An Experimental Study of Plate Forming for the High-density Nuclear Fuel Plates with the Al6061 Cladding

Kyeongmin Park [a*], Yonghwan Lee, Soontae Kwon, Hwayoung Song, Sunghwan Kim, Yongjin Jeong
Research Reactor Fuel Division, Korea Atomic Energy Research institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
[*]Corresponding author: pkmin@kaeri.re.kr

1. Introduction

KAERI and the SCK CEN have been cooperating on the qualifying program of high-density atomized U_3Si_2 fuels for the BR2, high-performance research reactors in Belgium, since 2021.

In Phase 1 of the cooperation, flat-type high-density atomized U3Si2 fuel plates, called KIMQI-FUTURE, had already been fabricated and irradiated in the BR2 from 2021 to 2022. For Phase 2, the plate forming process has been developed for the fabrication of the curved plates which will be swaged into the fuel assembly called KIMQI-GTA (Generic Test Assembly). Generally, aluminum alloys used for research reactor fuel plates are Al6061, 1100, 8001, and the European AG3NE. Among them, the AG3NE, a French cladding alloy similar to the 5000 series, has an advantage of the plate forming in terms of its lower yield strength. In KAERI, the Al6061 series which belongs to a class of age-hardenable alloys based on Mg and Si additions have been used for many applications. Although the Al6061 alloys have a disadvantage to hot forming, they have pros to use as nuclear fuel cladding in terms of mechanical properties and corrosion behavior. However, there were not enough studies for the plate forming of the Al6061 series, and almost none of them were performed on composite materials such as dispersion nuclear fuel plates. In this paper, the plate forming process of the high-density atomized U_3Si_2 fuel plates with Al6061 cladding and its results were described, respectively.

2. Methods and Results

The curved high-density atomized U_3Si_2 fuel plate for the KIMQI-GTA irradiation tests at the BR2 has a dimension of 70mm in inner radius. To fulfill the design specifications of the KIMQI-GTA fuel plates, the optimization of the fabrication variables such as fuel meat materials, pre-annealing, and punch sizes of the press-braking machine were carried out.

2.1 Fuel meat materials

High-density atomized U_3Si_2 fuel plates were fabricated in the order of blending atomized U_3Si_2 fuel powders/Al matrix powders, compaction of the blended powders, and subsequent rolling of compact/Al6061 components packages. It is noteworhty that the fuel meat dimensions were almost 40 % of the volume of fuel plates, so the plate forming was highly affected by the mechanical property of fuel meat materials. In this study, we used tungsten powders and U_3Si_2 powders as the fuel meat materials for the fabrication of dummy fuel plates to compare the effects of its property on the plate-forming process. The results showed that as fuel meat materials varied, the inner radius of curved plates varied more than 3 mm as shown in Fig. 1. In the figure, plate-forming depth, and plate-forming pressure are denoted by D and P, respectively.

Tungsten has higher yield strength than that of U_3Si_2, in that it is easier to form into curved surfaces due to its lower spring back after the process.

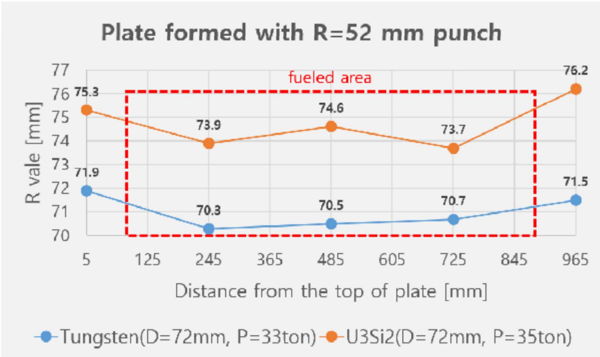

Fig. 1. Effects of fuel meat materials on the plate-forming

2.2 Pre-annealing

As shown in Fig. 1, it was hard to get a homogeneous inner radius along the length axis due to the difference in mechanical properties between the fueled area and the non-fueled area. Pure Al, denoted by the non-fueled area, has a higher spring back, and it was reported that a head and a tail of rolled plates have higher rolling-induced residual stress which affects the bendability during the plate-forming . The deviations for the inner radius from the targeted radius (70 mm) of the fuel plates, were measured, and the result showed that the max. 4.5 mm difference in deviation was discovered between fueled areas and non-fueled areas as described in Fig. 2 and Fig. 3.

To relieve the residual stress, pre-annealing was performed at temperatures from 300 to 450 ℃ for varying times. Subsequently, the plate-forming was carried out on the pre-annealed plates. After the plate-forming process, the inner radius and its deviations were measured, and shown in Fig. 4 and Fig. 5, respectively.

It should be noted that the pre-annealing effectively reduces the deviations of the inner radius. Especially, the deviations of the inner radius for non-fueled areas, the head, and the tail of fuel plates, decreased by more than half. Usually, for Al6061 alloy, residual stress relieving is performed by annealing the alloy about at 350 ℃ for 1hr. Furthermore, 450 ℃ is the most effective temperature to lower its yield strength of it. The plate-forming results in this study corresponded well with those references.

