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Specific welds for test blanket modules

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ABSTRACT

Fabrication and assembling test blanket modules needs a variety of different welding techniques. Therefore, an evaluation of plate joining for breeder units by tungsten-inert-gas, laser, and electron beam welding was performed by qualification of relevant mechanical properties like hardness, charpy, and creep strength. The focus was laid on the study of post-weld heat treatments at lowest possible temperatures and for maximum recovery of the joints. The most important result is that thin EUROFER plates may be welded by EB or laser techniques without the necessity of post-welding heat treatments that include an austenitization step.

1. Introduction

According to the current design for the European Helium Cooled Pebble Bed (HCPB) ITER Test Blanket Module (TBM) there are basically six subcomponents which have to be fabricated and assembled: first wall, caps, stiffening grid, breeding units, back plates/manifolds, and attachment system (for details see [1] and references therein). The main technology needed for blanket fabrication is joining of parts and applying suitable post-weld heat treatments. Both steps together determine the mechanical strength of the blanket, the ductile-to-brittle transition temperature (DBTT) which is important under neutron irradiation, and the potential for a compact design [2]. Therefore, welding and heat treatment may be considered as key technology for blanket fabrication. In contrast to the material question which is already solved (it will be EUROFER or another, comparable reduced activation 9Cr–WVTa steel), most joining procedures and processes have still to be developed, adapted, or qualified, although substantial advancements have been already reported (e.g. [2–4]).

Fusion welding techniques, in particular, need post-welding heat treatments. Fusion welding may be performed either by electron beam (with and without filler wire), laser beam, hybrid MIG/laser [5–7], or by tungsten-inert-gas (gas tungsten arc) welding with filler wire. Mechanical properties and microstructure of some electron beam (EB) and tungsten-inert-gas (TIG) welds of reduced activation 8–9Cr–WVTa steels (like EUROFER) and 9Cr–MoVNb steels (like P91) have been already investigated in the past, even after neutron irradiation [8–20].

As already mentioned, with respect to TBM weld fabrication there are still a lot of unsolved or unqualified technical procedures and unanswered questions. The present paper, however, contributes at least to the clarification of some of them.

2. Materials, welding procedures, specimens, motivation

Electron beam (60 kV, 19 mA, 10 mm/s) and laser (5 kW, 750 J/cm, 4 m/min) welding were applied to 5 mm EUROFER97 plates in the condition as received, that is, after post-production heat treatment of 980 °C/30 min + 740 °C/2 h. A second EB weld (60 kV, 80 mA, 10 mm/s) was fabricated with 12 mm plates. The plates were applied with beam stoppers (0.5 mm $\times$ 0.5 mm) at the lower part of the joining. In addition, TIG welds on the same material (5, 10, and 12 mm plates) were produced with EUROFER97 filler wire, The TIG weld geometry was 1/2 V joint with a root height of 1 mm and a distance of 2 mm. All welds were fabricated parallel to the direction of the last rolling step that was applied during plate production. Immediately before welding, the joining plate surfaces were dry milled by 0.1 mm and in the case of TIG welding the filler wire has been emerized blank. The TIG welds were manually fabricated in a glove box flooded with inert-gas. The motivation to produce these different TIG welds with 5–12 mm plates was to investigate possible post-weld heat treatments (PWHT) for the final assembly of breeding units. That is, after filling the breeder units with beryllium pebbles, temperatures have to stay below 750 °C, which excludes the application of the EUROFER standard heat treatment and which necessitates the investigation of other PWHTs.

Moreover, a 40 mm deep EB weld was fabricated of two EUROFER97-2 plates (100 mm $\times$ 24 mm $\times$ 40 mm), also in the as-received condition. The weld was produced with a 150 kV/596 mA beam and the feed rate was 5 mm/s. It was fabricated to study

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the possible application of joining TBM caps to the first wall [1] by EB welding.

