UK Atomic Energy Authority

UKAEA-STEP-PR(23)16

S. Chen, N. Correa Villanueva, S. Kirk, S, Capp, O. Fordham, A. Reeves, S. Jones, R. Khan, A. Sergi, C. Thompson

MANUFACTURING DEMONSTRATION OF A STEP INBOARD NEUTRON SHIELD

MANUFACTURING DEMONSTRATION OF A STEP INBOARD NEUTRON SHIELD

S. Chen, N. Correa Villanueva, S. Kirk, S, Capp, O. Fordham, A. Reeves, S. Jones, R. Khan, A. Sergi, C. Thompson

This is a preprint of a paper submitted for publication in Fusion Engineering and Design

MANUFACTURING DEMONSTRATION OF A STEP INBOARD NEUTRON SHIELD

S. Chen[a], N. Correa Villanueva[a], S. Kirk[a], S, Capp[a], O. Fordham[b], A. Reeves[b], S. Jones[b], R. Khan[c], A. Sergi[c], C. Thompson[d]

[a]*United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, UK*
[b]*Frazer Nash Consultancy, Narrow Quay House, Bristol, BS1 4BA, UK*
[c]*The Welding Institute, Granta Park, Great Abington, Cambridge, CB21 6AL*
[d]*Lucideon Limited, Queens Road, Stoke-on-Trent, ST4 7LQ, UK*

The UKAEA's Spherical Tokamak for Energy Production Program (STEP) is developing the STEP Prototype Powerplant (SPP), where an assessment of manufacturing strategies for the inboard shield identified several gaps in knowledge. Limits arose from the modularization of this component, geometric constraints of tungsten ceramic forming, joining with low-activation interlayers and dissimilar joining. These unknowns are addressed by tungsten and tungsten carbide manufacturing demonstrations for key features of the inboard shield. This began with an exploration into low activation interlayers and bonding techniques for tungsten, tungsten carbide and 316L joining.

Iron and vanadium and tantalum are all low-activation in a fusion environment, and it was found that these can produce good quality bonds for tungsten joining, tungsten carbide joining or dissimilar joining with 316L via hot isostatic pressing diffusion bonding. Vanadium and tantalum can produce acceptable tungsten -tungsten bonds. Tantalum is also compatible with tungsten carbide-tungsten carbide joints. Iron can produce good bonds for tungsten carbide-tungsten carbide joining, tungsten carbide-316L joining, and tungsten-316L joining. Higher temperature requirements for tantalum interlayers can compromise the steel microstructure for 316L dissimilar joints. Carbon-containing substrates were incompatible with vanadium interlayers due to brittle intermetallic formation at the interfaces.

It was concluded that the required joint quality between the relevant substrate materials can be achieved with the named low activation interlayers and hot isostatic pressing diffusion bonding. The results of this will inform a geometric demonstration which includes permanent and semi-permanent joints, dissimilar joints, bonded coolant pipes and cross-joint coolant channels.

Keywords: Inboard Shielding, tungsten, tungsten carbide, Dissimilar Joining, Low Activation, Diffusion Bonding

1. Introduction

Neutron bombardment of the SPP central superconducting magnets results in a limited operating lifetime. An inboard radiation shield is needed to reduce the neutron and gamma flux reaching the magnets, thus prolonging their operational lifetime. As the SPP is a spherical tokamak; it has a small centre column diameter, so sufficient neutron shielding needs is required in a relatively narrow thickness. For that reason, the inboard shield will need to use materials with high neutron absorption and scattering characteristics: two candidates are tungsten (W) and tungsten carbide (WC). Such materials will need to have high density following manufacturing and high purity to minimise interactions that may create active waste.

Neutron and gamma interactions will generate large volumetric heat loads (~10-15MW/m^3) within the shield so active cooling will be required via internal cooling pipes. For W or WC, it's generally unfeasible to create a monolithic component at the scale needed for the STEP design. As such, current concepts have modular designs. Hence, the quality of the interfacing between modules is imperative to ensure continuity of features such as a coolant channels, and homogeneity of properties such as density, thermal expansion, and thermal conductivity. Where direct joining of components cannot be achieved,
mechanical joining alternatives may also be explored.

