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HIP experiments on the first wall and cooling plate specimens for the EU HCPB blanket

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Abstract

First wall and cooling plates are considered the most important structural parts of the EU HCPB blanket concept which is based on the use of ferritic–martensitic steel as structural material, Li_4SiO_4 pebbles as breeder material, beryllium pebbles as neutron multiplier, and 8 MPa helium as coolant. Both the first wall and cooling plates contain complex arrays of internal He coolant channels. The favourite manufacturing technology is diffusion welding of two halves of plates applying the hot isostatic pressure (HIP) welding method that allows uniform distribution of the pressure acting on the outer surfaces of the welding objects. The HIP experiment was started with small MANET specimens with internal coolant channels. The objective of this work is to investigate the appropriate HIP technique, boundary conditions, and parameters in order to achieve good mechanical properties of the welding joints as well as to achieve a transition to test specimens of larger dimensions.

1. Introduction

Structural parts of fusion blankets are subjected to high neutron, thermal and mechanical loads. The use of ferritic–martensitic steel as structural material plays an important role in the development of the European blanket concepts, especially for the helium cooled pebble bed (HCPB) [1] and the advanced dual coolant (He/Pb–17Li) (A-DC) [2] blanket concepts which are developed at the Forschungszentrum Karlsruhe. The structural parts of these fusion reactor concepts, i.e. the first wall, the cooling and the stiffening plates (Fig. 1), are provided with complex arrays of helium cooling channels in order to meet thermohydraulic requirements.

For successful fabrication of such complex components the diffusion welding method is favored. Hot isostatic pressure (HIP) is one of the promising diffusion welding methods that allows uniform distribution of the pressure acting on the outer surfaces of the welding objects which generally consist of two halves of grooved plates. The objective of this work is to investigate the appropriate HIP technique, boundary conditions, and parameters (e.g. two-step HIP technique, surface preparation, pressure, temperature, holding time, getter material, etc.) in order to achieve good mechanical properties of the welding joints.

In the beginning, the single-step HIP method with a contact pressure on the welding surface in a range of 22–29 MPa and a temperature of 1050 °C was used, which already lead to the first useful HIP results except that the value of breaking elongation was still too small. Later on, two-step HIPing was found to significantly improve the HIP results. It was further developed, and successfully applied in the last experiment series and has now become our standard HIP technique for diffusion welding of ferritic steel structures since 1999. The following report will emphasis on this two-step HIP technique as described in detail in [3–5].

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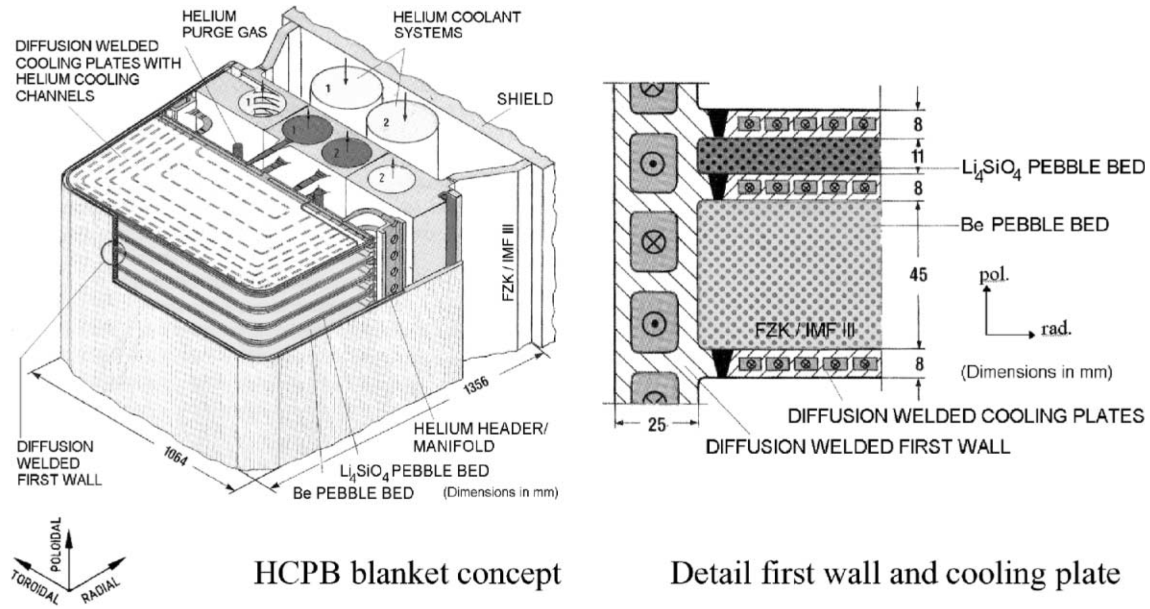


