INNOVATIVE FIRST WALL CONCEPT PROVIDING ADDITIONAL ARMOR AT HIGH HEAT FLUX REGIONS

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In this paper, the innovative FW armor design concept is presented. The "Design by Analysis" rather than "Design by Code" method as allowed by ASME for such high temperature components is used in this study. Incremental cyclic elasto-plastic analysis of considering the FW fabrication steps as well as for normal and transient operating modes is performed, accounting for stress relaxation by plastic deformations during a large number of temperature cycles. The resulting maximum strains are summarized.

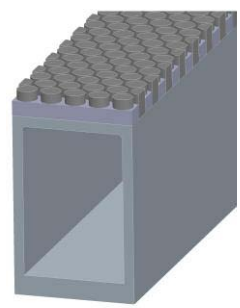
I. INTRODUCTION

The first wall in a fusion power plant is usually designed to accommodate a steady-state heat flux up to 1.0 MW/m^2, meeting the design criteria, including: (1) material temperature limits for avoiding embrittlement and thermal creep strength, (2) primary stress intensity limit in the elastic regime (S_m limit of the ASME code), and the sum of the primary and secondary stresses under 3 S_m,[1] (3) coolant pumping power influencing the cost of electricity. In our ARIES-CS[2] and ARIES-ST[3] power plant studies, the temperatures and stresses are very close to the limits for the selected reduced-activation ferritic steel (RAFS) as structural material and He as coolant with operating pressure of 8 MPa and a surface heat flux of 0.76 MW/m^2. However, there are indications that transient peak heat fluxes up to ~ 2 MW/m^2 for time periods up to a few seconds can occur at certain regions of the FW, accompanied by substantially higher erosion in such regions. In order to avoid intolerable damage during such transients, it is necessary to find a kind of the FW armor that can survive in such regions. It is mandatory that such transients do not require the FW exchange because this could lower the availability of the power plant to intolerable values.

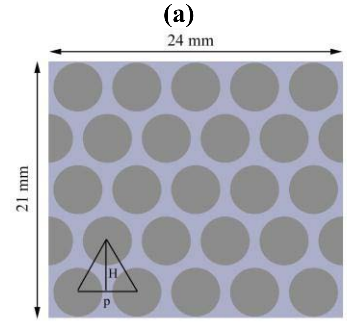
This paper presents the innovative FW armor design concept similar to the micro-brush concept developed for ITER divertor target. It is a combination of the pure W or W-alloy (such as WL10) and 12YWT ODS-steel for an assumed transient heat flux of 2 MW/m^2 over a 5 second period of time.

II. DESIGN DESCRIPTIONS

Design goals of this FW armor are to accommodate the heat flux of 1.0 MW/m^2 during the normal operation and up to 2 MW/m^2 during the fast transient event.



(a)



(b)

Fig. 1. First wall armor concept: (a) FW armor and cooling channel; (b) Layout of the W-pins

As illustrated in the Fig. 1, the FW armor is composed of brush-like W-pins embedded in a thin plate of the 12YWT on the top of the FW duct made of the RAFS (F82H), and brazed together in a furnace. The armor will be arranged at the anticipated locations where the FW may be subject to the large transient heat flux. With the FW armor concept, the effective thermal conductivity of the first layer plate (the 12YWT + the W-pins) is decisively increased by the high conductivity of W, reducing the temperature gradient and the thermal stresses. However, the thermal expansion mismatch between the W-pins and the ferritic steels leads to high thermal stresses during the cool-down phase from the brazing temperature (~1050 ºC) to ambient temperature exceeding the yield strength, and possibly during the thermal-cycling operation. The key issue for the feasibility of the concept is, if the plastic deformations will come to an end after a few cycles with allowable strains, or if ratcheting will occur. Other issues to be considered for the first wall design include: (1) increase of the FW temperature, (2) increase of the FW thermal stresses and the stresses exceeding elastic regime, and (3) decrease of the tritium breeding rate by the additional W material. All the issues will be addressed and evaluated by the engineering design.

