ELASTIC-PLASTIC ANALYSIS OF THE TRANSITION JOINT FOR A HIGH PERFORMANCE DIVERTOR TARGET PLATE

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The use of tungsten as a plasma-facing material necessitates a transition joint to the structural material of the primary coolant loop at some location in order to transport the coolant to the heat exchanger. A critical issue in transition joints is the thermal expansion mismatch between materials, which can lead to unacceptably high thermal stresses. Detailed 2D and 3D analyses were performed to study the behavior of a transition from tungsten to ferritic steel (FS) with an intermediate layer of tantalum, located outside of the high heat flux region. This paper describes the results of FEM analyses including primary and secondary stresses under various time-dependent loading conditions such as warm and cold shutdown, and allowing for inelastic behaviors leading to stress relaxation and ratcheting. The results show that the transition joint satisfies the design requirement on maximum accumulated principal strain during operation.

I. INTRODUCTION

In the divertor transition joint, the mismatch in coefficient of thermal expansion (CTE) between W and FS can lead to failure. The addition of an intermediate material such as tantalum with a CTE between that of W and FS helps alleviate the mismatch, but strains could still exceed individual material limits.[1,2] In our analysis, the maximum plastic strain accumulated over the operating life was used as the design criterion. No part of the joint should exceed 50% of the uniform elongation (ε_u) at any time during normal or off-normal operation.

The design of the joint uses conventional fabrication techniques. Strong metallurgical bonds, such as explosion welding, diffusion welding or brazing, have been used to create a robust structure. These bonds transfer thermo-mechanical loads across the material interfaces.[3] The geometry is dictated to a large extent by bonding limitations in the three materials, each of which is subject to different constraints.

FEM results show that thermal stresses dominate, especially at the cold shutdown temperature of 20˚C. The impact of thermal stress is largest when the coolant pressure is *not* applied, especially on the sharp tip of the Ta ring. In addition, cyclic thermal loading, especially with cold shutdown may cause ratcheting with plastic strains exceeding design limits. Care must be taken in the design and the choice of materials to reduce the maximum principle plastic strain.

Since the analyses were all in the plastic regime, maximum principal plastic strain was used as the primary metric for the evaluations. Design variations and material options were explored to determine the best choices. For example, picking a suitable alloy of tantalum was a challenging task; it should provide high yield strength, high uniform elongation and low radioactivity. Different geometries were explored, such as decreasing the number of sharp corners causing stress concentration. Inappropriate geometry may cause ratcheting. For any design variation, a credible fabrication technique must be available. Time-dependent loadings were analyzed including fabrication steps, cold and warm shutdown operating cycles. Finally, the transition joint was modeled in Pro/Engineer and imported into ANSYS to perform 3D analyses as a validation of the 2D results and conclusions.

II. THE STRUCTURE OF THE DIVERTOR TRANSITION JOINT

The divertor consists of oxide dispersion strengthened (ODS) steel, tantalum, and tungsten with tantalum serving as a compliant layer between ODS and tungsten.[3] Figure 1 illustrates the divertor plate with its bonds and materials.

II.A. Material Properties

For thermo-mechanical elastic-plastic analysis, several material properties including coefficient of thermal expansion (CTE), yield strength, and tangent modulus were used.[4] In the first analyses, pure Ta was used. However, it exhibited the highest plastic strain and ratcheting under cyclic loading. In an effort to mitigate ratcheting, other alloys of Ta were explored.

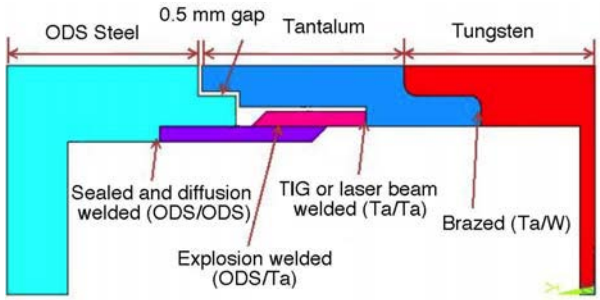

Figure 1. 2-D divertor joint showing materials, geometry, and bonding process.