HCPB blanket concept

Detail first wall and cooling plate

Fig. 1. HCPB blanket concept [1], principle and detail of the structural parts.

2. Two-step HIP process

In this HIP process each two halves of specimens are welded in two successive HIP welding steps. In the first step, the two specimen halves are covered on the outside with compression plates out of molybdenum alloy (TZM) so as to protect the internal cooling channels with their thin webs, and then packed in a sheet jacket, evacuated, and welded in place gastight. As separators for the avoidance of bonding together both the outer surfaces of the specimen and of the pressure plates with each other and with the sheet jacket quartz glass mats were used, instead of boron nitride spray which was used in the preceding experiments and was found to be not optimal. In this encapsulated HIP step a moderate gas pressure of maximal 12 MPa, resulting in a maximal contact pressure on the welding surface of about 32 MPa, is applied at 1050 °C on the totally enclosed specimens with a holding time of maximal 120 min. All specimen packages are then cooled down at a cooling rate of at least $\leqslant 0.4$ °C/min for MANET and about 10 °C/min for EUROFER, respectively, and undergo a heat treatment at 750 °C/2 h. Thereafter, the welded specimens are dismantled and cut into two equal parts. One of the parts is then subjected to the second HIP step at 200 MPa and 1050 °C with all cooling channels being now open, while the other part of the samples serves for the post-examination for the first HIP step. After finishing the second HIP step the specimens are subjected to the same procedure of cooling down, heat treatment and post-examination as done for the first HIP step in order to compare the results with each other.

3. HIP specimens, their preparations and the post-examination procedure

Typical specimens for the first wall and cooling plate (size: about 100×100 mm^2) were provided consisting of two halves of plates with complex arrays of internal coolant channels on each half (Fig. 2). In the last experiment series (internal designation: series 5 to 7) they were provided with different kinds of surface preparation, e.g. grinding or dry-milling (surface roughness $R_t \leqslant 3$ μm), etching (only series 5), acetone bath, as well as the use of zirconium wires as getter material, to study the appropriate conditions for achieving good HIP results. Table 1 shows the variation of surface preparation parameters in these experiment series. As specimen material MANET was mostly used according to the HCPB concept, while in the last experiment series 7 a transition to EUROFER, the current reference material for HCPB, was introduced by the use of such a set of specimens among others.

The welding quality is determined by non-destructive (e.g. ultrasonic, US) before separating the first-HIPed specimens and by destructive (mechanical properties) methods. Destructive post-welding examinations served to determine the tensile strength, ultimate elongation of special (non-standardized) specimens from the welding