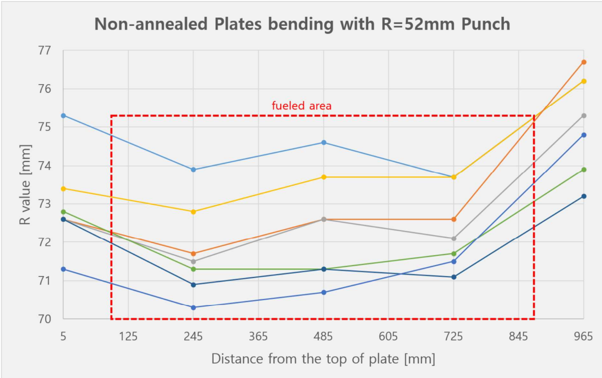

Fig. 2. Plate-forming results of non-annealed fuel plates

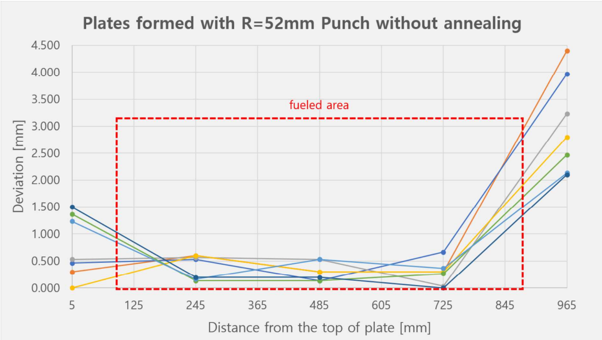

Fig. 3. Deviations for the plate-forming results of non-annealed fuel plates

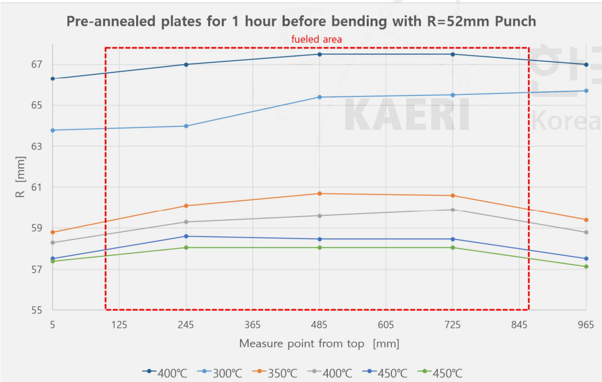

Fig. 4. Plate-forming results of pre-annealed fuel plates

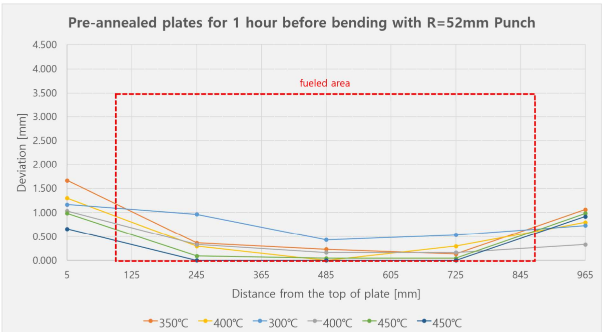

Fig. 5. Deviations for the plate-forming results of pre-annealed fuel plates

2.3 Punch radii for plate-forming

The punch radius for plate-forming should not be greater than the targeted inner radius of curved plates, and the length of the punch should be longer than that of the fuel plates.

To fulfill the specification for KIMQI-GTA, R70, the punches sized from R50, R52, R57.5, and R60 were prepared, and plate-forming was performed, respectively. From the results, we concluded that the R60 punch showed a set of satisfying results for the plate-forming. The fabricated plates showed 70 mm in inner radius with tolerances of 2 mm, as shown in Fig. 6 and Fig. 7.

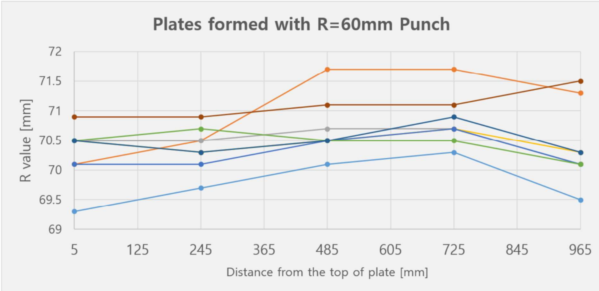

Fig. 6. Plate-forming results performed by the R60 punch

Fig. 7. Fabricated KIMQI-GTA curved fuel plates

3. Conclusions

KAERI and SCK CEN have been conducting the qualification program for the high-density atomized U_3Si_2 dispersion fuels. For the irradiation tests at the BR2 in 2023, KAERI is developing fabrication processes for curved fuel plates with the Al6061 cladding. Fabrication variables such as fuel meat materials, the pre-annealing, and punch radii were determined by experimental practices. As result, KAERI successfully fabricated curved fuel plates fulfilling the specification of KIMQI-GTA.