All chemical compositions are given Table 1 [21–23]. Tensile, creep and charpy specimens were fabricated perpendicular to the weld line, joint surface, and rolling direction. In the case of charpy specimens, the notches were fabricated either directly at the weld centre or, in some cases, in the heat affected zone (HAZ).

3. Results and discussion

3.1. PWHTs for breeder units

3.1.1. Microstructure, hardness, and defects

Prior to specimen fabrication, the weld microstructures were investigated. All TIG and the 12 mm EB welds show coarse grain formation which is typical for solidification micro structures that form during the welding cycles [9,10,12]. Both 5 mm beam welds do not show this severe grain coarsening. Also typical for TIG welds is the observation of soft regions in the HAZ [12]. The lateral extension of the beam welds is significantly smaller and distinct softening in the HAZ is not observed. Hardness in the fusion zones of all welds ranges from 400 to 450 HV1 (base material varies around 220 HV1).

All TIG weld show a very low defect density. In very rare cases formation of delta-ferrite could be detected (which is consistent to theory and other studies [24–28]) in the 5 mm weld and some inclusion have been found in the 10 mm weld. With a carbon content of 0.1% in the fusion zone of TIG welds decarbonisation of the filler material (see Table 1) was not observed.

But all beam welds (EB and laser) revealed more or less extended bubbles. Their size and distribution depends primarily on the beam intensity and purity of the weld surfaces. While the 12 mm EB weld showed even small cavities, in the 5 mm EB weld gas pores with diameters of 20–40 μm have formed. In the 5 mm laser weld the pores are even smaller.

3.1.2. Influence of PWHTs on microstructure and mechanical properties

In a first series six different two- and single-step PWHTs (see Table 2) have been applied to 5 and 10 mm welds in vacuum to examine their basic behavior. With respect to hardness all welds respond comparable to the PWHT (see Table 2). That is, both two-step heat treatments (PWHT 1 and 2) remove the coarse grained weld microstructure and lead to hardness levels around or below 250 HV1. All single-step treatments (PWHT 4–6) do not change the microstructure but soften the weld down to hardness levels of 290–350 HV1. Tempering below 700 °C does not lead to significant changes. PWHT 3 was just applied to verify a complete alpha–gamma transformation which was the case as can be clearly seen from the hardness of about 450 HV1 [29].

These findings have been taken into account for a second series of PWHTs that was applied to the 12 mm TIG and EB welds (see Table 3). The results of single-step heat treatments clearly show that longer tempering periods do not affect the hardness (PWHT 8, 11, and 13). Furthermore, below tempering temperatures of 700 °C the hardness increases clearly above 300 HV1 (PWTH 7–9) and for temperatures of 700 °C and above there is not much difference (PWHT 10–14). Only a two-step heat treatment (PWHT 15) softens the fusion zone to values of about 250 HV1.

Charpy tests have been performed first with specimens from the 5 and 10 mm welds. Generally, the charpy properties of specimens notched within the HAZ tend to result in better values (i.e. higher USE and lower DBTT) compared to the specimens with notches in the weld centre. This is mainly due to the coarse grained microstructure in the fusion zone. However, table 4 lists the results for these welds without PWHT and after PWHT 1 (standard two-step EUROFER heat treatment) and 5 (low temperature single-step treatment at 700 °C). After the standard heat treatment (PWHT 1) all welds show almost exactly the results of the base material (−90 to −110 °C/9 J) which is not surprising, since the microstructure and hardness is fully restored (as mentioned before). But without

Table 1
Chemical composition of different EUROFER heats. Values are given in wt.% by the according manufacturer [21–23].