T-111 was considered as a good alternative material because it has higher yield strength and uniform elongation that could reduce the maximum plastic strain or eliminate ratcheting. T-111 is composed of Ta-8W-2Hf. Due to the activation of Hf we chose to avoid its use. Ta2.5W was chosen because it has nearly the same yield strength and uniform elongation, reduced maximum plastic strain, and no special issues with radioactivity since it is composed of just 97.5% Ta and 2.5% W. For the analyses, pure Ta was used and just one case was run with Ta2.5W for observation.

TABLE I ODS Steel Properties

	Property	20 °C	800 °C
ODS Steel	Yield Stress σ_y	1300 MPa	323 MPa
	Tangent Modulus	463 MPa	8.22 GPa
	Coef. of Thermal Expansion	12.68 ppm/°C	12.68 ppm/°C

TABLE II Tantalum Properties

	Property	20 °C	800 °C
Tantalum	Yield Stress σ_y	500 MPa	180 MPa
	Tangent Modulus	525.4 MPa	525.4 MPa
	Coef. of Thermal Expansion	6.3 ppm/°C	6.3 ppm/°C

TABLE III Tungsten Properties

	Property	20 °C	800 °C
Tungsten	Yield Stress σ_y	3.50 GPa	860 MPa
	Tangent Modulus	1.53 GPa	2.20 GPa
	Coef. of Thermal Expansion	4.5 ppm/°C	4.5 ppm/°C

II.B. Fabrication Process

Fabrication is performed in three steps: [3]
Subassembly 1: ODS manifold, ODS ring and Ta ring. Explosion welding is used between the Ta and ODS rings. Diffusion welding is used between the ODS manifold and ring.
Subassembly 2: Ta manifold and W manifold. Brazing is used between the large Ta ring and W.
Subassembly joining:
TIG or laser welding is used between subassembly 1 and 2.

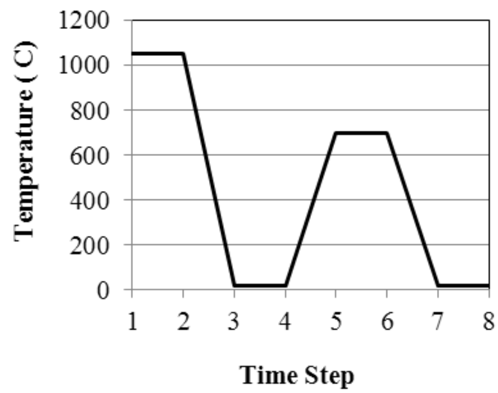

Figure 2. Loading cycle for subassembly 1.

Separate thermal analyses were performed on subassemblies 1 and 2. For subassembly 1, Ta and ODS rings are first bonded using explosion welding and then the ODS ring and manifold are bonded using diffusion welding. Diffusion welding starts at 1050 °C (load step 1) as the stress-free temperature for one load step and is cooled down to 20 °C. In load step 4, it is ramped up to 700 °C again for tempering the steel weld, and in load step 6 it ramps down to 20 °C until load step 8 (see Figure 2). Each of the mentioned load steps can cause plastic strains except load steps 1 and 2 where the temperature is identical to the stress free temperature. Figure 3 illustrates the principal strains. The ODS steel has zero plastic strain while the Ta ring experiences plasticity in a very small region at its tip. The Ta sees zero plastic strain during the first two load steps since the temperature is the same as the stress free temperature.

In subassembly 2, both tantalum and tungsten manifolds had zero plastic strain since the impact of thermal stress on them is small, especially on tungsten.

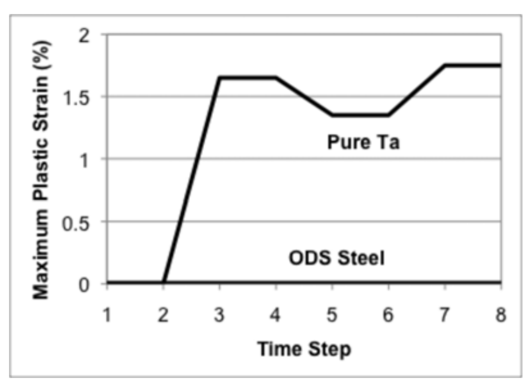

Figure 3. Plastic strain in subassembly 1.

III. 2-D THERMO-MECHANICAL ANALYSIS

III.A. Configuration of the model in ANSYS

The geometry of a model can be either created in ANSYS or imported. For our 2D analysis, the geometry (Figure 1) was created in ANSYS. As another effort to reduce plastic strain in the joint, several 2D models with different ODS steel and W rib thicknesses in the manifold regions were created to observe and compare the results. Figure 4 illustrates the 3D model with ODS and W ribs.

