SERIAL ELECTRON BEAM WELDING OF LARGE COMPONENTS MADE OF THICK-WALLED CRNI STEEL - USING ITER AS EXAMPLE

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ABSTRACT

ITER (International Thermonuclear Experimental Reactor) paves the way for a future of clean and endlessly available electrical power generated using fusion technology. A gigantic vessel is the core element of that international experimental plant, a vacuum chamber which will act as containment for the plasma, which will be heated to 150 million degrees Celsius – hotter than the sun itself.

The huge torus of the vessel consists of nine sectors. A European consortium has been awarded the contract for building five of them. It is specified that electron beam welding is generally to be used for any serial processing at least on the inner shell and structures. The lecture reports on the plant and process engineering challenges that had to be solved to ensure mass production.

INTRODUCTION

The technology of electron beam welding is normally associated with small and medium-sized components. This is because the process must be performed in a vacuum for optimum quality and repeatability, and standard chamber sizes are limited for this purpose. Of course, chambers with larger volumes for military applications have already been around for a long time, however, they have not been implemented for civilian applications until now.

This has all changed with pro-beam's participation in the ITER (International Thermonuclear Experimental Reactor) large-scale research project. In this project, we had the opportunity to employ the electron beam for nuclear pressure vessel construction for the first time and demonstrate the huge potential of low-distortion welding. That's why we decided to develop special large chambers with a volume of over 600 m^3. Ultimately, all components to be welded inside these chambers could be joined using an internal, robot-guided electron beam generator.

RESULTS

1 What is ITER?

ITER (International Thermonuclear Experimental Reactor, also "iter" (Lat.) = "the way") is an international research project currently operating out of Cadarache in southern France, which is working on paving the way for humanity to achieve a climate-friendly, efficient and safe source of energy. The magnet fusion device has been designed to prove the feasibility of nuclear fusion as a large-scale, carbon-free source of energy on our planet. A total of 35 nations are working on this mega project, among them Europe, Russia, USA and China.

The core component of the experimental power plant is a gigantic donut-shaped reactor: It contains a vacuum chamber weighing approximately 8000 tons. Inside, a strong magnetic field will in future contain one gram of deuterium-tritium gas on a narrow spiral track. This will be heated to 150 million degrees Celsius and transformed into the plasma state. The plasma will thus be hotter than the sun itself, enabling the replication of the principle that powers our own sun.

2 Structure of the Vacuum Vessel

The vacuum chamber is made up of a total of nine sectors. Each in the shape of a mandarin slice 11 m high with a 5 m inner span. At the end, all these sectors are combined into a "giant donut" with a 19 m exterior and 6 m interior diameter.

The chamber is made of thick-walled Cr-Ni steel with its own grade specified for ITER. Once everything is assembled, the vacuum chamber will exceed the mass of the Eiffel Tower.

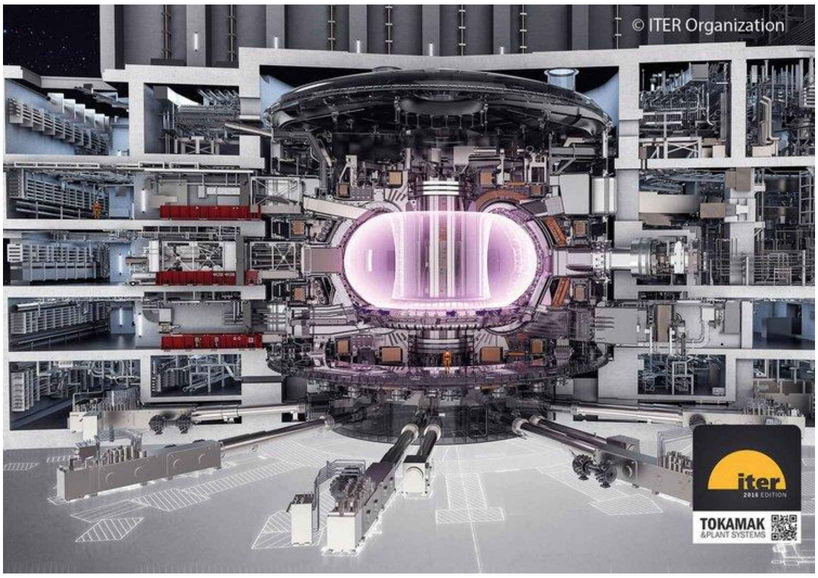


Figure 1: Structure of the tokamak. Source: ITER Organization

3 Vacuum Vessel data

Weight:	approximately 5,200 t (9,500 t with all internal components)
Material:	316 LN IG (Cr-Ni steel ITER grade)
Temperature:	plasma temperature up to 150 million °C

Figure 2: Structure of the vacuum chamber. Source: ITER Organization

4 Manufacturing with the help of electron beam welding technology

The manufacturing of five of the nine sectors has been assigned to a European consortium and the remaining four sectors will be manufactured in Korea.

