Title

Fabrication and Testing of U–7Mo Monolithic Plate Fuel with Zircaloy Cladding

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Abstract

Nuclear fuel designs are being developed to replace highly enriched fuel used in research and test reactors with fuels of low enrichment. In the most challenging cases, U–(7–10wt%)Mo monolithic plate fuels are proposed. One of the considered designs includes aluminum-alloy cladding, which provides some challenges in fabrication and fuel/cladding interaction during service. Zircaloy cladding, specifically Zry–4, was investigated as an alternative cladding, and development of a fabrication method was performed by researchers with the Comisión Nacional de Energía Atómica (CNEA) in

Argentina, resulting in test fuel plates (Zry-4 clad U-7Mo) which were subsequently tested in the Advanced Test Reactor in Idaho. Because Zry-4 and U-(7-10)Mo have similar high-temperature mechanical properties, fabrication was simplified in that the fuel foil and cladding could be co-rolled and bonded. The challenge was to prevent a thermal-expansion mismatch, which could destroy the fuel/cladding bond before complete bonding was achieved; the solution was to prevent the composites from cooling significantly during or between roll passes. The final product performed very well in-reactor, showing good bonding, very little fuel/cladding interaction—either from fabrication or in-reactor testing—and little swelling, especially no detectable heterogeneous bubble formation at the fuel/cladding interface tested to a fission density of up to $2.7\text{E}+21$ (average) fissions/cm³, $3.8\text{E}+21$ (peak).

Keywords

Low-enriched fuel, Monolithic fuel, Zircaloy cladding, RERTR, Research Reactor, Test Reactor

1. INTRODUCTION

The potential for fuel/cladding interaction has been a concern for the monolithic fuel-plate design with a U-xMo fuel meat. The cladding is usually relatively fixed at an aluminum-alloy composition, and the fuel foil would necessarily be in direct contact with the cladding. In the dispersion fuel design, nearly all of the fuel/aluminum alloy contact is between the U-xMo and the matrix material. To minimize fuel/cladding interaction, the fuel particles can be covered with a diffusion-barrier material and/or the matrix material. Even the fuel material can be tailored in composition. In monolithic fuel, the fuel layer is a solid fuel-alloy foil, and the fuel would be in direct contact with the cladding.

Two fuel-design changes to the monolithic fuel plate have been suggested to minimize potential interaction: first, incorporating a barrier material between the monolithic fuel and cladding, or second, changing the cladding material to one for which less interaction may be expected. One of the possibilities for an alternate cladding was a zirconium-based material. The challenge was to demonstrate both that aluminum cladding could be replaced by Zircaloy-4 (Zry-4) cladding and that Zry-4 could be bonded successfully to the fuel using a hot-rolling co-lamination technique. Earlier fabrication experience included co-extruding U-xMo with Zircaloy-2 (Zry-2) in plate and rod shapes.[1]

The United States High Performance Research Reactor Fuel Development branch is currently focused on developing the barrier type fuel for qualification. Significant development and testing has been done on this fuel type and have been summarized in the down selection report. [2]

Advantages are expected from using Zr-based cladding material on monolithic fuel plates. One is a minimal interaction between Zr and U-Mo alloys predicted by calculation.[3] In addition to the potential advantage for fuel/cladding compatibility, the Zircaloy cladding would have similar mechanical properties at elevated temperatures to the fuel-foil material (U-xMo) and would, therefore, make some fabrication steps easier to perform. For example, it was found that rolling at a higher temperature (~650°C) could be performed with this fuel/cladding combination, so delicate pre-rolling of thin fuel foils could be avoided.

The standard use of Al-alloy cladding like 6061-T6 prevents roll bonding. The aluminum melts at temperatures near 600°C while the U-xMo alloys are not stable in the gamma phase at temperatures less than 500°C during fabrication. The higher strength of the Zry-4 material compared to aluminum alloys like 6061-T6 could also permit thinner cladding, require no barrier layer, and provide additional space for fuel alloy, thus allowing for redesign to optimize the fissile material/moderator ratio.

