Benchmarking by high heat flux testing of W-steel joining technologies

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Abstract

For a future commercial fusion reactor, the joining of tungsten and steel will be of vital importance, covering the main part of the plasma facing area. However, the large difference, of more than a factor of 2, in the coefficient of thermal expansion (CTE) of W and steel results in high thermal stresses at their interface. The cyclic nature of the operation can cause fatigue effects and could result in a premature failure of the joint.

One possible solution is the insertion of a functionally graded material (FGM), with varying the CTE, as an interlayer between tungsten and steel, which could reduce these stresses. In this study, two processes, atmospheric plasma spraying (APS) and spark plasma sintering (SPS), are utilized to manufacture such FGMs. The gradation was accomplished by using two or three layers with a thickness of 0.5 mm each.

Another principle is the insertion of a ductile metal interlayer, which reduces the stress by plastic deformation. Vanadium and titanium foils of varying thickness were chosen, as both have a CTE in between W and steel and V forms a solid solution with W and Fe. These and a direct W-steel joint as baseline reference were made by current-assisted diffusion bonding. All samples consist of 3 mm thick W and steel tiles allowing a direct comparison of the different technologies.

An efficient high heat flux benchmark test procedure was developed and performed to investigate and compare the potential of the different joining technologies. For this, the complete stacks were brazed on actively cooled copper cooling modules and tested with high stationary heat loads of up to 5 MW/m² with 200 cycles at each level in the JUDITH 2 facility. Detailed thermal analysis including comparison with prediction based on FEM simulation are presented to understand the cause of the failure and track the degradation. This study allows to help focusing the further development of W-steel joining technologies.

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Keywords:

W/steel joints; high heat flux benchmark test; functionally graded material; atmospheric plasma spraying; spark plasma sintering; ductile interlayer

Highlights

- High heat flux test of several candidates for joining W and steel
- Functionally graded interlayers prepared by atmospheric plasma spraying (APS) and spark plasma sintering (SPS) were produced and tested
- Performance comparison with ductile (V, Ti) metal interlayer and direct joint
- Failure occurs at the interface next to W except using APS, where cracks open within the 75 vol% W layer
- Direct joints sustained with 4 - 5 MW/m² the largest heat load of all tested types

Introduction

On the way for a commercial fusion power plant a demonstrator reactor (DEMO), is foreseen which is until now only a placeholder and a huge variety of different design plans exist. For the first wall, which is the main part of the plasma facing area, impinging heat loads of about 1 MW/m² are typically envisioned [1]. Tungsten is the prime plasma facing material due to its high erosion resistance, melting point and thermal conductivity, together with its low activation, sputter yield and fuel retention [2]. The underlying structural material, however, will most probably be a low activating steel like EUROFER97, which is a ferritic-martensitic steel with a good creep-resistance [3]. Therefore, the question how to join these two dissimilar materials arise in particular considering the large mismatch in coefficient of thermal expansion (CTE) of W (4.4×10^{-6} /K) and EUROFER97 steel (10.5×10^{-6} /K) [4]. This connection has to sustain high number of cycles at standard heat load but eventually also some higher heat loads during off-normal events. As a vast area of more than 1200 m² has to be covered [5], larger tile sizes are favorable in terms of qualification and production costs. Embrittlement by forming intermetallic compounds, neutron irradiation and hydrogen reduces plasticity and can weaken the joints. Therefore, developing robust joining technologies, which offer a high safety margin, and corresponding testing techniques are highly important.

Several approaches have been discussed in the past, for instance including a ductile metal or functional graded interlayers (FGM). They are W/steel composites with a gradually varying concentration in order to soften the transition from pure W to steel and by this reduce the occurring thermally induced stresses. Numerical simulations done previously supported this idea and showed that thicknesses of at least 1 mm are necessary to have a substantial effect [4, 6] and larger ones would further reduce the creep in the steel [7], but of course also rise the temperatures in the W and the interface.

Three layers are proposed with 25, 50 and 75 vol% W (named 25W, 50W and 75W in the following) and a thickness of about 0.5 mm each, as a reasonable balance between manufacturability and stress reduction. As production techniques atmospheric plasma spraying (APS) and spark plasma sintering (SPS, also called field-assisted sintering) have been applied. As representative of the ductile metal approach, layers of V and Ti with different thicknesses have been employed and as reference the direct joint of W and Eurofer 97.