The European consortium chose the company pro-beam GmbH & Co. KGaA in Burg near Magdeburg as the development partner for the serial electron beam welding of all interior wall structures. pro-beam's work began right from the beginning with the design of the components.

Eventually, sectors were designed that were comprised of four individual elements each. "Mock-ups" were manufactured for all four elements to ensure the structure and quality of the ITER vacuum chamber.

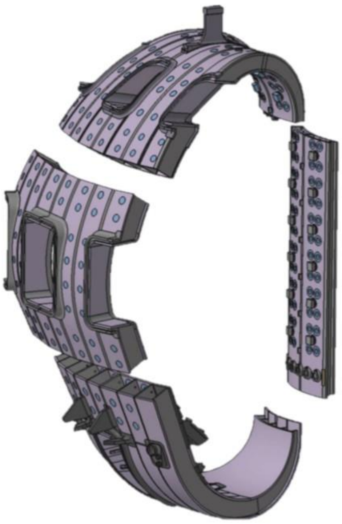


Figure 3: Example of the breakdown of one sector. Source: ITER Organization

After extensive parameter development and technical process testing using these sample segments, the welding of the actual components started using the large chamber system in Burg in 2015.

Figure 4: Vacuum Vessel component in a welding device at pro-beam in Burg. Source: pro-beam

This 700 m³ chamber for the electron beam manufacturing has an internal electron beam generator that is guided by a robot. This way, 3D welding is also possible without any problems even in tight spots.

Figure 5: Vacuum Vessel component in a rotating welding device at pro-beam in Burg. Source: pro-beam

5 Why use an electron beam?

All processes for electron beam technology are completely digital, from seam tracking to monitoring. The seam (up to a 90 mm wall thickness in this case) is subsequently welded in one pass and with the highest degree of precision and accuracy. In addition, the energy introduced into the component is relatively low. Therefore, practically warp-free welding can be achieved, ensuring extremely long-term stability as well as high dimensional accuracy. The latter is highly crucial for the fitting precision of the meter-long ITER components – at most, only warping in the millimetre range or lower is permitted.

The entire welding process also takes place in a vacuum, which keeps the seam especially clean and minimizes seam errors. For this special project, the seams are then checked afterwards in an X-ray bunker.

In addition, pro-beam also has modern, process-oriented and highly available machinery at its disposal as well as an in-house development team that is specialized in large-scale research projects. Due to our robust organizational structures, we were able to meet schedules spread out over several months.

6 Technical challenges of the project

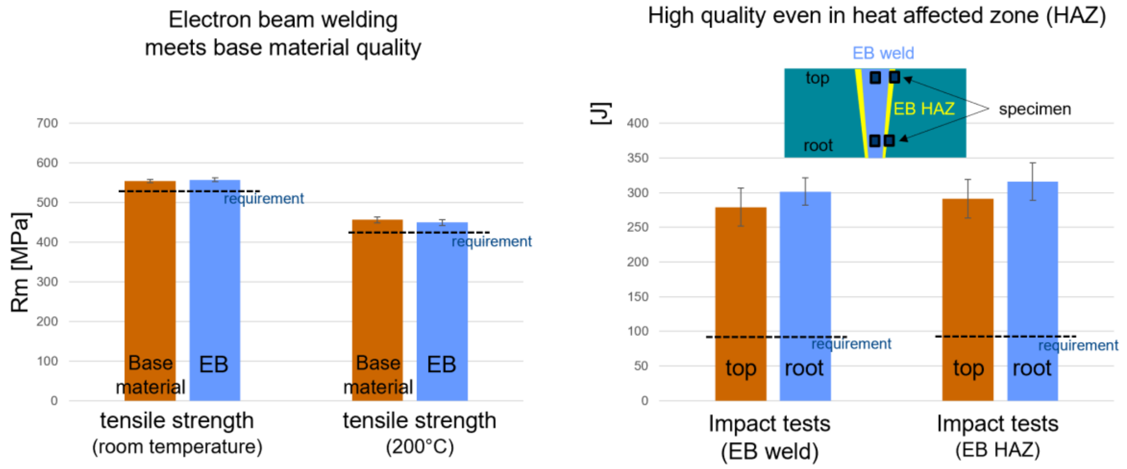
- All welding performed was subject to the French nuclear code RCC-MR, which was specially adapted to the electron beam technology
- Diverse seam lengths had to be considered – from 240 millimetres up to six meters
- Handling of components due to different weight and size dimensions

7 Summary

pro-beam has been involved in this research project since 2001. After the setup of a well-functioning project team as well as the preparatory work that was required for the welding of various sectors, the work at pro-beam was completed in 2021. At this point, the electron beam welded approximately 470 components and thus generated over 2,600 seam meters, as well as over 2,000 weld seams.

