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STUDY OF WELD RESIDUAL STRESS FIELD IN THE GIRTH SEAM H6A OF CORE SHROUD OF BOILING WATER REACTOR

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ABSTRACT

Many accidents have occurred in nuclear power plants due to the intergranular stress corrosion cracking (IGSCC) in the heat affected zone (HAZ) of welded joint of the core shroud of boiling water reactors (BWRs) in past years. The IGSCC is considered to be caused by the synergistic roles of corrosion environment, neutron irradiation and the welding residual stress. After several decades, the degradation of Type 316L low carbon stainless steel used in the core shroud occurs due to the neutron irradiation and thermal cycles. The degradation can be referred to the irradiation hardening, segregation of the local chemical composition at grain boundaries and swelling. The synergistic effects of those eventually lead to the initiation and propagation of the irradiation-assisted stress corrosion cracking (IASCC) in core shroud for long operation.

The HAZ of the girth seams H6a in the core shroud are sensitive to the stress corrosion cracking. We are focusing on the weld residual stress field around the girth seam H6a in the core shroud as weld. The analysis work adopted different approaches in ABAQUS to simulate the weld residual stress, and they are Static General Analysis (SGA) and Fully Coupled Temperature-Displacement Analysis (FCTDA) respectively. The former is much simple to finish the progress while cannot obtain much accurate results at the boundaries of beads due to the discontinuous temperature field in the model. The later analysis gave the much accurate results comparing with the experimental results. The axial stress field in the crossing section of the wall of the core shroud was also clarified.

1 INTRODUCTION

Stress corrosion cracking (SCC) is normally found in the core shroud of the boiling water reactor of a nuclear power plant after it has serviced several decades. During the operation, the core shroud has to bear the neutron irradiation from the nuclear reactor located in its center. Radiation of neutron gives rise to the hardening, segregation, which are dependent of the dose of neutron irradiation. The depletion of Chrome at the grain boundaries make the decreasing of the corrosion resistance of the material (normally Type 316L low carbon used) of the core shroud. The fuel fission in the nuclear reactor also leads to the production of heat. The temperatures in the core shroud are different according to the different distances from the center of the nuclear reactor. Moreover, the temperatures of outer surface are lower than the inner surface in the same location. As shown in Figure 1 the core shroud is composed of about 9 horizontal girth seams, which make the weld residual stress be produced inevitably in its weldment. Therefore, the synergistic effects of neutron irradiation, corrosion and weld residual stress eventually lead to the initiation and propagation SCC in core shroud for long operation.

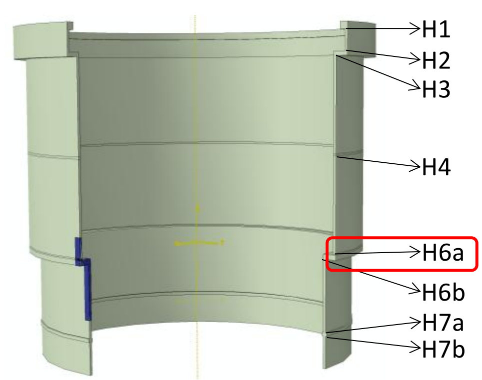


Figure 1. Girth seams arranged in the core shroud and the simulation model.

The lower part is much sensitive to the stress because the force of inertia of the core shroud has to be considered when an earthquake occurs. Therefore, the weld residual stress is one of the important factors of studying on the initiation and propagation of SCC. We are eager for study on the weld residual stress in girth seam H6a located in the lower region of the core shroud in Figure 1 in the present study. In the simulation of the multi beads welding progress, weld beads are heated one by one for being close to the actual welding progress. For obtaining much accurate simulation results of weld residual stress, two different analysis approaches were used and discussed.

2 SIMULATION OF THE RESIDUAL STRESS FIELD IN GIRTH SEAM H6A

The mechanical properties and thermal properties of Type 316L low carbon stainless steel used in the present thermal stress simulation are shown in Figure 2 and Table 1.