III. FIRST WALL FABRICATION METHOD

In most power plant studies, the RAFS (F82H) is used as a structural material for breeding blankets and the integrated FW. A key issue of this class of ferritic/martensitic steels is the required heat treatment especially after welding. In general, there are four steps to be performed: (a) heating up the steel to the temperature of ~1000 ºC to get an austenitic structure, (b) cooling the steel down to the ambient temperature, (c) tempering the steel by heating it up to ~700 to 750 ºC, (d) cooling it down again to the ambient temperature. In ARIES designs, we had suggested to combine this heat treatment with the plating of the FW with a layer of the 12YWT. Experiments have shown that such a plating is possible by diffusion welding in a HIP (Hot Isostatic Pressing) facility at the temperature of ~1000 ºC. Similar to this fabrication route, we suggest now to make the connection between the 2 mm thick FW and the 3 mm thick layer of the 12YWT with embedded W-pins in the furnace, but using a high temperature brazing material with melting point of ~1050 ºC for this attachment. Candidate brazing materials for the connections between the W-pins, the 12YWT plate and the FS FW are CuPd18 (melting point at ~1080-1090 ºC), and Cu86MnNi (Cu86, Mn 12, Ni 2; melting point at ~970-990 ºC). The first of these brazings is suggested by PLANSEE and used by FZK for their divertor concept, connecting the W-thimble to the 12YWT ring. The second brazing is used extensively in the fabrication of cutting tools for the attachment of the cutting edges made of WC, TiC or TiN to the steel body.

In general, the first wall fabrication method includes following processes:

(1) fabricate the first wall cooling panel by HIPing together the rectangular cooling ducts made of RAFS;
(2) lay the 12YWT sieve plate, the W-pins, and the brazing foils, rings or pastes on the top of the first wall cooling panel;
(3) put the entire first wall assembly into the furnace and heat it up slowly to the brazing temperature (1000~1100 ºC). At this high temperature and long time period, any fabrication residual stresses will be released;
(4) cool the assembly down to the room temperature. Some local plastic deformation by exceeding the yield strength will occur during this transient;
(5) heat the assembly up to the tempering temperature (~750 ºC) and hold the temperature for ~ 1 hour. Most of the residual stresses in the RAFS cooling panel will be released by exceeding the yield strength and by thermal creep, but the temperature is too low for creep relaxation in the 12YWT sieve plate and W-pins;
(6) cool the first wall assembly down to the room temperature, some plastic deformation by exceeding the yield strength may occur, especially in the RAFS cooling panel.

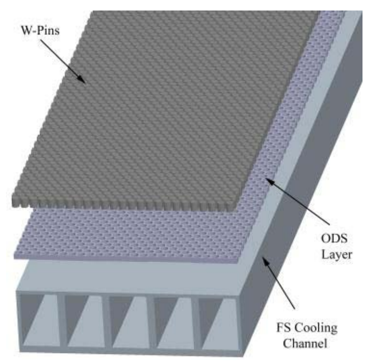


Fig. 2. Illustration of the FW fabrication

All the processes of fabrication and heat treatment will be completed in the furnace. The Fig. 2 shows the first wall assembly brazed together at temperature of 1000~1100 ºC.

IV. DESIGN METHODS FOR HIGH TEMPERATURE COMPONENTS

There are three design methods for the high temperature components as allowed by the ASME code. "Design by Code" is the simplest method which is always the first step of the analysis to limit the primary stress intensity to the elastic behavior of the structural material (< S_m) and the combined primary and secondary stresses remain below the 3 S_m.[1] If the calculated sum of primary and secondary stresses remains <3 S_m, the design is fine. However, there are provisions in the ASME codes allowing more sophisticated designs of highly loaded high temperature components in case the 3 S_m limit is exceeded. In such cases, the analysis has to show that the strain does not continuously increase with the number of temperature cycles ("ratcheting") but reaches its final value after a few cycles ("shakedown"). This design method for the high temperature components is called as the "Design by Analysis".[1] "Design by Experiments" is the third method allowed by the ASME code. It is possible to design by experiments, requiring an extensive test program to prove that the component will survive all anticipated transients.

