel in compliance with the position of the legs and saddle coils which will have to be installed later. The routing also had to condider the restricted geometrical tolerances. Next, the mounting and the welding of the heating and cooling pipes were carried out.
Presently, the brackets for the components inside the plasma vessel are being installed and welded by a positioning robot.
After the completion of these works, the heating and cooling pipes will have to undergo an integral leaktest in a vacuum chamber while applying an interior pressure of 90 bar.
Final factory inspection will comprise a check of the dimensions, the cleanliness and a control of the completeness of the documentation.

Figure 1: Integral helium-leak-test of a 27°half module sector

Figure 2: 27°half module sector with assembled heating and cooling pipes