Typical tungsten and tungsten carbide joining and manufacturing uses binders and interlayers with high activation characteristics which may not meet the active waste requirements for STEP (such as Cobalt [1], Nickel or Titanium [2]). Complex geometries during joining may also be required to include internal pipes and angled interfaces for shine path avoidance. It was decided that joining trials for candidate substrate materials, interlayers and joining methods would be performed to explore its feasibility, and to de-risk the future manufacturing demonstration of representative inboard shield features.

Author's email: Sunchi.chen@ukaea.uk

2. Uniaxial Diffusion Bonding (UDB) Trials

2.1 Objectives

Uniaxial diffusion bonding was trialled first to determine interlayer-substrate compatibility and to determine suitable parameters for later Hot Isostatic Pressing (HIP) trails. UDB trails also tested the effect of physical vapour deposition (PVD) on the interlayer-substrate interactions to see if this created a higher quality bond.

2.2 Method

25mm x 5mm circular discs of 316L, sintered tungsten and sintered tungsten carbide were procured and prepared for UDB with ultrasonic solvent cleaning. The WC material contain 8% Co binder. It was accepted for the trials whilst acknowledging that WC with Co binder would not be used in a fusion environment due to Co activation characteristics. It was accepted at time that a

.

WC 8%Co would be sufficient to understand that manufacturing limits of this material in this context. Some discs were coated in a 3um Ti layer followed by a 50nm gold coating via PVD. Fe, Ta and V interlayers were pressed out of 50 um foils. All parts were them assembled into their respective stacks and diffusion bonded within a graphite jig. The first runs of tungsten UDB trials had produced radial cracking in the tungsten discs. These discs were machined from a rod of tungsten, so it was concluded the residual stresses from this manufacturing method contributed to the radial cracking. This trail was repeated with circular tungsten discs machined from a tungsten sheet and this issue was resolved.

After the UBD process, a sample cross section was machined from every stack to examine under Optical microscopy and Secondary Electron Microscopy (SEM)

2.3 Results

2.3.1 Vanadium interlayers

W-V-W joints performed well with vanadium interlayers, showing good interaction at the W-V interface, and forming a complete bond.

W-V-316L joints displayed extensive interaction at the V-316L interface. EDX analysis determined this to be a vanadium-rich carbide layer.

WC-V-316L joints also displayed a thick V-316L interaction layer of vanadium-rich carbide, with cracking confined to this layer (Figure 2). This suggests this carbide is brittle, as the cracks do not propagate into the relatively ductile 316L substrate. WC-V showed some adhesion, though also had brittle intermetallic formation at the interface.

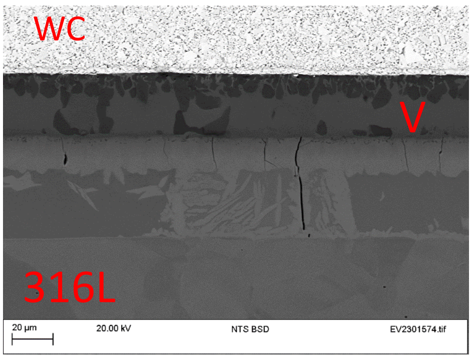

Figure 2 316L-V-WC UDB joint with reaction layers at interface.

PVD coating aided the formation of an interaction layer for WC-V bonds (Figure 1), likely due to good WC compatibility with Ti. PVD coating has little effect on any 316L joints.