The larger number of possible approaches, manufacturing and joining parameters and the influence of the testing conditions create the necessity of a fast, small-scale benchmark testing procedure. With that, the potential of possible approaches, the influence of process parameters and the goals for the further development could be identified.

Materials and methods

ITER-grade W manufactured by Plansee SE and EUROFER97 provided by the Karlsruhe Institute of Technology were used for the bottom and cover tiles, all with the same dimensions of 12×12×3 mm³. All W-tiles have been polished to the same mirror like surface finish to detect cracks after the production and achieve a comparable IR-emissivity.

An overview of the eleven tested joint types is given in Table 2 in the results and few exemplary SEM images of cross sections are shown in Figure 1. All FGM joints have been produced by 1000°C by diffusion bonding with slightly different values for pressure and time, optimized for the different candidates. Details for the production of the APS joint can be found in [8] and for the SPS one in [9]. The joint with the ductile metal V as interlayer was done at 1000°C, 30 min, 20 MPa whereas for the direct one 15 min had been enough [12]. For the thin Ti (0.3 mm) similar parameters were used (27 MPa instead of 20 MPa), but for the thicker (0.8 mm and 1.5 mm) ones lower temperatures till 800°C and longer times till 60 min were used to maintain the desired thickness and avoid cracking in the W. However, cracks occurred in all W tiles at the 0.3 mm Ti samples after the brazing. This indicated that lower temperatures should be used for thin Ti, too. Thus it has to be stressed that for the Titanium joint an optimum procedure still has to be found. A 0.3 mm thin V foil as filler was necessary to achieve a bonding between the 75W APS and the bulk W, which was one reason to include this thickness for the ductile metal ones for comparison. In a previous study, we had shown that an elaborate laser structuring of the W was necessary for a direct deposition of 75W using APS [10].

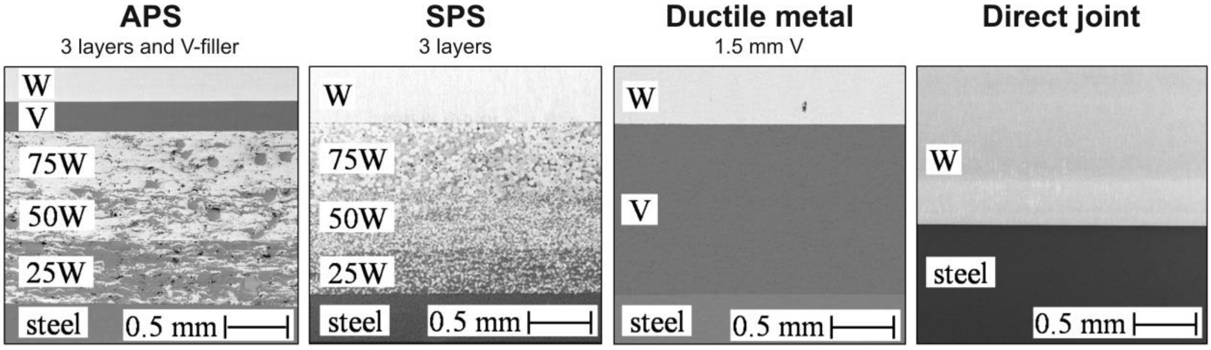

Figure 1: Exemplary cross sections of the tested joint types. All had a 3 mm thick W tile at the top and a 3 mm thick EUROFER 97 tile at the bottom [12].

The produced samples were then brazed with the steel side on simple copper modules using a silver-based brazing foil at 800°C. Four of these carriers were then mounted in the high heat flux testing facility JUDITH 2 located at the Forschungszentrum Jülich GmbH [11]. This allows an active cooling and thus a cyclic heat loading with the parameters given in Table 1 and some more details and pictures are given in [12]. It should be noted that these are not the same conditions as typically proposed for a DEMO first wall. However, this would mainly be relevant for future full component tests, whereas the aim here was a high throughput small-scale benchmark tests to compare the performance of different joining concepts. Furthermore, the additional copper and thus the larger distance between W-steel joint and the water compensates partly the lower coolant temperature. For instance, the temperature at the steel bottom is about 285°C at 4 MW/m², thus close to the 295°C – 325°C range proposed as coolant temperature for DEMO [13].