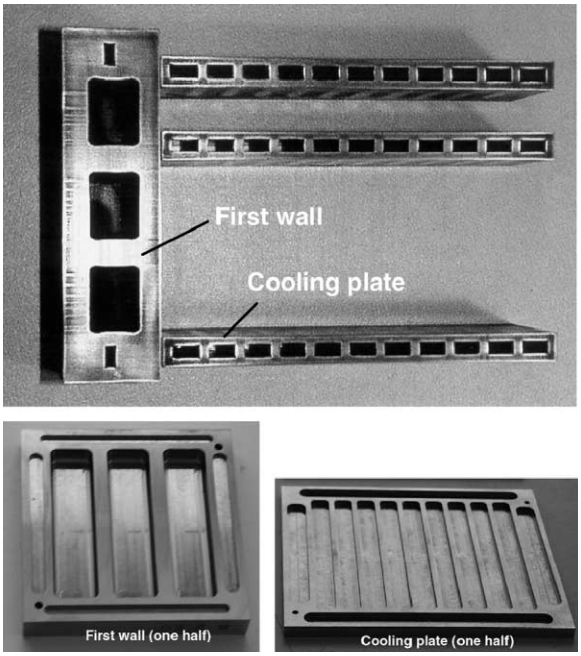


Fig. 2. First wall and cooling plate specimens used for HIP experiments [3].

Table 1
Preparations of joining surface

Experiment series	Specimen set no.	Material[a]	Joining surface preparation			Surface cleaning with		Zr getter material
			Dry-milled	Ground	EB seal welding[b]	Etching	Acetone US bath	
5th	1	M	–	×	–	×	–	×
	2	M	×	–	–	×	–	×
6th	1	M	×	–	–	–	×	×
	2	M	×	–	–	–	×	–
7th	1	M	×	–	–	–	×	×
	2	M	–	×	–	–	×	×
	3	M	×	–	×	–	×	×
	4	E	×	–	–	–	×	×

[a] M = MANET, E = EUROFER.
[b] At the edge of joining surface.

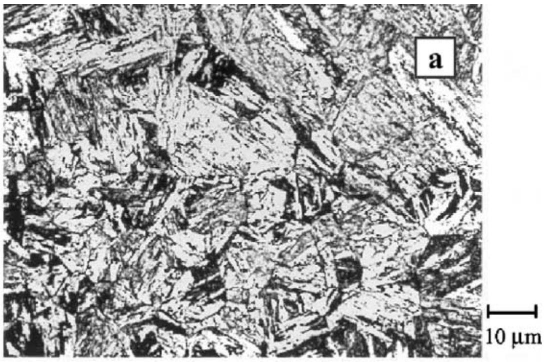
zone or made of the base (non-welded) material that undergoes the same boundary conditions as the specimens to be HIPed during the HIP process.

4. The HIP experiments and results

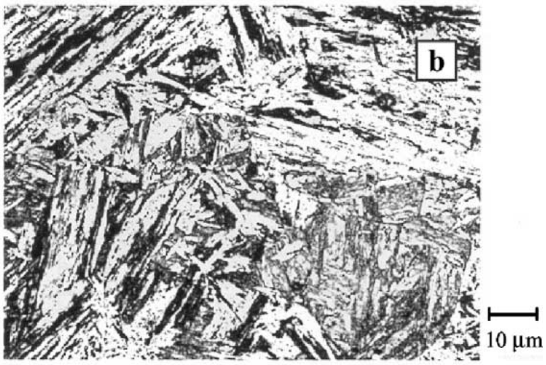
In the 5th experiment series [4] with the two-step HIP routinely applied for the first time two sets of specimens (Table 1) were provided with dry-milled and ground HIP joining surfaces which were etched. For the first time, Zr getter material was used for capturing oxygen and moisture. The US tests, which serve only as preliminary tests, showed so far no defects after the HIP steps. In the following experiments these US tests have been omitted. The overall results show a significant increase of the strength values in the second HIP step. Specimens with dry-milled joining surfaces showed better results than those with ground surfaces. For the first wall the yield strength was achieved in a range of 552–661 MPa and the tensile strength in a range of 625–735 MPa which are close to the base material. For the cooling plate the measured strength values are significantly lower than those of the first wall despite the same deformation range. A relatively large deformation of the webs was found both in the first wall and the cooling plate specimens so that a slight reduction of gas pressure was envisaged in the following experiments. In this experiment series also separate accompanying specimens were used for the investigation of the cause for the pronounced intermediate layer in the welding zone detected in the preceding experiments. The results of the evaluation in [6] show substantially that diffusion of vanadium to the surface took place at the evacuating temperature of 600 °C, which was applied in these experiments, leading to its reaction with oxygen and nitrogen forming oxide-nitride layers. Therefore, a lower evacuation temperature of 120 °C was recommended for the further experiments.