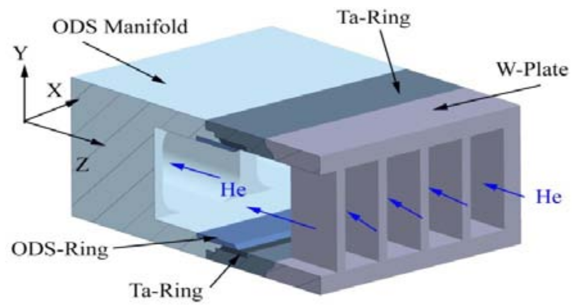

Figure 4. 3-D divertor model with 2-D cross section and He as a coolant

In this work, the ODS steel rib thickness is 8 mm and the W rib thickness is 2 mm. The material properties were applied with 1050˚C stress-free temperature for CTE. Based on the constraints applied to the model the appropriate element type should be chosen to obtain correct results. Plane Strain, Axisymmetric, and Generalized Plane Strain were tried. Finally, Generalized Plane Strain was chosen since it simulated best the real boundary conditions in terms of physical constraints such as U_x and U_y, temperature, and coolant pressure (Figure 5). The base element edge length for the mesh is 0.2 mm, which produces precise results.

To check the validity of the program, 10 MPa coolant pressure was applied inside the model with 20 ºC or 700 ºC body temperatures. 20 ºC is the worst case due to its large difference with the stress-free temperature (1050 ºC). Figure 5 illustrates the loading conditions. The results are not shown here, but they were well-behaved and validated the element choice and boundary conditions.

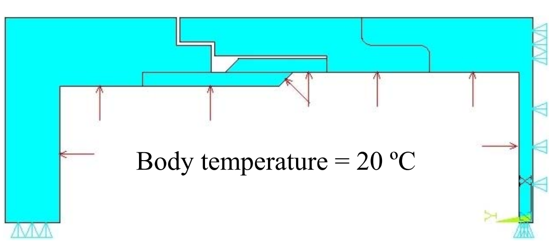

Figure 5. Divertor plate configuration with constraints (U_y=0 at right, and U_x=0 at the bottom), pressure (inner arrows), and body temperature.

III.B. Cyclic Loading Configuration

Warm shutdown and cold shutdown operating cycles were analyzed. Each of them was run for 100 cycles, although 100 cycles is extremely conservative for cold shutdown. In the lifetime of the divertor it might be shutdown only a few times but it was run to observe ratcheting in the process of cold shutdown. In the cyclic loadings, the operation started from 20 ºC and ramped up to 700 ºC as the operating temperature. In the step of ramping up to 700 ºC, the coolant pressure was applied as well. In the cold shutdown, the coolant pressure was turned off when it reached to 20 ºC. Figure 6 illustrates the warm and cold shutdown loading conditions.

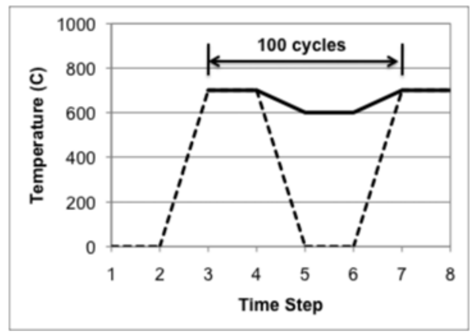

Figure 6. Thermal loading cycles for Warm shutdown (top) and Cold shutdown (bottom)

IV. RESULTS OF 2D ANALYSES

IV.A. Check Points (Non-cyclic Loading)

Usually, the maximum plastic strain was observed to occur on the tip of the Ta ring. Almost always tungsten exhibited no plastic strain. Due to its shape and physical properties, Ta mostly had the highest plastic strain both in non-cyclic loading, and as indicated in the next section, in cyclic loading as well. The maximum plastic strain is on the tip of Ta ring. The Ta ring seats on the ODS ring and the tip is seated almost in the middle of ODS ring. Its 45º geometry and the local thermal stress can be considered the main reasons for high local plastic strain there. Also, ODS steel exhibited plastic strain but in a lower range. Depending on the thickness of the ODS steel rib, the maximum plastic strain could be shifted from the corner of the ODS steel rib and manifold to the lower tip of the ODS steel ring. In the 2D analyses, the ODS steel rib was 8 mm thick as illustrated in Figure 1. Although the divertor will undergo cyclic loading, non-cyclic loading helped to find the locations with the highest strain so the geometry could be modified if needed. Figure 7 illustrates the maximum plastic strain results at 20 ˚C for ODS and Ta using generalized plane strain.