With our suggested FW armor concept, the "design by analysis" is utilized and sophisticated analyses will be performed to consider non-linear material behaviors, such as the plastic deformation and the thermal creep to allow materials to be pushed beyond the 3 S_m. A limited number of the transient loading conditions will be investigated:

(1) The plastic strains during the fabrication steps. There are three elements to be brazed together, i.e., the 2 mm ferrtic plate of the FW box, the 3 mm 12YWT plate with multiple holes (sieve plate) and the W-pins with a diameter of 4 mm to be inserted as a pin-array into the 12YWT sieve plate. All these elements are brazed together in a one-step furnace operation at the temperature of ~1050 ºC. This is the same temperature as required for austenicing the ferritic steel. All the material will be stress-free annealed at this temperature. The assembly is cooled down slowly to the room temperature. The different thermal expansion coefficient of the W and the steel leads to tensile stresses in the steel and compression stresses in the W-pins. The yield strength of the steel will be exceeded during this transient, resulting in the plastic strain of the steel. As standard post weld heat treatment required for this class of the steel, the assembly is heated up to ~750 ºC for about 1 hour. This leads again to a relaxation of the stresses in the different elements by the plastic deformation. Therefore it can be assumed that the assembly is at the "stress free" condition at this temperature. There may also be some plastic deformations if the assembly is cooled down after this tempering, which will be the starting condition for the FW operation.

(2) The plastic strains during the operation of the plant. During the start-up of the plant, the FW is heated up slowly to the coolant temperature of 384 ºC. With this uniform temperature field, all elements may remain in the elastic conditions. However, if the surface heat flux rises to its normal operation value, the temperature gradient in the FW assembly may result in some plastic strains. Cooling the assembly down during off-power situation, the FW stresses will reverse, causing perhaps the plastic strains in opposite direction. In such cases, the analysis has to show that the strain does not continuously increase with the number of the temperature cycles ("ratcheting") but reaches its final value after a few cycles ("shake down"). The crucial issue is if all materials will remain in the elastic region after a few cycles.

(3) The plastic strain during anticipated fast transients. Such transients can raise the heat flux up to 2 MW/m^2 at some anticipated regions of the FW surface, more than twice the normal operational value in milli-seconds. This means that the cooling at these locations has to be adequate for the high heat load all the time. Assuming that those regions to not cover more than about 20% of the entire FW surface, and that those regions are continuous in toroidal direction, it is possible to design the coolant channels in such regions for much higher helium velocities than in the major part of the FW, resulting in a local heat transfer coefficient up to twice as large than in the normal region with a tolerable increase of the entire pressure drop. This means that the temperature and the strains in such regions can be maintained at lower values during the normal operation than in the normal FW, and there is hope that the design survives the fast transients without damages. This, however, has to be verified by detailed analyses.

V. THERMO-MECHANIC ANALYSES

The incremental cyclic elastic-plastic analysis for considering the FW fabrication steps as well as for the normal and transient operating modes are performed, accounting for the plastic deformations during a large number of temperature cycles. The finite element code, ANSYS, was employed.

V. A. Elastic Structural Model

The goal for the fast transients is to maintain the RAFS (F82H) below 550 ºC and the 12YWT below 700 ºC during the steady-state operation. A value of HTC (heat transfer coefficient) for the normal operation (q''=1 MW/m^2) scaled from the ARIES-CS first wall design needs to be doubled for cooling the first wall during the transients with the heat flux up to 2 MW/m^2. Parameters, loads and cooling conditions for the FW were assumed to be the same as the ARIES-CS first wall and blanket, and a neutron volumetric heating generation of 44 MW/m^3 was assumed in the calculations. The helium inlet and outlet temperature for the FW were assumed to be 385 ºC and 430 ºC, and it was heated up to 460 ºC at the exit of the blanket. The coolant operation pressure is 8 MPa. The temperature-dependent material properties were used in the ANSYS model. Thermal results indicate that the temperature of the FW armor can meet the material temperature limits (<550 ºC for the RAFS, and <700 ºC for the 12YWT). The elastic structural analysis confirms that the primary stress intensity of the FW armor assembly stays in the elastic regime and the combined primary and secondary stresses remains below 3 S_m during the normal operation with the heat flux of 1 MW/m^2. However, both the W-Pins and the RAFS cooling ducts exceed the ASME code (3 S_m) limit for the fast transients.