Because Zry-4 materials have long been used as fuel cladding in water-cooled reactors, they would be an obvious choice to minimize the qualification testing required to introduce a new cladding material.[3] A potential disadvantage is introduced by the mismatch between the thermal expansion coefficients of U-xMo and Zry-4. This created fabrication challenges since a 100% fuel/cladding bond is required to establish a bond strong enough to accommodate the mismatch strains created by the factor-of-two-higher coefficient of thermal expansion.[5]

In addition, there is nearly an order of magnitude reduction in thermal conductivity from Zr to Al alloys. Peak fuel temperatures would be increased if Zr alloy cladding was used to replace Al alloys. For example, an analysis of conceptualized MURR-conversion fuel, clad with Al-alloy versus Zircaloy-4, showed an increase of 19°C at clad centerline and 47°C for fuel centerline [6]. Other reactors to be converted may see a greater or lesser temperature change.

Also, Zr-alloy cladding has a higher density than the Al-alloy cladding. This would potentially test the capability of fuel-handling equipment or the viability of structural core components, and each of these factors would have to be analyzed.

Since 2003, an Argentine group has been working on monolithic fuel hot-roll bonding, using stacked plates of Zry-4/U-Mo/Zry-4.[7,8,9,10,11,12] Researchers at the Comisión Nacional de Energía Atómica (CNEA) in Argentina developed the fabrication techniques to produce two fuel mini-plates that were irradiated as part of the RERTR-7A experiment. The progression of this work has been documented.[4,13] The fabrication and irradiation of these two mini-plates, MZ25 and MZ50, are analyzed in detail in this paper.

2. FUEL-PLATE FABRICATION DEVELOPMENT

Historical fabrication tests of U-xMo alloy fuels with Zircaloy cladding were accomplished by using co-extrusion methods.[1] No experience has been reported previously concerning hot-roll bonding of plates using these two alloys. This may be attributed to the difficulties in step/sequential bonding together of the U-Mo and Zr plates due to their very different thermal expansion coefficients.

The rule of thumb in roll bonding is that deformations of 50% at the contact surfaces are needed to obtain 100% bonded interfaces. Because U-xMo alloys allow only small deformations, total bonding can only be achieved through sequential deformations (rolling passes). Partial bonding is only obtained after each lamination rolling step, and as the plate cools from that working temperature, the stresses caused by differential thermal expansion can dislocate the partially bonded spots. This can be mitigated if the plates are not allowed to cool in between lamination/rolling steps. Once the contact surfaces are totally bonded, the mismatch strains when the plates are finally cooled are of the order of 0.5% upon cooling from 500°C. With the interface completely bonded, the mismatch can be accommodated by plastic deformation. Past successful extrusion experiences have demonstrated this.

Preliminary tests were done to study the possibilities of hot-rolling Zry-4/U-Mo and Zry-4/Zry-4 interfaces. Diffusion studies were performed coupling U-xMo and Zry-4 alloys and hot-roll bonding was used to join three Zry-4 plates (~6.5 cm²). The diffusion couples were tested at 800°C for several hours in an inert atmosphere. Following metallographic preparation of the diffusion couples, bonded (Figure 1) and non-bonded (Figure 2) regions were observed. Completely bonded regions had a small fuel/cladding interaction layer, and the non-bonded regions were assumed to have de-laminated during cooling either along the U-Mo/Zry interface or within interaction layers formed during heat treatment. The roll bonding of three superposed Zry-4 plates that were tungsten inert gas (TIG)-welded laterally (~38 amperes) did not present mechanical problems at the several rolling temperatures tested between 650 and 850°C, which is in the α -phase region of the phase diagram.

Insert Figures 1 and 2.

