Thermal safety analysis of aluminum matrix B4C irradiation in-pile (Postprint)

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Date: 2023-06-18T00:00:00+00:00

Abstract

Aluminum matrix B4C is a new structural material for spent fuel storage and related performances need in-depth research, especially the irradiation-resistance capability. The thermal calculations were completed by using the CFD software to ensure the safety of the in-pile irradiation test. Considering the characteristic of the irradiation project, the thermal safety feature of the in-pile test was analyzed, and the irradiation project was optimized.

Full Text

Preamble

Thermal Safety Analysis of Aluminum Matrix B4C In-Pile Irradiation

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Abstract

Aluminum matrix B4C is a novel structural material for spent fuel storage that requires comprehensive investigation of its performance characteristics, particularly its irradiation resistance. To ensure the safety of the in-pile irradiation test, thermal calculations were performed using CFD software. Based on the specific features of the irradiation project, the thermal safety characteristics of the in-pile test were analyzed and the irradiation project was subsequently optimized.

Key words
Aluminum matrix B4C, In-pile irradiation, Thermal, Safety analysis

2 Samples and Irradiation Device

B4C is a specialized non-metallic material whose applications in nuclear physics, microelectronics, space technology, and other fields continue to expand. Featuring a broad energy spectrum and large neutron capture cross-section, B4C exhibits strong neutron absorption performance, surpassed only by gadolinium, samarium, cadmium, and a few other elements. Additionally, its low cost, excellent corrosion resistance, and good thermal stability make B4C increasingly important for nuclear reactor applications. The development of "B4C pellets for nuclear industry" was included in China's State 863 Program during the 10th Five-Year Plan period. Currently, B4C applications in nuclear reactors primarily focus on radiation shielding, reactor control rods, and preventing radioactive material leakage[1].

As a novel structural material for spent fuel storage, aluminum matrix B4C offers numerous advantages, including cost-effectiveness, strong neutron absorption capability, and excellent mechanical properties. We conducted in-pile irradiation tests on samples to evaluate the material's irradiation resistance performance, and performed thermal safety analysis to ensure test safety. The study employed the CFD software Fluent to obtain thermal-hydraulic parameters of the irradiation device, including flow distribution and temperature field[2].

Aluminum matrix B4C is manufactured through a process involving mixing of B4C powder and aluminum powder, followed by pressing, sintering, extrusion, hot rolling, and other procedures. The irradiation specimens were machined into two geometries—tensile and rectangular—according to the requirements of standards GB/T228-2002 and GB/T230-2002, and also to facilitate in-pile irradiation and post-irradiation performance testing. The specimen geometries are shown in Fig.1. To compare the irradiation properties of samples with different B4C contents, three types of specimens were prepared with B4C volume fractions of 10%, 25%, and 31%.

Fig.1 Irradiation specimens (a) and samples (b) of Aluminum matrix B4C.

3 Heat Power of Samples

The heat power densities of the samples and cadmium skin under full reactor power, calculated using MCNP, are listed in Table 1. Irradiation samples were assembled from two specimens and placed in the irradiation box. To simplify modeling and computation, gaps and contact resistance between specimens were neglected, resulting in rectangular solid samples in the computational model. The irradiation box features an open top, holes in the bottom, and an aluminum cross placed beneath the sample to prevent hole blockage. The aluminum matrix B4C irradiation test technically requires irradiation with gamma rays and fast neutrons while excluding thermal neutrons; therefore, the irradiation box is covered with cadmium skin on the outside and aluminum skin on the inside. The structure of the irradiation boxes is shown in Fig.2.

Fig.4 Structural sketch of sample's cross-section.

Table 1. Heat power of irradiation samples and cadmium shell with full reactor power. Irradiation Samples: First, Second, Third, Fourth. Heat power / W · cm 3: Cd skin around, Cd skin at the bottom. Being small, the heat power's change of each sample in the axial direction is ignored. The aluminum material gives out little heat, 3.38 W/cm^3.

4 Thermal Analyses

Due to the complexity of the computational model, two simplifications were made: the influence of the topmost handle was neglected, and the ribs fixing the irradiation boxes were ignored. All other structural details of the irradiation device were fully considered, including the holes at the bottom of the irradiation boxes, the outer cadmium skin, the aluminum crosses, and the tank within the aluminum blocks.