IV.B. Cyclic Loading

The significance of cyclic loading is its temperature variation. For instance, when the temperature in the divertor plate is changed from 20°C to 700°C, the system encounters thermal strain due to the different materials' CTEs and that is probably the main reason for ratcheting in the Ta ring.

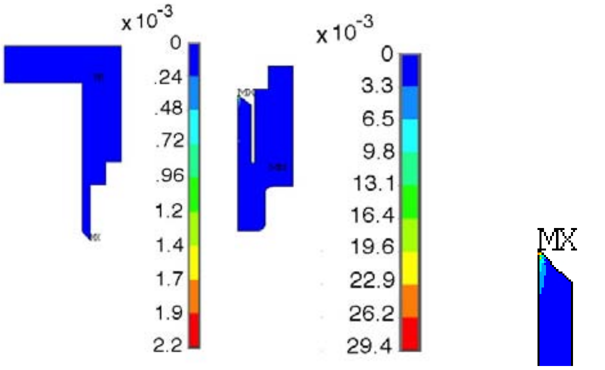

Figure 7. Maximum plastic strain in the ODS steel (left) and Ta (right) after the first warm shutdown

Based on the loading profile in Figure 6 (cold and warm shutdown), the results of the transition joints are illustrated in Figures 8 and 9. Pure Ta was used for this analysis.

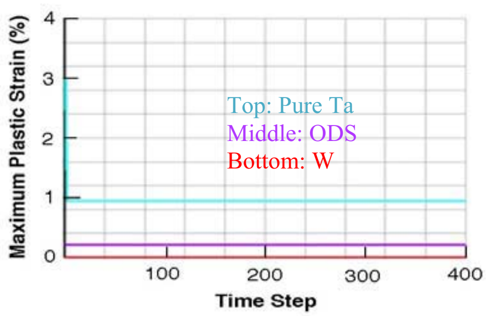

Figure 8. Results of plastic strain for 100 cycles during warm shutdown

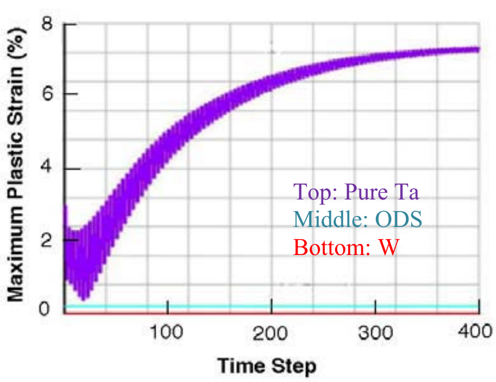

Figure 9. Results of plastic strain for 100 cycles during cold shutdown.

As mentioned above, we attempted to reduce or eliminate the amount of ratcheting caused by Ta in a cold shutdown operating cycle. Cold shutdown cycles were analyzed using Ta2.5%W properties under similar conditions as before. Although it did not eliminate ratcheting completely, it reduced the magnitude almost by half compared with pure Ta. Figure 10 illustrates the results with Ta2.5%W.

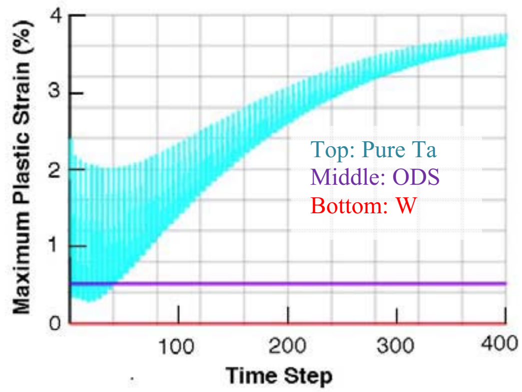

Figure 10. Results of plastic strain with Ta2.5%W for 100 cycles during cold shutdown

V. THREE DIMENSIONAL THERMOMECHANICAL ANALYSIS (NON-CYLIC LOADING)

3-D analysis can be considered a confirmation of 2-D analysis. In 3-D analysis SOLID 45 was used as the element type with the same material properties as 2-D.[4] The parts were modeled in Pro/Engineer and imported in ANSYS. Figure 11 illustrates a quarter of the 3D configuration with 3 materials and the mesh shown. To run 3-D analysis, only a checkpoint was used with almost the same boundary conditions: 10 MPa pressure and T= 20 ºC with 1050 ºC stress free temperature.