From the 6th experiments series [4] on, HIP specimens with dry-milled joining surfaces were used following the knowledge mentioned above. For cleaning of the joining surfaces the complex procedure of etching was replaced by the use of ultra-sonic acetone bath directly after dry-milling which was also used in other experiments in [7]. The experimental results showed that for the first time good mechanical properties for both the first wall and cooling plate types (MANET) were already achieved after the first HIP step and was even significantly improved by the second HIP step. The achieved average values of about 650–720 MPa for the yield strength and about 750 MPa for the tensile strength correspond to the values of the base material. The breaking elongation is sufficiently high but still improvable, e.g. ≈7% for the first wall and 12% for the cooling plate for the specimens with getter material, which are clearly higher than those obtained for the specimens without getter material.

In the 7th experiment series [5] four sets of specimens (Table 1) were welded where the first two sets were provided each with dry-milled and ground joining surfaces for a check of the reproducibility. In a further specimen set the dry-milled joining surfaces were sealed at the edge by EB welding as also applied in [7] and in the last specimen set EUROFER was used for the first time. After execution of the experiments six of eight specimen plates were intact. The deformation of the channel webs of the MANET specimens was in the range desired, while it was somewhat too high for the EUROFER specimens. For the first time, strong deformation of two specimen plates was observed after the first HIP step. This deformation was due to the pressure break-through at the sheet-jacket during the HIP process. All intact specimen plates, except for the first wall plate with the ground joining surface, were found to have strengths (Rp0.2, Rm) and ultimate elongation (*A*) that correspond to those of the basic material (MANET: Rp0.2 ≈ 605 MPa, Rm ≈ 725 MPa, *A* ≈ 14%; EUROFER: Rp0.2 ≈ 471 MPa, Rm ≈ 608 MPa, *A* ≈ 16%). It could be confirmed again that better results were achieved by specimens with dry-milled joining surfaces in comparison with those with ground surfaces. Evaluation in case of EB seal welded specimens that could be done for only one specimen because of failure of other specimen due to the gas break-down showed higher value of ultimate elongation and lower strength values. For the first time, the notch impact test was carried out but the strength values obtained were subjected to considerable large scattering so that the measurement should be repeated in the future experiments using EUROFER specimens. Fig. 3 shows for example the metallographic photos of the MANET first wall specimens with dry-milled and ground joining surfaces (Table 1, nos. 1 and 2) after the second HIP step, which do not differ from those after the first step. The welding zones are only recognizable from the partly existing preferred direction of the grains. This is in particular clearly recognizable in the case of ground joining surface.



FW specimen with dry-milled joining surface



FW specimen with ground joining surface

Fig. 3. Light-optical microstructure of the MANET first wall specimens of the 7th experiment series [5] with dry-milled (a) and ground (b) joining surface after the second HIP step.

5. Conclusion and outlook

With the use of two-step HIP process in our experiments good HIP results were achieved. The values of tensile and yield strength in the welding zones lie in the range of the base material. The values of the uniform elongation are useful. First measurement results for notch impact strength showed large scattering and should be repeated with some improvement of sample preparation in the following experiments. As significant knowledge gained from these experiments following parameters for preparation of HIP joining surfaces were found suitable for improving the welding results: dry-milled surface, acetone ultra sonic bath (no etching) and the use of zirconium wires as getter material. A transition from the use of MANET to EUROFER as sample material has been introduced. In future experiments the continuation of this work will emphasise the HIP joining of EUROFER/EUROFER and ODS-EUROFER/EUROFER which is considered necessary e.g. for the development of the advanced dual coolant blanket concept [2].

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