Element	EUROFER97 heat 83698 14 mm plate	EUROFER97 heat D83350 Ø1 mm filler wire	EUROFER97-2 heat 993402 25 mm plate
Cr	8.82	8.93	8.95
C	0.11	0.11	0.11
Mn	0.47	0.39	0.55
V	0.20	0.19	0.20
W	1.09	1.09	1.04
Ta	0.13	0.14	0.14
N_2	0.020	0.026	0.038
O_2	0.0010	0.0018	0.0011
P	0.005	<0.005	0.0025
S	0.004	0.004	0.001
B	<0.001	<0.0005	0.0008
Ti	0.005	0.006	
Nb	<0.0016	<0.001	0.004
Mo	<0.0010	0.001	0.005
Ni	<0.0200	0.02	0.03
Cu	0.0016	0.074	0.005
Al	0.009	0.007	0.005
Si	0.04		
Co	0.006	0.005	0.009
As + Sn + Sb + Zr	<0.015	<0.02	<0.009

Table 2
PWHTs applied to 5 and 10 mm welds (TIG, EB, and laser). The hardness in the fusion zones of all welds is within the given range.

PWHT	Annealing	Tempering	Hardness in fusion zones
1	980 °C/0.5 h	760 °C/2 h	220–230 HV1
2	900 °C/2 h	760 °C/2 h	250–255 HV1
3	900 °C/2 h		445–450 HV1
4		760 °C/2 h	290–295 HV1
5		700 °C/2 h	320–340 HV1
6		650 °C/2 h	330–350 HV1

Table 3
PWHTs applied to 12 mm EB and TIG welds. Hardness is given in pairs where the left number refers to EB and the right to the TIG weld (EB/TIG).

PWHT	Annealing	Tempering	Fusion zone hardness (12 mm EB/TIG)
7		650 °C/2 h	305/335 HV1
8		650 °C/16 h	318/320 HV1
9		680 °C/2 h	312/310 HV1
10		700 °C/2 h	290/285 HV1
11		700 °C/16 h	285/295 HV1
12		720 °C/2 h	280/285 HV1
13		720 °C/4 h	275/315 HV1
14		740 °C/2 h	270/280 HV1
15	900 °C/2 h	740 °C/2 h	245/250 HV1

Table 4
Charpy properties (DBTT in °C/USE in J) for 5 and 10 mm welds (TIG, EB, and laser).

PWHT	10 mm TIG	5 mm TIG	5 mm laser	5 mm EB
Without	40 °C/5 J	25 °C/7 J	−10 °C/9 J	−65 °C/12 J
700 °C/2 h	10 °C/7 J	−15 °C/8 J	−70 °C/10 J −80 °C/10 J	−65 °C/12 J −100 °C/12 J
980 °C/0.5 h + 760 °C/2 h	−90 °C/9 J	−90 °C/9 J	−90 °C/9 J	−100 °C/9 J

PWHT, the 5 mm EB weld yields a DBTT near to those of the base material which is amazing. While both TIG welds are far too brittle without PWHT, the laser weld is significantly, but still not too far away from the DBTT of the base material. A single-step PWHT at 700 °C (which would be perfectly safe for a final breeder unit assembly including Be pebbles) merely improves the brittleness of the EB and laser welds to values comparable to the base material. The TIG welds, however, are useless with such a low temperature one-step PWHT.

Based on these results, further charpy tests on the 12 mm welds have been performed after PWHT 9, 10, 14, and 15 with specimens notched directly at the weld fusion zone (see Fig. 1). This study clearly demonstrates that base material ductility of TIG welds will only be restored by tempering temperatures of at least 740 °C or higher. Of course, the charpy properties may be pushed to an optimum by grain refinement with help of a 900 °C austenitization step. The investigated EB weld, however, leads to acceptable DBTT values (but still higher than those of the base material) even with a one-step heat treatment at 700 °C. Lower tempering temperatures are clearly useless.