Several small fuel plates (Zry-4/U-xMo/Zry-4) were next hot-rolled using the typical picture and frame set up. Roll-bonding was tested in the temperature range within which the γ U-xMo phase is stable (>650°C) and Zry-4 is in α phase (<850°C). No significant benefits were noticed in the mechanical behavior as temperature was increased in this range. Therefore, the lowest temperature was preferred to minimize oxide-layer growth and thermal expansion mismatch between roll passes.. Mini-plate fabrication was not planned to be performed in an inert atmosphere (an unwanted complication if it could be avoided), and the inter-diffusion-thickness growth could also be minimized at the lower temperature. A nominal 7wt% molybdenum alloy was selected for work at the lowest temperature (650°C) in the γ U-7Mo stable zone. Dimensional

tolerances were selected to guarantee good contact of the lateral faces of the meat with the Zry-4 frame to avoid blister formation during roll bonding.

The hot rolling procedure to achieve 100 % bonded (welded) interfaces included minimizing the temperature drop during the lamination steps. This is needed because the total bonding is obtained only after several reduction passes. The process of extraction, lamination and placement again in the furnace was done as quickly as possible, and time-consuming thickness measurements were replaced by a quick measurement of the plate length, from which the reduction of the pass was estimated. This was used only as in-process estimation of the thickness and had to be verified after the lamination process was completed.

When the plate was reintroduced into the furnace insufficiently quickly, repeated “crick” sounds were heard, indicating the breaking of the partial welds that had formed. This simple auditory control method proved to be satisfactory for process control during the hot-roll-bonding process. In addition, following completion of the lamination process, a soft drop of the plate onto the surface of a table produced very different sounds: an applause or rattling sound was noted for insufficiently welded surfaces, while a metallic sound was heard for a sufficiently bonded surface-welded mini-plate. This simple check of bond quality during fabrication was later verified using ultrasonic scanning and X-ray radiography as a final check for abnormalities after lamination.

3. FABRICATION OF THE MZ25 AND MZ50 MINI-PLATES FOR IRRADIATION TESTING

Two plates with monolithic U-7Mo fuel and Zry-4 cladding were required for irradiation in the RERTR-7A experiment, with each given a unique identification of MZ25 and MZ50. The letters standing for Monolithic meat and Zircaloy-4 cladding, and the numbers indicate a nominal 0.25 and 0.50 mm meat thickness. The size of the plates was 10.1×2.5 cm; the thickness of the plates was 1.4 mm, thinner than typical plates used in the capsules of the RERTR experiments. (Figure 3 shows the dimensions of typical mini-plates for RERTR experiments.) The Zry-4 cladding thickness of the MZ50 mini-plate was some 0.25 mm thinner than the typical (0.35–0.40 mm) aluminum-cladding thickness. Low-enriched uranium (20% ^{235}U) was used for both mini-plates. Nuclear quality Zry-4 plate was used as raw material for the cladding. High-purity molybdenum wire of 1 mm diameter was used as feedstock in the casting of the nuclear-fuel alloy.

Insert Figure 3.

3.1 Alloy Melting

The U-7Mo alloy for both the MZ25 and MZ50 mini-plates was prepared from a single melt in a high-frequency induction furnace with a surrounding graphite inductor and argon atmosphere. Approximately 500 g of U-7Mo alloy were melted in a magnesium-oxide crucible. Pickling of LEU uranium lumps (19.86% ^{235}U) with a purity greater than 99.7% U was done with a 50/50 v/v mixture of concentrated nitric and acetic acids, a distilled water rinse, and drying. Chips of high-purity molybdenum wire were pickled in a molten bath of pure sodium-hydroxide, rinsed with distilled water, and dried.

The melting procedure involved heating the uranium lumps and molybdenum chips to 1300°C for longer than 15 minutes until all the floating refractory metal was dissolved in the molten uranium. A high-purity-graphite vertical mold was used to cast a 2-mm-thick plate measuring approximately 75 mm $\times$ 100 mm. The process resulted in a final U-7Mo plate with a very brilliant surface and a composition of $[92.91 \pm 0.09]$ wt% U and $[7.04 \pm 0.07]$ wt% Mo.