8 Some facts and figures

Material properties regarding electron beam welding of 316 (N)-IG:



Material: 316 (N)-IG
Sheet thicknesses: 40mm – 60mm

Figure 2: Material properties regarding electron beam welding of 316 (N)-IG. Source: pro-beam

Performed weld length per month according RCC-MR:

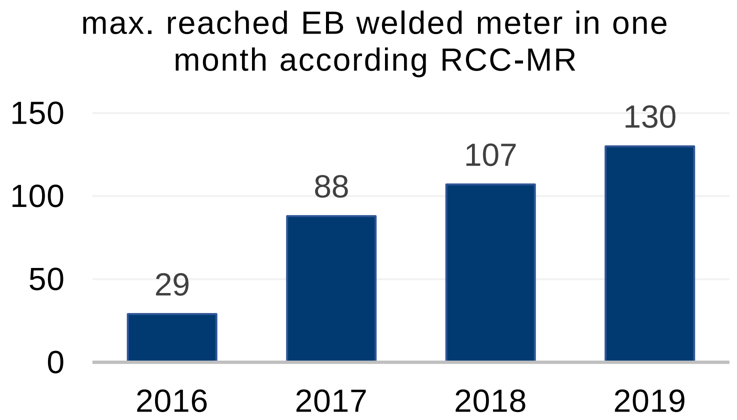


Figure 3: Performed weld length per month according RCC-MR Source: pro-beam

Status of production (February 2021):

Figure 4: Status of production (February 2021). Source: pro-beam

Weld quality over all WPQR:

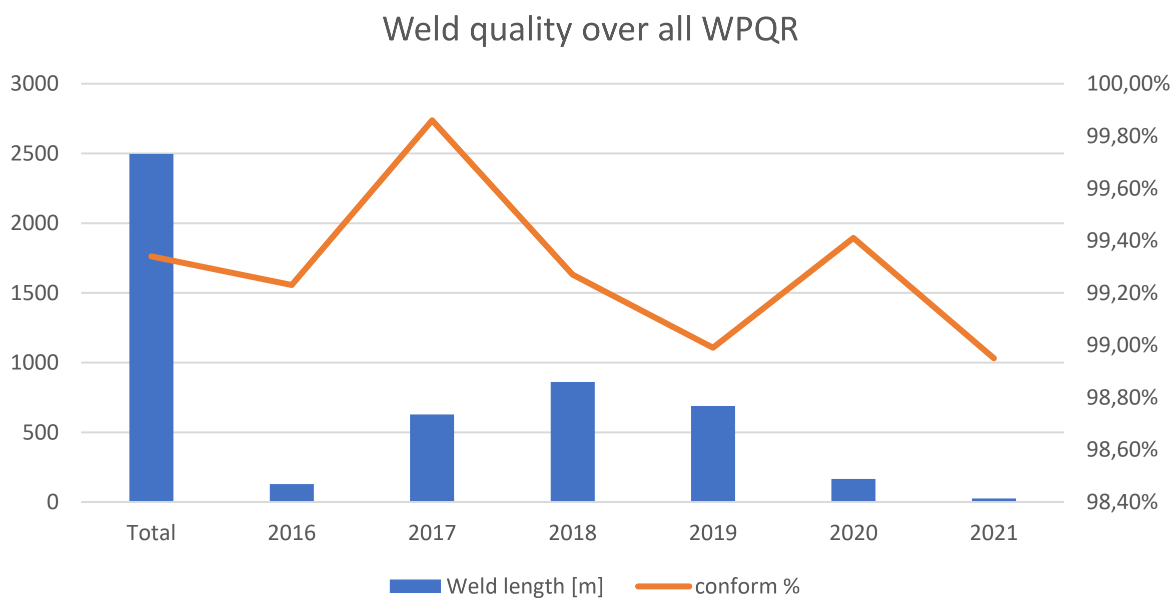


Figure 9: Weld quality over all WPQR. Source: pro-beam