Table 1: Testing conditions of each module and planned loading steps. A screening at 1 MW/m² was performed.

Parameter	Value	Unit
Inlet water pressure	2.5	MPa
Inlet water temperature	20	°C
Water velocity	3.5	m/s
Absorbed power density	1.0 – 5.0 0.5 stepwise	MW/m²
Load time during cycling (ON/OFF)	30	s
Planned cycles at each level	200	#

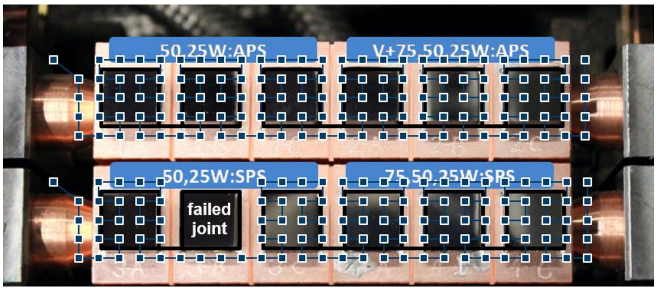

Figure 2: Developed beam pattern illustrated on a picture of two equipped Cu-modules mounted in JUDITH 2.

The electron beam of the JUDITH 2 facility is controlled by a list of points, which allows the development of a special beam pattern for a homogeneous loading of each individual sample. The FWHM of the beam is about 6 mm allowing a local homogeneity of the loading better than 5%. If the joint of one sample fails, a different point list is used, which excludes the failed one as illustrated in Figure 2. By this method, the testing of the other samples can be continued without the need to remove or cover the failed one. Failure is defined as either full detachment of the W-tile, reaching no steady state during the loading phase or surface temperatures well above 2000°C. The temperature is determined by IR thermography and verified by one- and two-color pyrometer.

Beginning at 1 MW/m², the heat load is increased stepwise by 0.5 MW/m² after every 200 cycles. At every new power level, first a 1 MW/m² screening has been performed in order to detect also a subtle joint degradation of previous cycles. Every cycle consist of 30 s ON and 30 s OFF, enough to reach the steady state temperature as determined during the screening.

Results

In total 42 joints of the different types have been tested in two campaigns with two or more samples per type (see Table 2). It is worth noting that most samples of one joint type failed at nearly the same power level, thus a high reproducibility of manufacturing and testing can be assumed for these types. Further details of some of the joints were provided earlier by Ganesh et al. [12]. The main results that were obtained are listed as follows:

- 2/3 of the two-layer APS and SPS joints failed already during beam positioning/setup with <1 MW/m² or during the brazing
- Only the three-layer APS with the V filler type failed within the 75W, all others at the interface to the bulk W tile
- Ductile metal outperforms the FGM approach and the layer thickness with the best lifetime is not the largest, but about 0.8 mm
- Failure occurred most often during the screening or the first cycles of a new power level accompanied with distinct increase in temperature with every cycle
- Most astonishing: no other joint type sustained higher loads than the direct one where failure occurred at cycling at 4 MW/m² or higher

Table 2: Overview of the joint types with number of tested samples, the heat load range at which they failed and where the crack/detachment occurred. At the three samples with 0.3 mm Ti all the W tiles showed cracks after brazing, as well as the one SPS-3 layer sample which sustained 3.5 MW/m², the others failed at 2 or 2.5 MW/m². The temperature at the bottom of the W-tiles is also given, namely during the screening of the power level at which the best sample of each type failed.

Joint Type	Numbers tested	Failure at [MW/m²]	Failure at Location	Estimated temp. at bottom of W [°C]
direct	**6**	**4 – 5**	**W – steel**	**880**
APS – 2 layer	3	< 1	W – 50 W	620
APS – V+3 layer	3	3.5	in 75 W	900
SPS – 2 layer	9	0 – 2	W – 50 W	650
SPS – 3 layers	6	2 – 3.5	W – 75 W	1020
V – 0.3 mm	3	2 – 2.5	W – V	460
V – 0.8 mm	2	4	W – V	1120
V – 1.5 mm	3	3.5	W – V	720
Ti – 0.3 mm	3	4 – 4.5	W – Ti	1040
Ti – 0.8 mm	2	2.5 – 5	W – Ti	1200
Ti – 1.5 mm	2	3	W – Ti	1050

Discussion

First, as indicated before, the goal of this study was to experimentally identify the most promising candidates and development routes by comparing different joining techniques and possible material combinations. The sample size used here is too small for a perfect representative of a FW modul and thus the absolute power levels at which the joints failed cannot transferred directly to the real application. However, the relative comparison of the power levels and failing mode of multiple candidates with several samples each, offers an efficient way to reach this goal and streamline the further development.