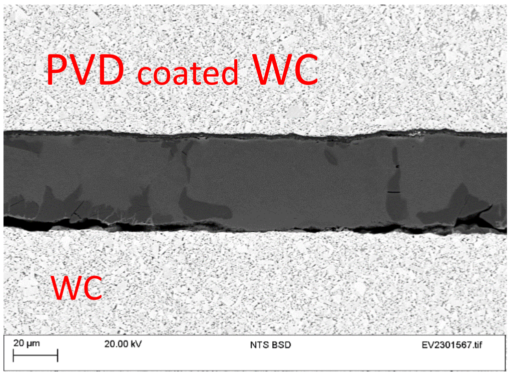

Figure 1 WC (PVD)-V-WC UDB joint displaying stronger adherence at W (PVD)-V interface.

2.3.2 Tantalum Interlayers

The elevated processing temperature required for tantalum interlayers cause significant grain growth and deformation within the 316L discs (Figure 3). 316L-Ta interfaces displayed good interaction with 3 to 4 distinguishable diffusion layers. Intermetallics were observed in the 316L substrate.

Figure 3 W-Ta-316L UDB joint with large grains in 316L substrate

W-Ta-W bonded with no presence of intermetallics at the W-Ta interfaces.

PVD coating appeared to increase the interaction layer thickness at both 316L-Ta and W-Ta interfaces. Cracking was observed within the reaction layer at the 316L-Ta interface, attributed to 316L deformation during the diffusion bonding process. Complex Ti phases were found at the 316L-Ta interface, and Ti-rich precipitates were found at the W-Ta interface suggesting that the Ti PVD coating aided the formation of the reaction layers.

2.3.3 Iron Interlayers

W-Fe-W joining did not produce a successful bond as it had delaminated at the interlayer-substrate interface. 2 diffusion layers were observed at the interfaces. At a lower bonding temperature, W-Fe-W displayed a full bond, with a W-Fe intermetallic reaction layer that the interfaces. These reaction layers contained small defects (Figure 4).

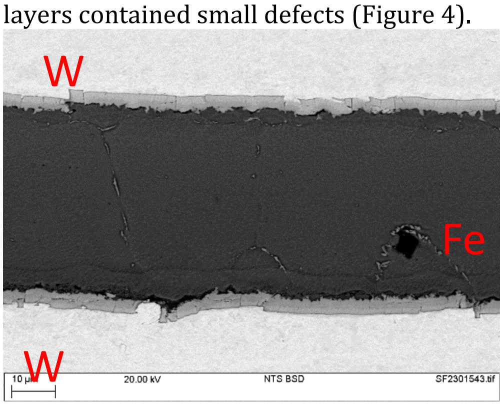

Figure 4 W-Fe-W UDB joint with intermetallic reaction layer at interfaces.

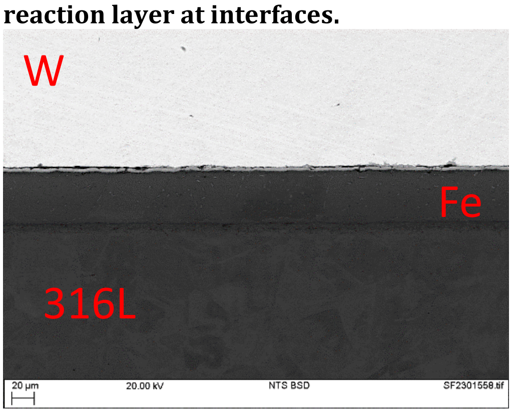

Figure 5 Fully bonded W-Fe-316L UDB joint with small precipitates above W-Fe interaction layer.

W-Fe-316L successfully bonded, there was also an intermetallic W-Fe reaction layer at the W-Fe interface with small defects (Figure 5). 316L-Fe interfaces displayed good adherence with no detectable defects or precipitates.

WC-Fe-316L and WC-Fe-WC joints showed full adherence with no detectable defects or precipitates at the interfaces.

PVD W-Fe-W and PVD W-Fe-316L joints delaminated at all W-Fe interfaces (Figure 6). Ti-rich precipitates were found in the Fe foil and along the W-Fe interfaces.