The general-purpose finite element program ABAQUS Version 6.9 [2] was used in this study. We had used two different methods to simulate the weld residual stress of the H6a girth seam of the core shroud. Firstly, the simpler Static General Analysis (SGA) in ABAQUS with directly defining temperatures to the weld beads one by one is adopted while there is no heat transfer to the neighboring parts such as other beads and base metal. The other one Fully Coupled Temperature-Displacement Analysis (FCTDA) is much complicated, in which the heat flux via the subroutine is used. Thus the continuous temperature fields in the weldment can be obtained. The whole four constitutive equations (1-4) can be used to explain the FCTDA in ABAQUS while the SGA can only embody the equations 3 and 4 for simulating the thermal stress.

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\frac{\alpha}{c}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\alpha}{c}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\alpha}{c}\frac{\partial T}{\partial z}\right)+Q_0 \quad (1)$$

$$\alpha\frac{\partial T}{\partial n}=-q+k(T-T_0) \quad (2)$$

$$\varepsilon^T=\alpha(T-T_0) \quad (3)$$

$$d\sigma=D(d\varepsilon-d\varepsilon_p-d\varepsilon_c-d\varepsilon_T) \quad (4)$$

where, ρ, c and α are the density, specific heat and coefficient of thermal conductivity of material, respectively. Q_0 is the initial inner energy of material. T and T_0 denote the temperature of the material and ambient temperature, respectively. n presents the normal orientation of the surface of thermal emission. q is the quantity of heat inputting per unit area. k is the emission coefficient of the surface. σ is the stress. D is the constitutive elasticity vector. ε presents the total strain, and the subscripts of p, c and T denote the plasticity, creep and heat strain.

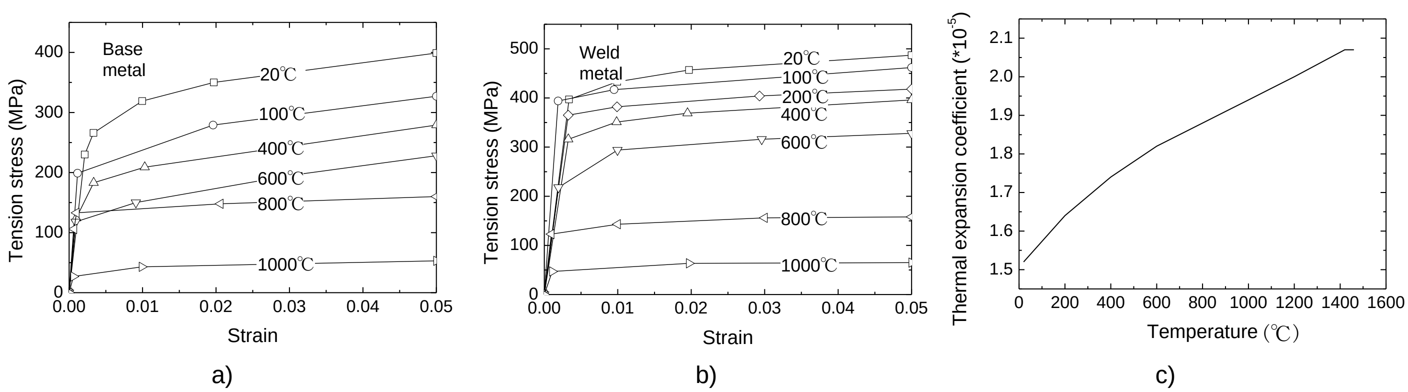


Figure 2. Mechanical properties a) and b) for base metal and weld metal respectively, and thermal expansion coefficient c) for Type 316L low carbon stainless steel [1].

Table 1. Thermal properties of Type 316L low carbon stainless steel used for FCTDA [1].

Temperature ℃	20	100	200	400	600	1000	1500	2000
Thermal conductivity kJ/mms℃	1.46E-05	1.56E-05	1.70E-05	1.97E-05	2.24E-05	2.76E-05	3.43E-05	4.12E-05
Specific gravity kg/mm^3	7.86E-06	7.86E-06	7.86E-06	7.86E-06	7.86E-06	7.86E-06	7.86E-06	7.86E-06
Specific heat kJ/kg℃	0.452	0.493	0.523	0.553	0.578	0.62	0.678	0.737
Emission coefficient kJ/mm^{2}s℃	Air: 1.16e-8; Water: 6.66e-5							

As shown in Figure 3, the model for SGA and FCTDA was constructed by revolving the profile section with $\pi/180$ degree in radian. The model is composed of 12 beads and base metal region.