Detailed thermal analysis was performed to get more insight into the potential and failing behavior of the joints. Taking the measured thermal properties of the produced FGMs [8, 9] and values of the ITER material handbook for the metals, the evolving surface temperature at each power level can be determined using FE solver of ANSYS. These values are included as solid lines in the graphs of Figure 3. On the other hand, the mean surface temperature during the screening of each power level of the best performing sample of each type are included as symbols.

Large discrepancies between simulated temperatures and measured ones from the start and throughout the complete experiment indicate non-ideal contacts at the interface after manufacturing like voids, cracks or no metallic bond, acting as thermal barriers. The direct joint, the V joints and more or less the 3 layer APS+V performed quite like expected until failure. The other types show higher temperatures already much before failure. The best of the 3 layer SPS for instance, despite each layer having better thermal properties than the APS ones [8, 9], reaches at each power level higher temperatures than the thicker stack with additional V filler (V+APS 3). Quantitatively, using linear interpolation, the surface temperature of the 3 layer SPS raised by 320°C per MW/m² instead of simulated 220°C, whereas, for the 3 layer APS+V 290°C per MW/m² was measured and 250°C simulated. In contrast, the surface temperature of the direct joint raised by 200°C per MW/m² which matches very well with the simulated 190°C.

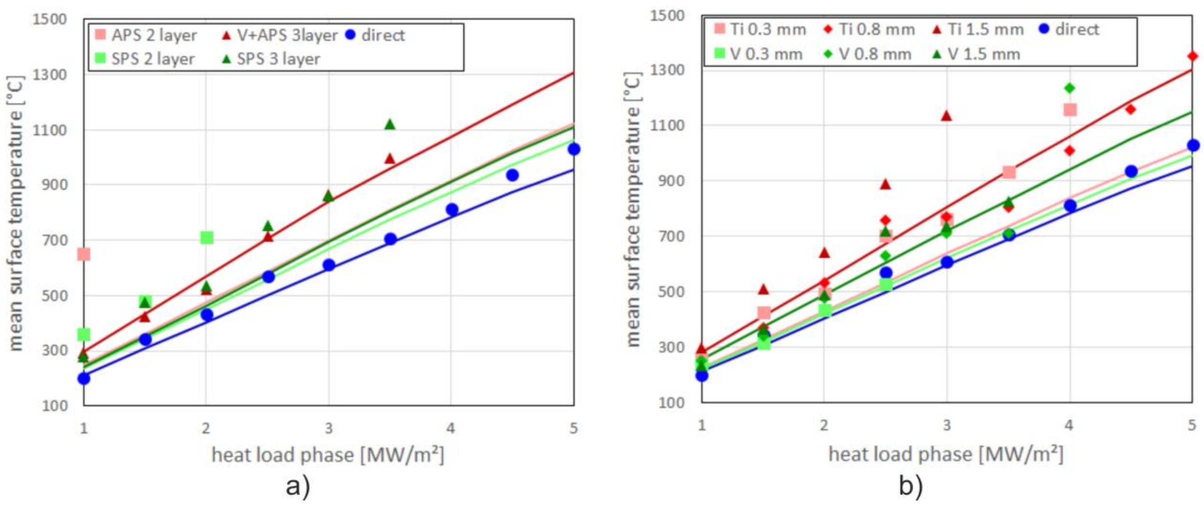

Figure 3: Mean surface temperature during the screening at the beginning of each loading phase of the best samples and compared with FEM simulation (solid lines). In a) the FGM types are shown together with the direct reference and in b) the ductile metal interlayers with the direct reference. There the simulation of the 0.8 mm thickness was omitted for the sake of clarity. Simulations indicate that the temperature at the bottom of the W-tile is about 30°C per MW/m² heat load lower than the surface.