Fig. 2 shows the creep test results on the 12 mm welds. Above 550 °C the creep strength of TIG welds decreases with rising test temperature compared to the base material. Electron beam welded specimens with the same PWHT of 700 °C are even worse. Here the creep strength is further reduced by about 10–20 MPa. The influence of different PWHTs has been tested at 600 °C only. By increasing the tempering temperature to 740 °C the creep strength is deteriorated by about 10 MPa while a full PWHT with austenitization at 900 °C and tempering at 740 °C slightly improves creep strength. That is, there are at least two observations that have to be explained: (1) electron beam welds show lower creep strength. (2) Compared to the base material, all welds show worse creep strength with increasing temperature. Point (1) can be explained by the fact that EB welds have finer grained microstructures than TIG welds. Since in the present stress range creep is dominated by diffusion activated climb processes, grain boundary diffusion is more enhanced in the fine grained EB welds than in the coarse grained TIG welds. This in turn, triggers more climb processes and, therefore, creep. Point (2) might be reasonably explained by lower climb activation energies in the softened heat affected zones in the welds. This would also explain the deterioration of creep strength by increasing the tempering temperature from 700 to 740 °C in the examined one-step PWHTs.

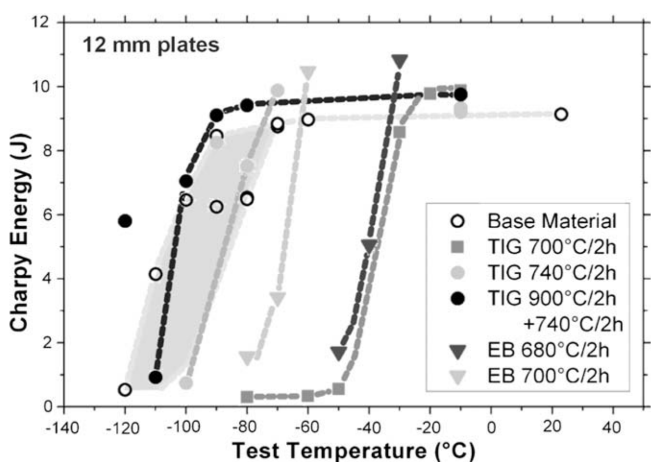

Fig. 1. Charpy test results of 12 mm EB and TIG welds after different heat treatments. The notch of the charpy specimens was fabricated in the centre of the welds.

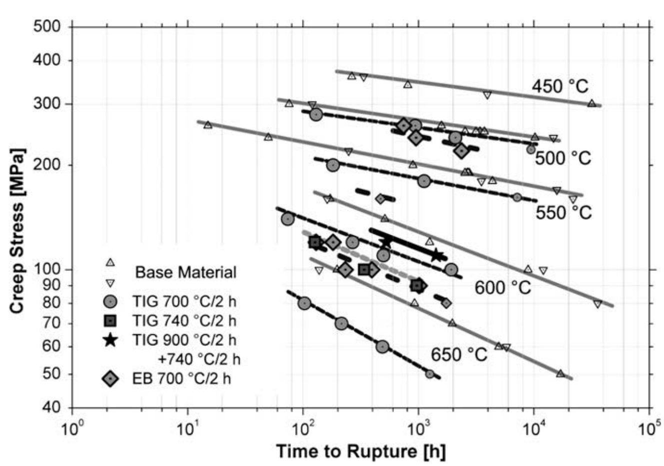

Fig. 2. Results of creep tests with 12 mm EB and TIG welds after different PWHTs compared to the base material.

3.2. Deep EB weld

The cross-section of the 40 mm deep EUROFER EB joint is shown in Fig. 3. As can be seen, the fusion zone varies only between about 1.5 and 2 mm from top to bottom which is rather constant and narrow. Its hardness varies between 440 and 480 HV1 and its grain is clearly coarser than that of the base material. A distinct fine grained HAZ with a width of about 0.5 mm is also visible. Here the hardness shows some single soft spots with much smaller values than the base material (220 HV1). Defects like bubbles or micro cracks have not been observed.