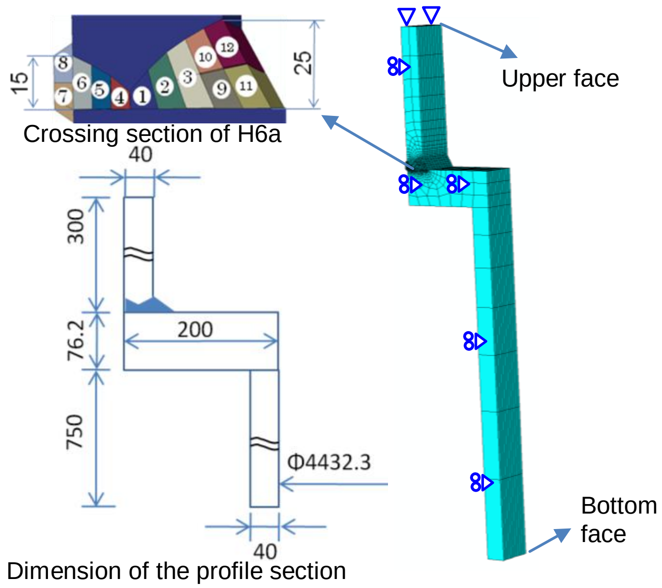


Figure 3. Geometries and dimensions of the simulation model (revolving π/180 degree in radian) containing girth seam H6a and arrangement of beads (Unit: mm).

2.1 Simulation of Weld Residual Stress with SGA

The dimensions and geometries of the profile section of the finite element model are shown in Figure 3. It was meshed with 9178 8-node linear brick elements. We gave the temperature to every bead directly as shown in Figure 4. When bead 1 was heated to deform, the follow beads would not join the calculation. After the bead 1 was cooled to room temperature, the bead 2 was heated. Thus the following beads were given temperature in turns. The progress was achieved by using the definition of contact pairs of the adjacent surfaces between of weld beads and base metal.

As for the boundary conditions for the simulation, all six degrees of freedom (DOF) on the upper face and 2 DOF in local cylindrical coordinates on the profile faces of the model were fixed.

2.2 Simulation of Weld Residual Stress with FCTDA

It was meshed with 9207 8-node trilinear displacement temperature elements in the model used in FCTDA. Its mechanical boundary conditions for the model are the same as that in SGA.

The heat transfer was considered in the present simulation. The subroutine in simulation was adopted to produce the heating source. The inputting heat flux of every bead and those heat histories were shown in Figure 5. The maximum heat flux was defined as 0.002kJ/(mm^3·s) in order to obtain more than 1200°C as the maximum temperature in beads. The temperatures for every bead were also plotted, and the layer temperature was controlled lower than 180 ℃ [3]. Transformation of solid to liquid was not considered in the analysis. After the procedure of cooling of the prior bead finished, the same procedure of heating and cooling was given to the later bead. The predefined temperature and ambient temperature of the model was 20℃. The heat transfer between the adjacent surfaces of the neighboring beads was considered. The weld procedure was assumed to conduct in atmosphere.

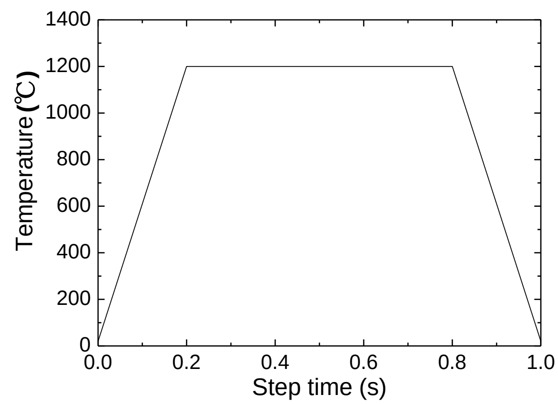
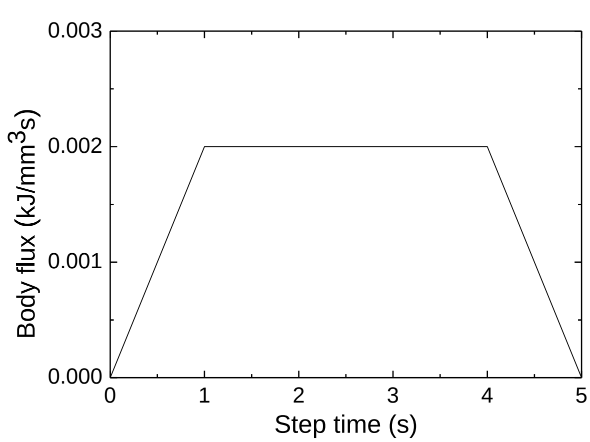
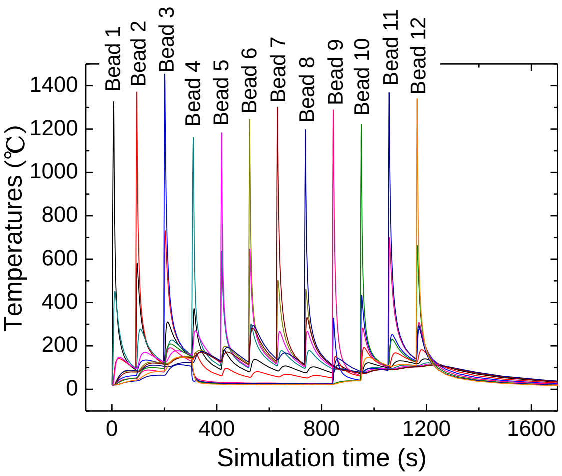