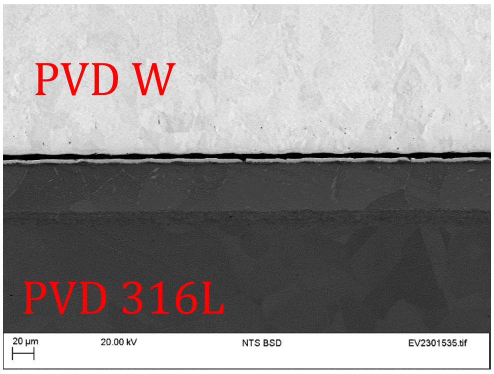

Figure 6 W(PVD)-Fe- 316L(PVD) UDB joint with delamination at W(PVD)-Fe interface.

2.3.5 Summary

The UBD trials concluded that V interlayers were unsuitable for any tungsten carbide or 316LN bonding due to excessive brittle Vanadium-carbide formation. At temperatures of 1200°C, grain growth in 316L was observed, so the temperature and dwell times were reduced for the latter half of the UDB trials, which produced better retention of the original 316L microstructure. It was found that PVD did improve some interlayer-substrate interaction, but the most relevant non-PVD coated samples still performed well, thus PVD was not carried forward into further trials.

3. Hot Isostatic Pressing Diffusion Bonding (HIP-DB) Trials

3.1 Objectives

HIP-DB trails were performed to reaffirm the selected interlayers and evaluate HIP parameters to be carried forward to the bonding of the geometric demonstrator by testing some lower and some higher temperatures.. The effectiveness of a diffusion barrier was also assessed here for potential application in manufacture.

3.2 Method

316L sheet metal was machined, bended and welded to create cannisters for the HIP-DB trails. The W, WC AND 316L 25mm X 5mm discs were prepared via ultrasonic acetone cleaning and stacked into their respective cannisters**Error! Reference source not found.Error! Reference source not found.**. An evacuation tube was welded to the cannisters, and they were helium-leak checked. They were outgassed and then sealed via crimping of the evacuation tube. Following the HIP-DB process, the cannisters with diffusion barriers were circumferentially cut at the approximate location of the barrier, to demonstrate that it had successfully prevented bonding at that interface (Figure 7). All cannisters were then cut cross-sectionally and prepared for optical and SEM analysis.

3.3 Results

3.3.1 Vanadium interlayers

W-V-W joints showed good bonding with no detectable defects (Figure 8 W-V-W HIP-DB joint displaying full adherenceFigure 8 W-V-W HIP-DB joint displaying full adherence

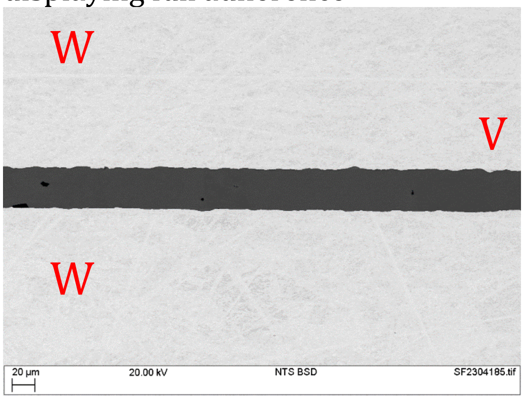

Figure 8 W-V-W HIP-DB joint displaying full adherence

W-V-316L did produce a full bond, however a thick V-Carbide layer was produced at the 316L-V interface. Similarly, to the UDB trials, this interaction layer had cracking throughout the brittle V-Carbide material.

3.3.2 Tantalum Interlayers

W-Ta-W did not successfully bond when HIPed at 1050°C. At 1150°**C**, W-Ta-W bonded successfully with no evidence of precipitates/defects within the joint.

316L-Ta-W at 1050°C showed good bonding at the 316L-Ta interface but extensive delamination at the Ta-W interface (Figure 9).
Similarly, at 1150°C, the 316L-Ta-W joint displayed no W-Ta adherence and a full 316L-Ta bond, however there was now a thicker interaction layer at the

Figure 7 HIPed and machined cannister showing that the diffusion barrier successfully prevented bonding of 316L disc to

316L-Ta interface.