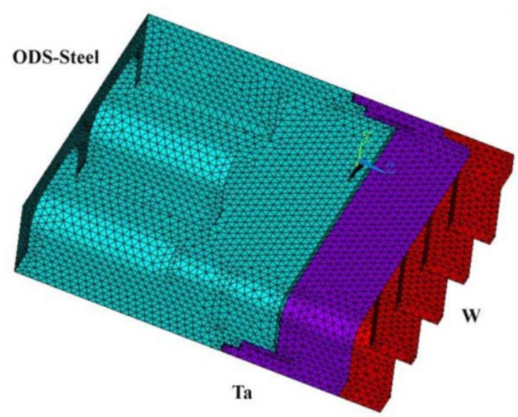

Figure 11. 3D configuration showing 3 materials and the mesh

Figures 12 and 13 illustrate the 3-D results for the whole configuration and the ODS part respectively. It can be seen that the maximum strain in Ta reaches a value of 2.7 %, and about 1.46 % in the ODS steel.

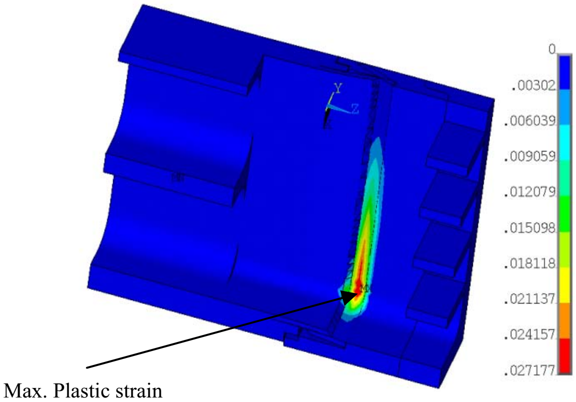

Figure 12. Maximum plastic strain in the full 3-D model

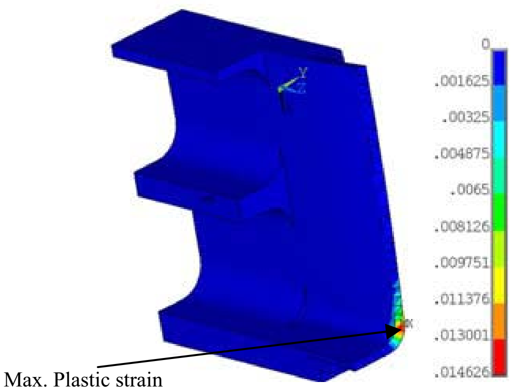

Figure 13.Maximum plastic strain highlighting the ODS steel

Three dimensional analysis will be continued using a more powerful computer to refine the mesh of FEM model especially at the corners and then they can be compared with 2-D results better.

VI. SUMMARY AND CONCLUSIONS

The main challenge in the divertor transition joint arises due to differences in CTE, which cause thermal stress and strain that potentially could lead to failure. In our analyses, materials were studied and their behavior was observed using ANSYS. To fully explore this design concept, 2D steady, 2D cyclic and 3D analyses were performed. This study was performed to understand the validity of the design and to optimize it.

Alloys of tantalum were used in some of our analyses to reduce the maximum plastic strain. For future design and analyses, Ta2.5%W is recommended as a better material than pure Ta due to its superior uniform elongation and yield strength.

Further investigation is needed to better understand the differences between 2-D and 3-D analysis. In addition, effects such as thermal and radiation creep need to be included in future analysis. The scarcity of data on creep makes this difficult.

Since our analysis pushes the limits of component behavior beyond ASME elastic limits, testing will be an important part of concept validation. This testing should include individual materials properties measurements as well as component and subcomponent fabrication and testing under prototypical conditions.

ACKNOWLEDGEMENTS

The authors would like to thank Steve Zinkle (Oak Ridge National Laboratory) for advice on material properties. This work was performed under DOE contract number DE-FG02-04ER54757.

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