The 1 MW/m² screening after each sustained heat load level was done to track precisely the degradation caused by the cycling. The cool-down behavior is fitted with an exponential decay law, determining a time constant, which is less prone to the emissivity changes caused by surface alterations during the test, like oxidation or recrystallization, which in turn change the absolute IR temperature reading. The mean time constants are shown in Figure 4, and no clear or significant degradation is detectable caused by the cycling at lower heat loads than the failing one. It should be noted, that no values after failure are shown here as usually no steady state could be reached anymore, even at 1 MW/m². However, if it was possible, the time constant increased drastically by several seconds.

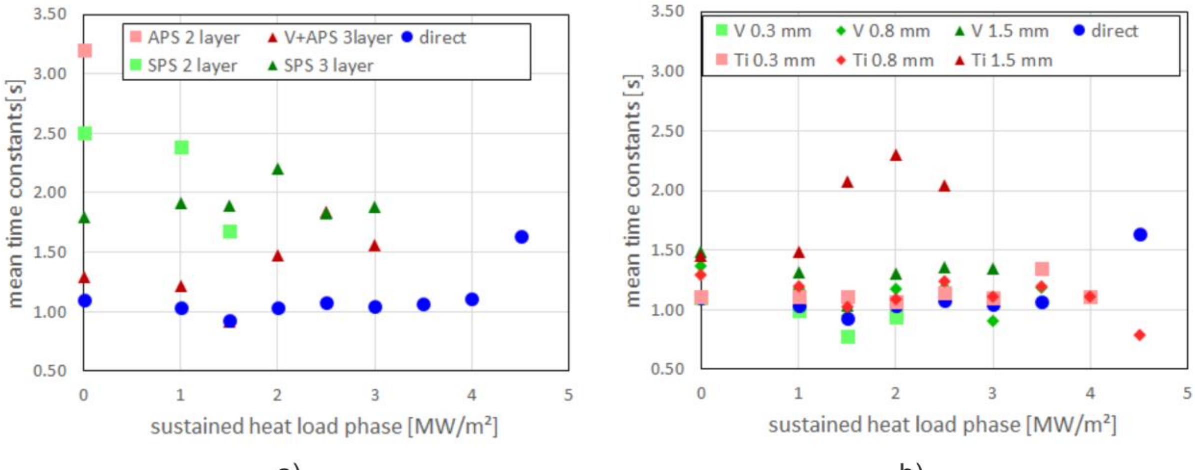

Figure 4: Mean time constants of the cooldown behavior determined from 1 MW/m² screening after each heat load phase. In a) the FGM samples are included and in b) the ductile metal ones.

Finally, from the simulation one can determine the temperature at the W-steel interface when failure occurs/starts. It is about 30°C per MW/m² lower than the corresponding surface temperature, i.e. taken the surface values as shown in Figure 3, the interface of the best direct joint started to fail at about 880°C (worst sample at 680°C). This interface temperature is given for the best sample of each type also in Table 2. For the 3 SPS layer samples, where all samples failed during the cycling at a power level corresponding to surface temperatures of about 1100°C, the interface to the W tile failed above 900°C (1020°C best case). From this point of view, the FGM approach works and increases thermal stability of the joint. However, in terms of power handling this is overcompensated by the higher temperature due to the additional layer, the low thermal conductivity of the FGM and a bad heat transfer between W tile and FGM. The FGM using 3 APS+V layers could also sustain higher temperatures than the direct joint, but is further limited than the SPS ones by their worse mechanical stability. Regarding the ductile interlayer of V and Ti, although their manufacturing process was by far not optimized, outperformed the much more complicated FGMs. However, one has to keep in mind, that for the 0.3 mm Ti interlayer, the reason for the high performance could partly be the fact that the W-tiles showed cracks after the brazing. Also, it could be that this is only the case, because neither irradiation, hydrogen nor other embrittlement processes were included in this study.

This study also indicates that the understanding of the failing mechanism of joints prepared by SPS needs further investigations. Thermo-mechanical simulations usually assume a stress free temperature at the maximum temperature during joining [4, 14, 15] (thus here 1000°C) and, therefore, suggest a tensile stress normal at the W-steel interface during cool down and this as the major crack initiator. The fact that no clear sign of degradation after the cycles can be seen here and together with the observation that samples often fail or heavily degrade during the loading phase of the start screening of a new, slightly higher power level, indicate that this assumption could be wrong. A for instance much lower stress free temperature could change the counter intuitive result of these simulations that such W-steel joints have to endure the highest stresses during the production and thus no failure should happen during such relative low cycle HHF testing. As shown in Table 2, the interface temperature of even the best samples in this study, where below 1000°C when failing.