V. B. Elasto-Plastic Structural Analyses

Sophisticated non-linear analyses need to be preformed to investigate the behaviors of the FW armor in order to further optimize the design and prove its viability, such as to calculate the plastic strains for different scenarios: (1) during the FW fabrication steps and the heat treatment; (2) during the normal operation (q''=1 MW/m^2) and the anticipated fast transients (2 MW/m^2); (3) during the operation with the cold shutdown. The key issue for the feasibility of the FW armor concept is if the plastic deformations will be within allowable strain limits after a few cycles in spite of a large mismatch of the thermal expansion coefficient between the W-Pins and the 12YWT plate or the RAFS cooling duct causing high thermal stresses under thermal cycles. A 2D ANSYS plane strain model and the element PLANE182 were utilized in the analyses. ANSYS Bilinear Isotropic Hardening Material Model[3] was used to account for the material responses. The temperature-dependent properties for the pure W, 12YWT and F82H were used. [4,5,6] SFT (stress-free temperature) was assumed to be the brazing temperature of 1050 ºC, and it is a conservative assumption because it maximizes the temperature differences between the SFT and the room temperature as well as the differences between the SFT and the FW operation temperature.

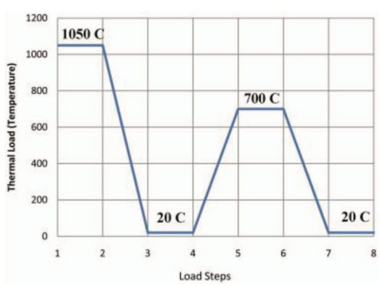


Fig. 3. Loading profile for the fabrication and heat treatment

Fig. 3 illustrates the thermal loading profile for the FW fabrication steps:

1. Starting from brazing temperature, T=1050 ºC
2. Holding at the temperature of 1050 ºC for 30 minutes
3. Cooling the FW assembly uniformly down to the room temperature for 30 minutes
4. Holding the room temperature for 30 minutes
5. Heating the FW assembly uniformly up to the tempering temperature (~750 ºC) for 30 minutes
6. Holding the tempering temperature for 30 minutes
7. Cooling the FW assembly uniformly down to the room temperature for minutes

The thermal cyclic loading steps during the normal operation with warm shutdown after the fabrication are described as the followings:

1. The room temperature is applied at t=0
2. The FW assembly is heated up slowly and uniformly to the coolant temperature of ~385 ºC for 1 hour
3. The temperature is held at 385 ºC for 1 hour
4. The plasma power is on, and the power is raised to operational value (q''=~1 MW/m^2) in the order of seconds (Δt=50 s assumed)
5. The heat flux is held at 1 MW/m^2 for 1 hour
6. The fast transient occurs and the heat flux rises to ~2.0 MW/m^2 in the order of seconds (Δt=1.0 s assumed)
7. The transient is held as 2.0 MW/m^2 for ~5 s
8. The plasma power goes back to the normal operation (q''=~1.0 MW/m^2) in the order of seconds(Δt=1.0 s assumed)
9. The heat flux is held at 1.0 MW/m^2 for 1.0 hour
10. The plasma power is off in ~50 seconds (q''=0)
11. The FW assembly is operated at the coolant temperature of ~385 ºC in 1.0 hour

The helium pressure load of 8 MPa will be applied at the load step 2. The additional thermal cycles are applied by repeating the load steps 3-11. The cold shutdown for the power plant is necessary for replacement of the power core components, and all the components will be cooled down to the room temperature. The thermal loading cycles for the cold shutdown are almost the same as the normal operation, except that at the loading step 11, the FW assembly will be cooled down to the room temperature within 1 hour during the cold shutdown. The pressure load of 8 MPa is applied at the step 2 and removed at the step 11. Additional loading cycles are applied by repeating the loading step1 to 11.