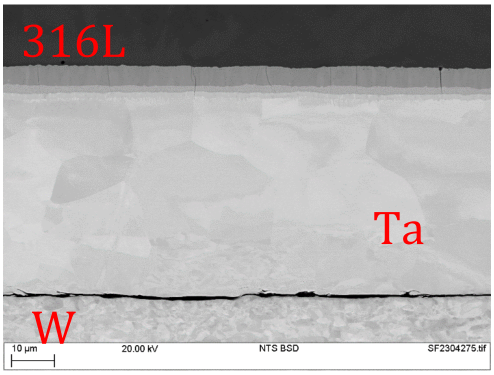

Figure 9 316L-Ta-W HIP-DB joint showing interaction layer 316L-Ta interface and delamination at W-Ta interface.

WC-Ta-WC had successfully bonded with diffusion layers present at the WC-Ta interfaces (Figure 10). However, 316L-Ta-WC bonding did not produce a successful joint. Here, the 316-Ta had fully bonded but the WC-Ta interface had delaminated.

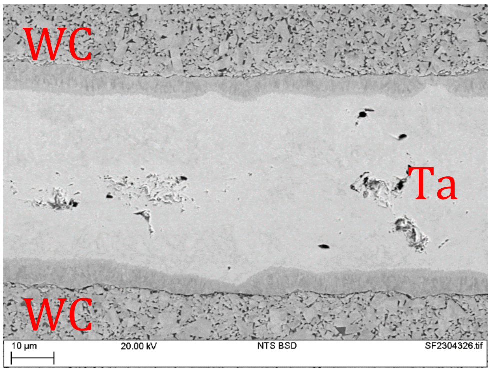

Figure 10 W-Ta-W HIP-DB joint displaying fully adhered joint with diffusion layers

3.3.3 Iron Interlayers

W-Fe-316L HIP-DB produced a successful joint with a thin reaction layer at the W-Fe interface (Figure 11).

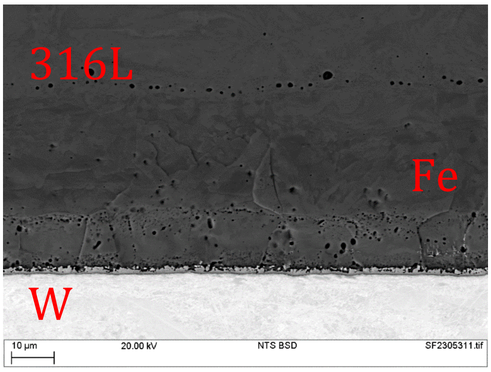

Figure 11 316L-Fe-W HIP-DB joint showing complete bond with intermetallic a W-Fe interface.

At both HIP-DB conditions, WC-Fe-WC bonding produced successful joints with no measurable defects.

WC-Fe-316L had bonded successfully. However, under higher temperature HIP-DB conditions, the Fe interlayer has experienced some grain growth and delaminated at the WC-Fe interface (Figure 12).

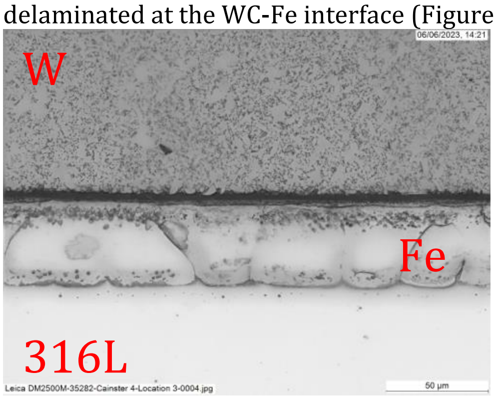

Figure 12 W-Fe-316L HIP-DB joint showing Fe grain growth at higher HIPing temperature

3.3.5 Summary

HIP-DB is a viable joining technique for the candidate materials. Fe interlayers perform best for W-316L and WC-316L joints due to high compatibility between Fe and 316L. WC-WC joints are best achieved with either Ta or Fe interlayers, and W-W joints with either V or Ta interlayers. Other factors such as activation, price and availability may affect the final interlayer choice.