Figure 4. Amplitude curve of temperatures defined for bead during simulation.



a) Heat flux input in steps.



b) Temperatures for the bead in simulation FCTDA2.
Figure 5. Heat history for weld beads in FCTDA.

The cooling conditions of the inner surface were considered in air and with water relative to FCTDA1 and FCTDA2, respectively. Water cooling was used only when the weld beads (beads 4, 5, 6, 7 and 8) of outside of the core shroud were heated.

3 RESULTS AND DISCUSSIONS

The difficulty of thermal stress analysis in the complicated progress is caused by the large deformation of beads. The shapes of beads were dependent on the progress of heat and cool of prior beads. It is troublesome because we have to modify the shapes and sizes of the every bead step by step as shown in Figure 3. Some large gaps between the beads are observed in predefining for meeting the requirement of deformation. Penetration and separation (as shown in Figure 6) always occur if the sizes and shapes of beads were not modified well, and the penetration normally suspends the simulation progress.

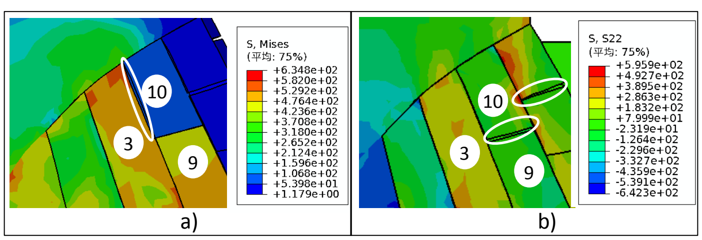


Figure 6. Penetration and separation between the adjacent surfaces of the neighboring beads after simulation.

The large difference of deformation between adjacent surfaces in a contact pair is also difficulty. The connecting between surfaces of the neighboring beads cannot be avoided in the progress with the simple temperature field with using the SGA in ABAQUS. The temperature for a weld bead was increasing from 20 with step time in the static general analysis. After reaching at maximum temperature 1200°C, the temperatures decreased to room temperature at the end of step time. For example in the progress the bead 10 were given high temperature after the bead 9 was cooled as shown in Figure 6. Therefore, the surfaces of bead 10 have large deformation due to high temperature while its connecting surface of bead 3 and 9 did not deform because they were defined the room temperature in the same time. Thus the contact pairs to define the two adjacent surfaces cannot be controlled easily in the simulation and eventually lead to inaccurate simulation results. However, the FCTDA can solve the problem due to the consideration of heat transfer in the progress.

The simulation results (solid lines) comparing the experimental results (solid symbols) of the axial stress in H6a weldment of the core shroud are shown in Figure 7 (in inner surface) and Figure 8 (in outer surface). The zero coordinate of the paths were defined by the upper bond line of weld metal and base metal.

