

# Electron Beam Welding of Large Components for The Nuclear Industry

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**Abstract.** The nuclear industry requires rapid and high quality joining of large scale components. Electron beam welding (EBW) has the potential to respond to these requirements. The aim of Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC) is to develop solutions for the future application of this technology. One example is the research on deep penetration EBW for joining large scale pressure vessels for small modular nuclear reactors. This will require several circumferential welds of ~ 6 metres length each. In addition joining of sections of the upper and lower vessel heads and of HIP sections with varying wall thickness must be developed. In collaboration with the US Electric Power Research Institute (EPRI) the Nuclear AMRC is working to produce two-thirds scaled demonstrators of the lower and the upper pressure vessel assembly (based on a generic NuScale model). 100 mm deep single track, full penetration welds of pressure vessel steel have been demonstrated. In addition, within 26 minutes joining of shells was achieved with 6 metres long circumferential welds (78 mm full penetration). In future the joining of complex sections and sections with variable thickness will be investigate.

## 1 Introduction

One of the main goals of the Nuclear Advanced Manufacturing Centre (Nuclear AMRC) is to support the application of advanced manufacturing technologies in the nuclear manufacturing industry. This entails new build, operations, decommissioning, naval, but also other innovative energy sectors. It is our strong belief that by developing innovative techniques and technologies, cycle time and quality will be significantly improved and lead time, cost and risk will be reduced.

The approach to support advanced manufacturing technologies is to perform research and development projects using large scale, industrial sized equipment. Electron beam welding (EBW) is considered to be one joining technology which can progress nuclear manufacturing considerably. The Nuclear AMRC operates a large EBW facility (Figure 1). In addition, the Nuclear AMRC supports the ASME code case development for EBW together with EPRI.

In the following a status report of a project which aims to produce two-thirds scaled demonstrators of the lower and the upper pressure vessel assembly.

## 2 Set-up

The pro-beam® K2000 EBW facility operates the largest EB vacuum chamber (working volume of 208 m<sup>3</sup>) in the UK (Figure 1). The internal mobile 80kV/40kW EBW gun is mounted on a gantry system which provides CNC linear movements of the gun in

three directions and two axis rotations. CNC manipulation of samples is achieved by a turn table (up to 100 tonnes) or a smaller turn/tilt table. The evacuation to a working vacuum ( $\sim 10^{-4}$  mbar) can be achieved in less than 45 min.



**Fig. 1.** Open vacuum chamber of the pro-beam® EBW facility K2000 showing a welded mock up of a pressure vessel (front)

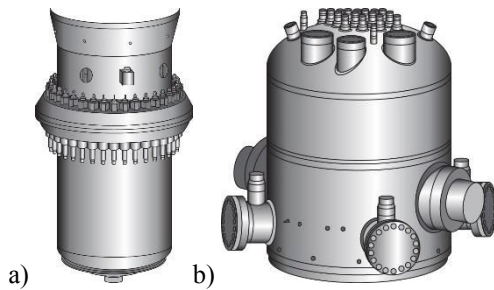
## 3 Two-thirds scale SMR pressure vessel

Small modular reactors (SMRs) are nuclear fission reactors providing energy between 50 and 500 MWe. In some countries they are considered as one solution to reduce manufacturing costs of nuclear plants in the future [1]. This is mainly based on the vision that mass production of nuclear plants will be possible ( $\sim 10$  SMRs per year for the US alone). Multiple SMRs on one site allow sequential build and commissioning, which in turn enables a revenue stream once the first reactor is operational.

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This prospected manufacturing rate of SMRs can only be achieved by the introduction of advanced manufacturing technologies in modularisation, machining, joining, cladding and others.

In collaboration with EPRI, supported by the US Department of Energy and NuScale Power the Nuclear AMRC is working to demonstrate the applicability of laser cladding and EBW. This shall be done in a four-year project where at the Nuclear AMRC a two-thirds scaled demonstrators of the lower and the upper pressure vessel assembly shall be produced. The assemblies are based on a generic NuScale model for a 50 MWe, passively safe, integral pressurised water reactor (Figure 2). In order to realise that large scale, full penetration EBW joints must be achieved. This will require several circumferential welds of shells and flanges (weld length of ~6 metres each), joining complex sections to create the upper and lower vessel heads, linear welds of quadrants, and welds of powder metallurgical hot isostatic pressed (PM HIP) sections with varying wall thickness (75 mm up to 108 mm). The material is pressure vessel steel (forged or HIPed) SA508 Grade 3.