3.2 Sandwich Preparation

The picture and frame technique was used to prepare the stack sandwich for hot-rolling the MZ25 and MZ50 mini-plates. The monolithic U-7Mo meat is surrounded by a Zry-4 frame and two covers. The thicknesses of both stacks were the same, compensating for the different frame/meat thickness by using covers of different thicknesses. Zry-4 plates of three different thicknesses (1, 1.5 and 2 mm) were prepared by cold rolling and intermediate annealing in a vacuum furnace for the cutting and sizing of the two frames and the two pairs of covers. The overall thickness of both packs was 4 mm. The MZ25 pack had covers of 1.5 mm thickness, and the frame of 1 mm; MZ50 had covers of 1 mm thickness and frame of 2 mm. The side dimensions of the Zry-4 pieces were obtained using a water-jet cutting machine, and a frame drawing common to both sandwiches is shown in Figure 4. The cover dimensions were the same, but without the hole where the fuel meat was placed. The fuel-meat size, in both cases, was $18 \times 20 \text{ mm}^2$, with the longer dimension parallel to the rolling direction. The Zry-4 pieces were cleaned using fine silicon-carbide wet sanding paper.

Insert Figure 4.

The U-7Mo coupon for the MZ50 sandwich was only cut and smoothed, keeping the plate thickness of 2 mm. The fuel coupon thickness of 2 mm was reduced by hot rolling in several passes to obtain the 1 mm MZ25 U-7Mo coupon. The coupon was heated in a furnace without atmospheric control between passes. Therefore, intermediate pickling between the reduction passes in the rolling mill was necessary to remove surface oxides. The final thicknesses of both U-7Mo coupons were adjusted to be the same as the corresponding frame thickness or, preferentially, slightly thicker (0.1 mm).

3.3 Hot Co-lamination

The MZ25 and MZ50 fuel plates were fabricated by hot-roll bonding (i.e., co-laminating) the Zry-4/U-7Mo/Zry-4 stacked plate sandwiches. A Stanat rolling mill with 15 cm diameter rollers was used for hot-rolling the stack sandwiches. Entrance guides were incorporated to quickly center the stack to be laminated perpendicular to the roller. The furnace temperature was set to 675°C in an air atmosphere. The heating time between passes was reduced as much as possible so as to minimize the oxide-layer growth. Eight passes were required to achieve the desired reduction with totally bonded interfaces. The time outside the furnace between passes was shortened to minimize the breaking of the partial welds formed during each lamination pass.

Table 1 shows a representative rolling schedule for each lamination step, indicating heating temperatures, time between passes, orientation of the stack-sandwich entrance, measured length, and percent reduction/length change. The 45° notch of the stack-sandwich (see Figure 4) is the reference to identify the corner position in each lamination pass; the orientation numbers—1, 2, 3 and 4 in Table 1—are the corner positions that were located at the front right-side entrance position of the stack sandwich for the specific lamination pass. The percent length increment in each pass is numerically similar to the reduction percent of the thickness. Heating temperatures were between 650 and 675°C and, after the long (16 minute) initial heat-up, the subsequent heating times were 6–7 minutes. The stack-sandwich reduction for the passes was between 15 and 23%, with the exception of the first-pass reduction which was 8.3%. The initial length and thickness of the sandwich were 60 and 4 mm, respectively, and the sandwich was 50 mm wide. Final thickness in this lamination case was 1.11 mm, corresponding to a 72% total reduction. The thickness after hot-roll bonding is slightly thicker (by ~0.1 mm) than was planned for the final mini-plate thickness to account for the eventual oxide-layer removal and surface finishing. The total heating time was ~1 hour. The relatively low temperatures and short times for both the heating and cooling involved in the process also guaranteed that the thickness of the U-7Mo/Zry-4 interaction layer was minimized and still achieved a good bond.