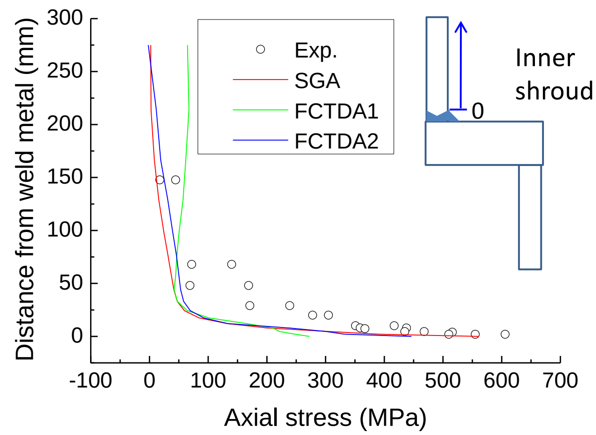


Figure 7. Simulation of axial stress in the inner surface of the core shroud model by SGA and FCTDA (FCTDA1: cooling in air and FCTDA2: cooling with water) comparing with experimental results [1].

The axial stress by simulations in the inner surface of the base metal region is lower than the experimental results as shown in Figure 7. The maximum axial stress is 564MPa, 273MPa and 446MPa by SGA, FCTDA1 and FCTDA2, respectively. The simulation results in the inner surface of the core shroud model by SGA are much agreement to the experimental results while the FCTDA1 can only give poor results.

The axial stress by SGA is much larger than the experimental results in base metal close to weld metal in outer surface of the core shroud and much lower in the weld metal as shown in Figure 8. The axial stress by FCTDA is close to the experimental results in weld metal. The values of axial stress in weld metal region by FCTDA2 are smaller than that of FCTDA1. The quick cooling in the inner surface of the core shroud is used to reduce the tension stress in the outer surface while the tension stress in the inner face increases (Figure 7) by stress equilibrium. The simulation results of FCTDA2 are acceptable comparing with FCTDA1. The compression stresses by SGA and FCTDA are much smaller than the experimental in the weld metal region far from the bond line.

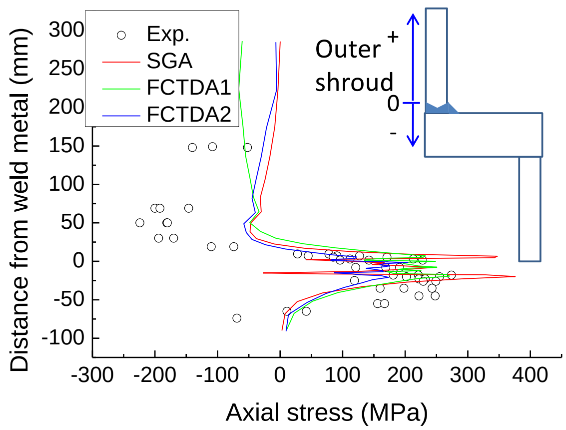


Figure 8. Simulation of axial stress in the outer surface of the core shroud model by SGA and FCTDA (FCTDA1: cooling in air and FCTDA2: cooling with water) comparing with experimental results [1].

The contours of axial stress at the final step of the simulation of SGA (upper) and FCTDA (lower) are shown in Figure 9. The values of axial stress in the boundaries of weld beads have local stress concentration (tension stress in one side while compression stress in the other side) by SGA. The axial stress changing deeply also can be found by the lines with open symbols through weld metal path (WM) in Figure 10. The axial stress in base metal path (BML, which is 3.6mm far from the weld metal.) is smooth, the maximum tension stress are about 350MPa at outer face and 400MPa at inner face of the core shroud model. The maximum compression stress is located in Bead 1 and about 500MPa. The FCTDA can give a much smooth contour as shown in the lower figure (Figure 9) since the heat transfer is considered as stated above. We believed that the local stress concentration in the SGA was caused by no heat transfer during simulation, so that a bead in high temperatures while the neighboring beads are still defined as the temperature (20℃). The connecting beads having different temperatures in the same time make the local stress concentration.

Comparing with the experimental results, the simulation of FCTDA provided much accurate results than SGA. Though the simulation results at the inner face of the core shroud model by SGA are much better, the simulation results through the wall of the model are not correct (in Figure 9 and 10). Moreover, FCTDA2 is much better than FCTDA1 due to the fast cooling in the inner face during welding.