Conclusion

A very efficient HHF benchmark testing procedure was developed allowing to assess and compare the potential of different joining technologies with little amount of material and machine time. By using same lateral geometries, surface finish and proper references, conclusive assessments of the potential and drawbacks of different joint types could be made.
Eleven types with several samples each were manufactured and tested including four joint types using a FGM approach based on atmospheric plasma spraying and spark plasma sintering and six types employing a ductile metal interlayer (V, Ti) of varying thickness.
To conclude, despite the fact that the FGM layers reduce the CTE difference as expected and failed at higher temperatures, none of the prepared joints could sustain the same heat fluxes as the direct ones let alone higher ones. However, the FGM approach should be investigated further in particular using SPS in combination with a thin metal adhesion layer to bulk W, since it can presumably only realize its

full potential at larger sample sizes and when embrittlement processes like irradiation or hydrogen loading are also involved. The metal interlayers have not performed better than the reference either, despite their ductility and having a CTE between W and steel. Thus, for the future development of W-steel joints, the simple direct one should not be easily disregarded as it sustained at least 3.5 MW/m² and some of the specimens even up to 4.5 MW/m². So even reasonably larger tiles than used here are expected to sustain the envisioned operational heat load of about 1 MW/m².

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References

1. Federici, G., et al., *An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort.* Fusion Engineering and Design, 2019. **141**: p. 30-42.
2. Cismondi, F., et al., *Progress in EU Breeding Blanket design and integration.* Fusion Engineering and Design, 2018. **136**: p. 782-792.
3. Tavassoli, A.A.F., et al., *Materials design data for reduced activation martensitic steel type EUROFER.* Journal of Nuclear Materials, 2004. **329-333**: p. 257-262.
4. Heuer, S., et al., *Overview of challenges and developments in joining tungsten and steel for future fusion reactors.* Physica Scripta, 2020. **T171**: p. 014028.
5. Federici, G., et al., *European DEMO design strategy and consequences for materials.* Nuclear Fusion, 2017. **57**(9): p. 092002.
6. Heuer, S., et al., *Aiming at understanding thermo-mechanical loads in the first wall of DEMO: Stress–strain evolution in a Eurofer-tungsten test component featuring a functionally graded interlayer.* Fusion Engineering and Design, 2018. **135**: p. 141-153.
7. Qu, D.D., W.W. Basuki, and J. Aktaa, *Numerical assessment of functionally graded tungsten/EUROFER coating system for first wall applications.* Fusion Engineering and Design, 2015. **98-99**: p. 1389-1393.
8. Ganesh, V., et al., *Manufacturing of W-steel joint using plasma sprayed graded W/steel-interlayer with current assisted diffusion bonding.* Fusion Engineering and Design, 2021. **172**: p. 112896.
9. Ganesh, V., et al., *Processing and Properties of Sintered W/Steel Composites for the First Wall of Future Fusion Reactor.* Journal of Nuclear Engineering, 2023. **4**(1): p. 177-192.
10. Matějíček, J., et al., *The Role of Laser Texturing in Improving the Adhesion of Plasma Sprayed Tungsten Coatings.* Journal of Thermal Spray Technology, 2019. **28**(7): p. 1346-1362.
11. Majerus, P., et al., *The new electron beam test facility JUDITH II for high heat flux experiments on plasma facing components.* Fusion Engineering and Design, 2005. **75-79**: p. 365-369.
12. Ganesh, V., et al., *High Heat Flux Testing of Graded W-Steel Joining Concepts for the First Wall.* Energies, 2023. **16**(9): p. 3664.
13. Martelli, E., et al., *Advancements in DEMO WCLL breeding blanket design and integration.* International Journal of Energy Research, 2018. **42**(1): p. 27-52.

14. You, J.H. and G. Breitbach, *Deformation of ductile braze layer in a joint element under cyclic thermal loads.* Fusion Engineering and Design, 1998. **38**(3): p. 307-317.
15. You, J.H. and H. Bolt, *Analysis of singular interface stresses in dissimilar material joints for plasma facing components.* Journal of Nuclear Materials, 2001. **299**(1): p. 1-8.