Bonding can easily be prevented by use of a diffusion barrier between substrate materials, and this may assist in the HIP-DB manufacture of larger components.

4. Brazing Trials

4.1 Objectives

Brazing was explored as an alternative to diffusion bonding. Here compatibility of Nioro foil were assessed along with the effect of braze cycles on the substrate materials.

4.2 Method

Nioro (82Au-18Ni) foils of thickness 100um where placed between substrate materials. Each sample was vacuum brazed then gas quenched. Cross-sections were machined from the sample and underwent optical microscopy.

4.3 Results

W-W Joint brazed correctly with no presence of defects. Secondary phases were uniformly dispersed in the joint (Figure 13).

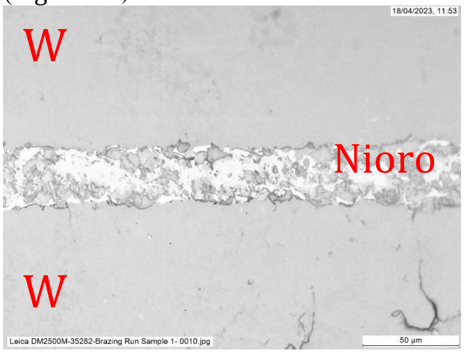

Figure 13 W-Nioro-W brazed joint showing full bond with secondary phases dispersed in joint

W-316L joint also had no presence of defects with good interaction between Nioro and 316L

For WC-WC joint, there was a greater interaction with the base material, with fine secondary phases observed in the joint.

There were no detectable defects observed in the WC-316L joint, though there were some defects in the base material (Figure 14). This may have been induced by the brazing cycle.

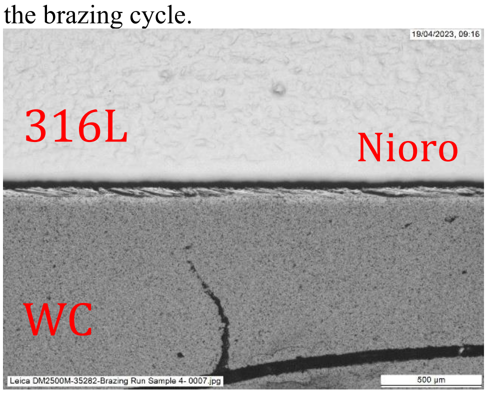

Figure 14 316L-Nioro-WC brazed joint displaying full adherence at interface and large crack in WC substrate

4.3.5 Summary

At this trial scale, brazing performed well for the candidate materials. Applying this manufacturing technique to a larger scale with more complex geometries may be problematic, as the braze melt pool may be affected by gravity and compromise the uniformity of the joint. It may also be more difficult to produce uniform heat conditions in larger component, which can also affect braze quality.

5. Planned Manufacturing Demonstration

The results of the joining trials will inform a manufacturing demonstration of key features in the