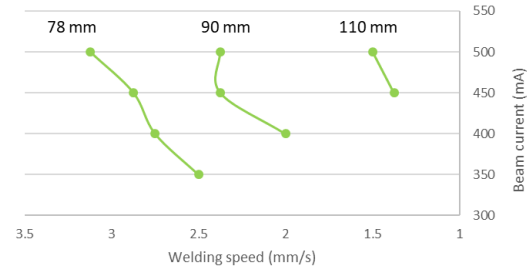


**Fig. 2** Drawing of lower (a) and upper (b) vessel heads, courtesy to NuScale ©2017 NuScale Power, LLC

### 3.1 Linear welds on rectangular coupons

In preliminary work, a matrix of key process variables (KPVs) was investigated to achieve good welds for different wall thicknesses. Figure 3 shows parameter sets for linear EBW in horizontal position (1G ASME / PA ISO 6947) in melt runs on the steel S355 which has achieved visually good crowns and roots (other KPVs with unsatisfying visual inspection are excluded in this graph). It is clear that even at 60 kV full penetration was achieved at a wall thickness of 110 mm. It is noteworthy that even at these high thicknesses the melt pool was self-supporting. No drip tray for retaining the liquid metal was necessary.

At 80 kV full penetration melt runs were achieved recently on 150 mm thick S355. Further work is currently under way for SA508 at 80 kV and. It is already clear that the melt of SA508 appears more liquid than the one of S355, potentially requiring a drip tray for further work.



**Fig. 3** Linear melt runs at 60 kV(PC/2G, S355)

Figure 4 is exemplary for all butt welds investigated. As already mentioned, even without the support of a drip tray a good crown with only minor sink-in and a good root has developed. The fusion zone is parallel and has a high depth/width ratio, with no lack of fusion.



**Fig. 4** Cross section of a 90 mm thick butt weld (PC/2G, S355)

### 3.2 Circumferential welds on shells

Figure 5 shows the circumferential EBW of a shell. Visual inspection of the weld seam indicates that the slope-in and slope-out of a circumferential weld is a challenge and further work on SA508 grade 3 shells will be required. More details about the observed defects in this region are reported in [2] Table 1 gives examples for different shells. The possibility of joining a shell with diameter of 1.8 m and a wall thickness of 78 mm within 26 minutes highlights the competitiveness of EBW compared with other joining technologies.



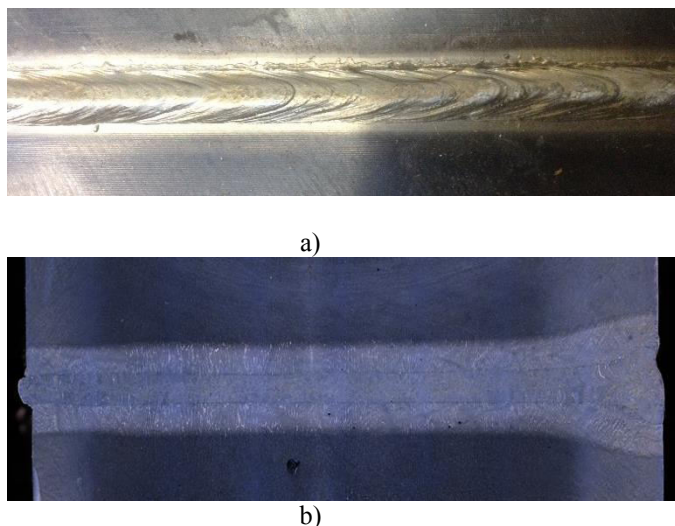
**Fig. 5** Circumferential EBW of a shell

**Table 1** Investigated butt EBW at 60 kV on S355 shells

Outer shell diameter [m]	Wall thickness [mm]	Welding time [min]
0.6	45	6
1.5	30	11
1.8	78	26

Figure 6 gives an example of a circumferential EBW of a shell. The beam energy was 30 kW and the welding speed 0.2 m/min. No drip tray was required. Visual

inspection indicated a good crown (Figure 6a) and root. Ultrasonic testing showed that defects were only observed in the overlapping slope-in/slope-out region near the root. Further optimisation of the EBW strategy is planned.



**Fig. 6** Circumferential EBW of a S355 shell (1.8 m outer diameter, 78 mm wall thickness). a: view on the crown, b: cross section

## 4 Conclusion

The Nuclear AMRC, in collaboration with the EPRI has started a four-year project to produce two-thirds scaled demonstrators of the lower and the upper pressure vessel assembly. Preliminary EBW work indicates that large scale circumferential, linear and complex welds with wall thickness between 78 mm and 108 mm will be possible with the 40 kW EBW gun available at the Nuclear AMRC. Future work packages will investigate the joining of complex sections and sections with variable thickness.

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## References

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