Ratcheting is an important mode for the high temperature components under thermal cyclic loading, and should be avoided in the design. Another design criterion is the maximum principle plastic strains accumulated over the operating life should be less than 50% of the uniform elongation.[7]

V. C. Results

The maximum plastic strains are reached when the FW assembly was cooled down to the room temperature after brazed together at the temperature of 1050 ºC. There were no additional plastic strains for all following fabrication steps. The maximum plastic strains in the F82H plate and the 12YWT plate are ~0.65% and ~0.5%, respectively, and they are below the allowable plastic strains (ε_{allow}=2.4% for the F82H and 2.3% for the 12YWT at the RT). There is no plastic deformation in the

W-pins. Fully transient thermal analysis was performed based on the assumed operation loading cycles, and the temperature distributions were mapped to the structural model for calculating the plastic deformation. The heat transfer coefficient was scaled from the ARIES-CS FW design (q"=0.76 MW/m^2). The maximum temperature of the 12YWT plate is 648 ºC during the fast transient with the heat flux up to 2 MW/m^2 in the order of seconds, below the temperature limit of 700 ºC. The maximum temperature of the RAFS coolant duct is ~607 ºC during the fast transient, exceeding the temperature limit of 550 ºC. However, the temperature limit of 550 ºC was set to limit thermal creep for the RAFS, and the thermal creep is not a concern issue for the fast transient events because the fast transients happen in the order of seconds. The temperature of the W-pins is much lower than 800 ºC limit and the assumed embrittlement limit of W. However, the embrittlemet of the W-pins is not a concern because there is no plastic deformation at the very beginning of the lifetime.

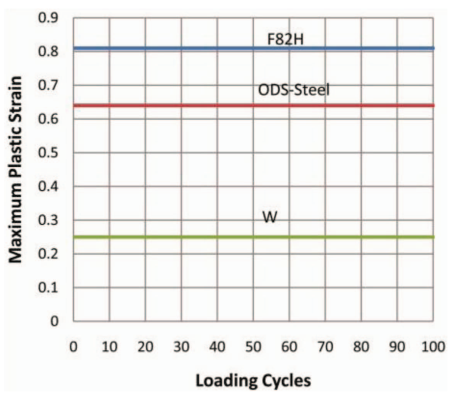


Fig. 4. Plastic strain for the operations with the cold and warm shutdown (for 2 mm case)

There is no ratcheting observed after 100 operating cycles for the power plant with the warm shutdown. For the thermal cycling with the cold shutdown, however, the FW assembly would ratchet if the thickness of the RAFS front plate is 1 mm. The ratcheting would be eliminated when the primary stresses are reduced by increasing the thickness of the RAFS front plate from 1 mm to 2 mm and the plastic strains are identical for the operations with the warm shutdowns, as illustrated in the Fig. 4. The plastic strains reach saturation at the first load step (at the RT). The maximum plastic strains of the RAFS duct and the 12YWT plate are ~0.8% and 0.63%, respectively, and they are less than the allowable strain limits at the corresponding temperature after 100 cycles.

VI. CONCLUSION

In this paper, the innovative FW armor design concept is presented. The "Design by Analysis" method is utilized in this study to push the higher surface heat flux. The elasto-plastic nonlinear analyses for the fabrication steps as well as for the normal and the transient operating modes are performed, accounting for the plastic deformations during a large number of temperature cycles. The results indicate that the FW assembly meets the plastic design criteria and the material temperature limit during the fabrication and the fast transients with the surface heat flux up to 2 MW/m^2. Full time-dependent thermal creep analysis of the FW assembly is not yet included in the present analyses. However, the thermal creep, irradiation induced creep, fatigue and fracture failure are very important to the high temperature components, and the analyses are underway at UC-San Diego and UW-Madison.

A rough estimation of TBR (tritium breeding ratio) indicates that the TBR for adding the FW armor covered ~20% of the total FW area will only be reduced by ~0.1%.

ACKNOWLEDGMENTS

The work at UCSD was supported under U.S. Department of Energy Grant number DE-FG02-04ER54757.

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