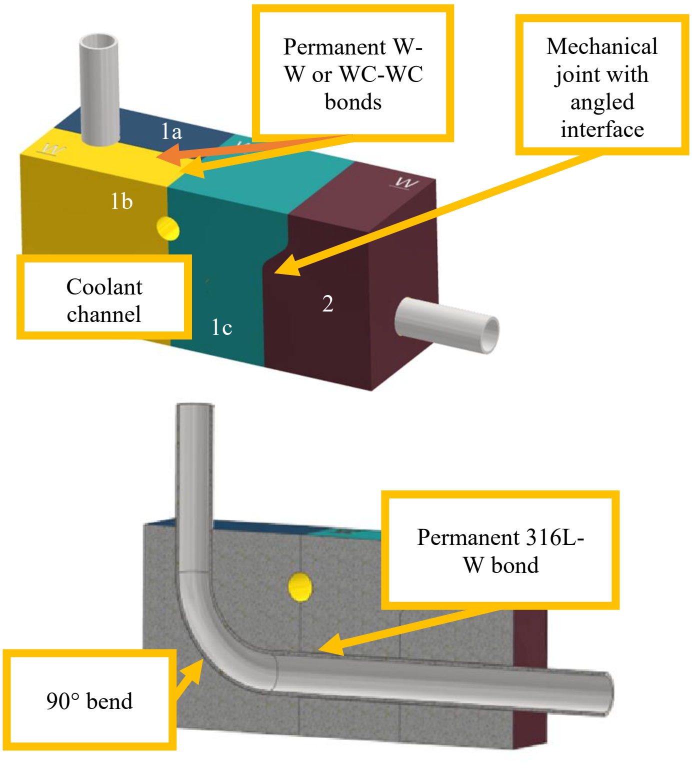

Figure 15 CAD images of W sheilding demonstrator

inboard shield design. Assessing the manufacturability of HIP-DB joining with the candidate materials at realistic dimensions is essential to understand their tolerances, along with scoping out a design-to- fabrication process that works best with these materials and manufacturing techniques. Due to the complex geometry of this demonstration, it is likely that a hybrid interlayer approach will be adopted to produce successful bonds throughout the demonstrators.

The demonstrator will be a modular assembly of pre-consolidated W or WC parts that are machined to specification. Submodules and the 316L pipe will be joined via HIP-DB. There will be a mechanical joint between to demonstrate assembly/disassembly. This will also have an angled interface for shine path avoidance. Non-destructive Evaluation (NDE) of the final demonstrators is required to assess joint quality and defects, however tungsten and tungsten carbide at such dimensions are not easily penetrable by typical NDE measures such as x-rays or ultrasound. Dedicated, high power NDE facilities may be required for adequate defect detection in large tungsten components [3].

6. Conclusions

HIP-DB with low-activation interlayers (Fe, Ta and V) is a viable manufacturing technique to utilize for larger scale tungsten/tungsten carbide manufacturing demonstrations. V interlayers cannot be used with carbon containing materials due to carbide formation. Higher processing temperatures for Ta bonding may not be suitable for steels. In general, there is a trade-off between joint quality and substrate mechanical properties when choosing bonding process parameters. Limits due to cost and availability may also affect the final choice of interlayer.

Brazing was successfully trialled at small scales, but may be unsuitable for large scale joining due to the effect of gravity on the melt and residual stresses in the final component.

As a result of the joining trials, it is likely that larger scale demonstrators will have a submodular design, and hybrid interlayer approach will be required to have embedded features such as pipes and channels. Non-Destructive Evaluation of internal features and bonds are difficult due to opaque nature of tungsten.

Acknowledgments

This work was funded by the STEP program of the UKAEA. Gratitude is extended to the project team for taking on this challenge. Thank you to Simon Kirk, Nicolas Correa Villanueva and Samuel Capp for their support and leadership during Sunchi Chen's first post as a technical lead. Thank you to Steph Jones and Oliver Fordham for their project management, and Alex Reeves for his design work. Thank you to Raja Khan and Alessandro Sergi for their expertise and perseverance in the manufacturing portion of this project. Thank you to Chris Thompson for his advice on WC manufacture.

References

[1] Windsor, C.G. *et al.* (2018) 'Design of cemented tungsten carbide and boride-containing shields for a fusion power plant,' *Nuclear Fusion*, 58(7), p. 076014.

[2] Robin, I. *et al.* (2023) 'Evaluation of Tungsten—Steel Solid-State Bonding: Options and the role of CALPHAD to screen diffusion bonding interlayers,' *Metals*, 13(8), p. 1438..

[3] Minniti, T. and Lewtas, H. (2022) 'Are tungsten-based nuclear fusion components truly invisible to x-ray inspection?,' *Nuclear Fusion*, 62(6), p. 066003.