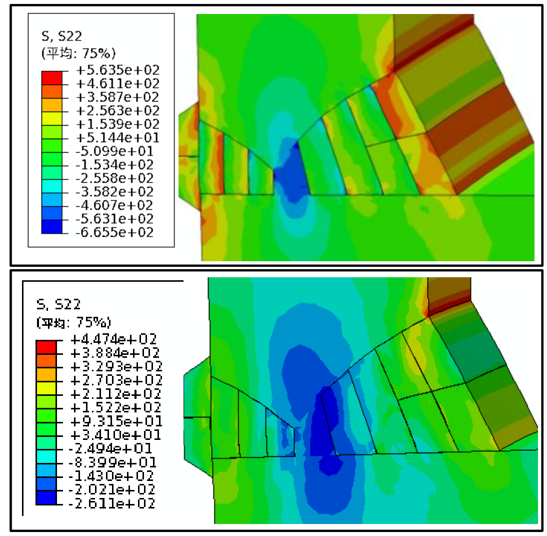


Figure 9. Contours of the S22 (axial stress) in the last increment of the last simulation step by SGA and FCTDA2 (MPa).

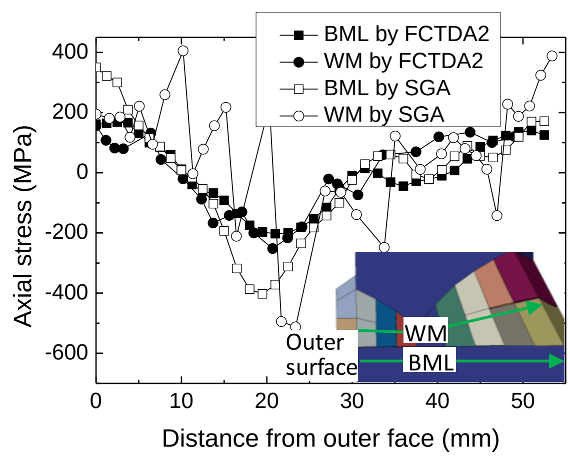


Figure 10. Distribution of axial stress in the crossing section WM and BML of the model calculated by FCTDA2 of ABAQUS.

As shown in Figure 10, simulation results for axial stress by FCTDA2 in two paths begin with the outer surface and end at the inner surface of the model. The shape of the two curves shows like "V" along the crossing section of the wall of the model. The figure shows that the axial stress (tension stress in the region close to surfaces and compression stress in center of the wall) is about 170MPa in outer surface and a little higher than that in inner surface. The tension stresses in surfaces of the model begins changing into compression stress at about 10mm in depth (about 1/4 of the thickness of model wall) in the wall of the model. The maximum compression stress in weld metal path is about 261MPa in Bead 1 of the model.

The actual working conditions for the core shroud in the BWR are complicated as we stated in the introduction section.

The operating core shroud is bearing the neutron irradiation and high temperature water. When a crack initiates under the synergistic effects of the neutron irradiation, corrosion and weld residual stress, the stress in the tip zone of the SCC redistributes. Therefore the simulation results of the weld residual stress are not enough to evaluate the propagation of SCC. The stress relaxation due to irradiation and thermal creep also occurs, which prevents the SCC occurring in some degree. With long term operation, the Chromium contents at the granular boundary decrease due to radiation segregation and the radiation hardening occurs, which make the material be prone to SCC. Therefore, the evaluation of SCC in the weldment of the core shroud should be conducted necessarily with consideration of the synergistic effects of the neutron irradiation, corrosion and weld residual stress. The future work is conducting the FEM on the evaluation of SCC in weldment H6a with consideration of stress relaxation, chromium contents changing and radiation hardening due to neutron irradiation.

4 SUMMARIES

Two different approaches to stress analysis were adopted to simulate the multiple-bead welding progress. The SGA is simple while the surfaces contact is too difficult to obtain the accurate results due to the discontinuous temperature field in the model. The FCTDA can give the much better simulation results comparing with the former approach since the heat transfer was considered. The deformation of parts in the model makes the simulation difficult, and normally leads to penetration and separation of the adjacent surfaces. Water cooling at the inner face of the core shroud model was conducted to reduce the tension stress at the outer face.

The maximum tension stress is in the surface region of HAZ close to the weld metal of the core shroud. The distribution of the axial stress in the cross section of the wall of the core shroud was also studied. The tension stress in surfaces of the core shroud begins changing into compression stress at the depth of 10mm from surfaces of the H6a of the core shroud.

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