The computation employs the k- two-equation turbulence model and sets the pressure loss between inlet and outlet equivalent to that of standard fuel rods. The coolant's thermodynamic parameters are specified as the values at the reactor core inlet under full power conditions. The wall roughness height is set to 0.0016 mm, equivalent to that of cold-drawn tubes[3].

A symmetry plane was created by cutting the model along the diagonal axis. The shape of the irradiation device and aluminum block in the irradiation channel is similar. Four irradiation boxes are placed in the device, secured with an aluminum block (hollow rods) at either end or with surrounding ribs. An aluminum cross and cadmium plate are placed at the bottom of the top aluminum block, with the cross width being smaller than the hole diameter. The bottom aluminum block is slotted at both ends.

Fig.2 Structure picture of irradiation box.

Fig.3 Scheme of irradiation device. The outer channel between irradiation box and irradiation device is to cool the cadmium skin, and the inner channel between irradiation box and samples is to cool the samples. Fig.4 shows the cross section of the irradiation device.

The temperature distribution is shown in Fig.5. Despite its high heat power, the cadmium skin's temperature approximates that of the irradiation samples at the same depth due to its small thickness and location between the inner and outer flow channels. The temperature of the symmetry plane gradually increases, reaching a maximum of 59ºC at the bottom of the fourth box.

Temperature curve of irradiation device in axial Fig.6 direction.

Temperature distribution of Fig.5 symmetry face. The temperature curve on the irradiation device's central axis is presented in Fig.7. The temperature begins to rise rapidly from the 0.42 m position (the top of the first box), after which four wave crests appear, progressively increasing in height and representing the temperature variation trend of the four boxes. The first maximum occurs at three-fifths of the box height, after which the temperature drops rapidly due to heat transfer from the box bottom to the coolant. Between the peaks, some temperature points are lower than their surroundings, corresponding to regions in the irradiation box structure occupied by coolant. This occurs because the box is not completely filled, leaving space at the top filled by coolant. The temperature variation trend is similar for each box, and the cadmium skin on the fourth box generates more heat, causing a temperature rise. On the central axis, the coolant channel follows the four boxes, so the temperature curve drops sharply after the four wave peaks.

Fig.7 Temperature curve of Cd shell in axial direction.

In Fig.6, the samples' center temperature reaches its maximum at 850 mm; the temperature distribution at this position is shown in Fig.8.

Fig.8 Temperature distribution of irradiation device cross- section at 850 mm position.

The cadmium skin cross-section is a square ring. A temperature profile was created using values from the center axis of each side. As shown in Fig.6 and Fig.7, the cadmium temperature variation trend is similar to that of the samples at the same height, though slightly lower.

Since there are no ribs in the irradiation box to fix the samples in the radial direction, the samples are likely to contact the box wall. Additionally, sample swelling may occur during irradiation, reducing cooling efficiency. Both scenarios would degrade heat transfer, making it necessary to consider these conditions in the calculations[4]. Results from simplified models addressing these conditions are presented in Fig.9.

5 Conclusion

The highest temperatures of cadmium and irradiation samples in the full-scale model under ideal conditions are 52ºC and 60ºC, respectively. The highest sample temperature of 117ºC in the simplified model with a completely blocked flow channel remains below the limit value. In actual situations, these factors will influence heat transfer. The full-scale model does not consider the irradiation boxes, which will decrease the outer channel flow, reducing coolant flow.

Fig.9 Temperature distribution sketch of irradiation device cross-section with different conditions.

In the simplified model under ideal conditions, the cadmium skin temperature is approximately 10ºC lower than the samples, which is slightly lower than in the full-scale model, but the sample temperature does not change significantly. Therefore, the simplified model is considered reliable. The highest temperatures in the simplified model under various conditions are: 61ºC for ideal conditions, 90ºC for samples clinging to box walls, 74ºC for samples expanded to block

50% of the flow channel, and 117ºC for samples expanded to block 100% of the flow channel. The test design requirements specify that sample temperature should be below 400ºC and cadmium temperature below 200ºC, indicating a substantial safety margin.

Thermal contact resistance was neglected, but according to experience, this simplification has minimal impact. The sample heat power was treated as uniformly distributed, which differs slightly from the actual situation.

Aluminum matrix B4C is a novel structural material for spent fuel storage, and in-pile testing will advance research in this area. The simulation results demonstrate that the irradiation test is safe and reliable, providing theoretical assurance for future work.

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Note: Figure translations are in progress. See original paper for figures.