Anyway, the weld is far too brittle to be useful without PWHT. This is shown in Fig. 4 where the DBTT of the weld can be estimated to be about 20 °C. However, after a standard PWHT (for EUROFER this is 980 °C/30 min + 750 °C/2 h) ductility is fully restored. The results from Fig. 4 shows further that the weld properties are distributed homogeneously (i.e. the charpy energies from specimens of the weld top are comparable to those of the root).

With these results the present EB weld would be perfect for joining the caps to the first wall of a TBM. But unfortunately, the

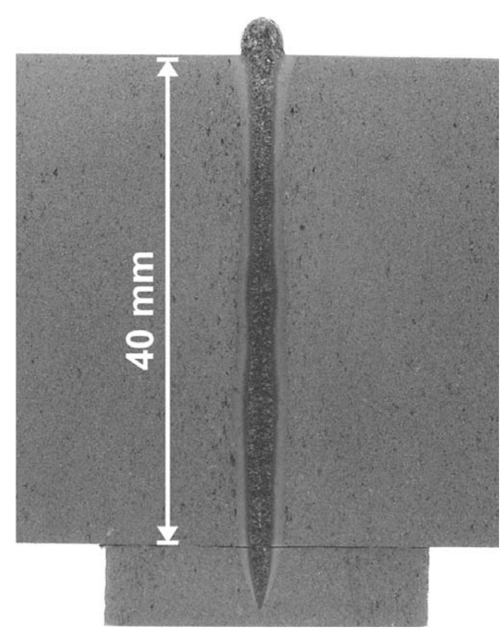

Fig. 3. Cross-section of the 40 mm deep EB weld. The smaller plate at the bottom acted as beam stopper.

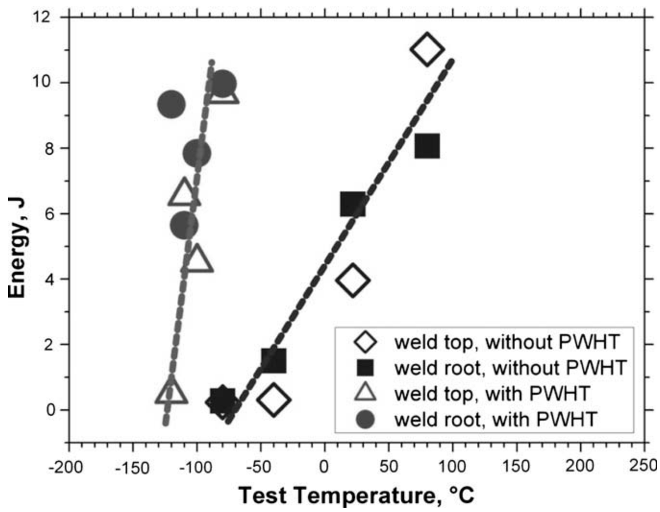

Fig. 4. Charpy test results of 40 mm EB weld specimens from the top and root. The influence of the standard PWHT (980 °C/30 min + 750 °C/2 h) is obvious.

microstructure examinations have revealed a high content of delta-ferrite which most probably results from too fast cooling rates during EB welding. Therefore, further optimization of beam and welding parameters is necessary to produce a microstructure comparable to that of the 5 mm EB welds.

4. Conclusions

One interesting result of these investigations is that EB or laser welds of 5 mm and TIG welds of 12 mm EUROFER plates may be used without (under certain conditions) or after just a one-step PWHT. This allows for more design options in connection with beryllium pebble beds and breeding units. Compared to TIG welds, more defects (pores, bubbles) have been detected in beam welds but they never acted as fracture initiator. Coarse grain forms preferably in TIG welds and thick EB welds which necessitates two-step PWHTs in any case.

In general, creep strength is reduced in all welds and may be restored with two-step PWHTs only, if at all. However, at maximum operation temperature (i.e. 550 °C for EUROFER) the effect might be tolerable.

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