Table 1. Typical lamination steps used for the fabrication of monolithic U-7Mo/Zry-4 mini-plates.

Pass	Temp.	Time	Orient.	Length	Length Δ
<i>n</i>	$^{\circ}\text{C}$	<i>min</i>	-	<i>cm</i>	%
1	670	16	2	65	8.3
2	655	6	3	75	15.4
3	660	6	1	92	22.7
4	675	7	4	111	20.6
5	670	6	2	134	20.7
6	660	7	3	161	20.2
7	650	6	1	189	17.4
8	660	6	4	217	14.8
Σ or avg.	662 ± 13	60	-	-	362

3.4 Flattening and Finishing

After the hot-roll bonding process, the plates required straightening and oxide removal. The plates were then polished and trimmed to final dimensions. No final room-temperature lamination pass was performed. After the oxide removal and polishing, the desired final thickness was achieved. Several of the mini-plates fabricated during development of the hot roll bonding processes were used for testing and performing plate-flattening and finishing. A multi-roller straightening machine was used. This process was performed with the plates at room temperature in several highly lubricated passes.

The oxide removal and polishing of the plates were performed using a modified belt sander. All the sanding was done in wet conditions on both sides of the two mini-plates using silicon-carbide abrasive belts with mesh numbers 320 and 400. Both the mini-plate straightening and the oxide removal must be done with extreme care because the cladding thickness uniformity is directly influenced by these two processes.

3.5 Quality Inspection

After the surfaces were polished and the final thickness achieved, dimensional inspection and ultrasonic testing were performed to ensure 100% bonding between fuel and cladding (in the fuel zone) and cladding to cladding in the framed area. X-ray radiography was also used for meat dimension measurements and to check quality (fuel-meat folding, homogeneity of fuel-meat density, etc.).

The final characteristics of MZ25 and MZ50 are summarized in Table 2. The same batch of fuel-alloy melt was used in both mini-plates, with a composition of 92.91 ± 0.09 wt% U and 7.04 ± 0.07 wt% Mo and a uranium enrichment of 19.86% ^{235}U . Some of the values in the table were measured while others were calculated. The overall size of the mini-plates was $25 \times 100 \text{ mm}^2$. The characteristics in Table 2 include plate and cladding thickness, the dimensions of the monolithic U-7Mo fuel zone, as well as the total uranium mass, bulk-fuel-uranium volume density and uranium areal density.

Table 2. MZ25 and MZ50 general characteristics. [5]

Mini-plate Characteristics	Units	MZ25	MZ50
Plate thickness (measured)	mm	0.99	1.01
Cladding thickness (calculated)	mm	0.36	0.25
Meat thickness (calculated)	mm	0.26	0.51
Meat width (measured)	mm	18.8	18.6
Meat length (measured)	mm	73.0	71.0
Total uranium	g	5.9	10.9
Meat uranium density	gU/cm ³	16.5	16.2
Aerial U density	gU/cm ²	0.21	0.41

4. Irradiation in RERTR-7A

The RERTR-7A test was performed in the ATR during Cycles 136A and 136B for a total of 90 effective full power days.[14] Twenty-five mini-plates of varying design were irradiated, including the two U-7Mo/Zry-4 plates, MZ25 and MZ50, in positions B8 and C4 respectively. The RERTR-7A was the seventh test train assembled to examine the performance of uranium-molybdenum alloy-based fuels. It was inserted on November 24, 2005 and irradiated in the ATR B-11 position through the end of cycle 136A for a total of 51 days, ending January 14, 2006. After this irradiation cycle, the experiment was moved from the reactor to a canal for short-term storage during a 6-day outage. The experiment was then reinserted into the ATR B-11 position for cycle 136B (22 additional days). Cycle 136B was interrupted on February 13 and was restarted on February 19 for another 17 days. Cycle 136B finished irradiation on March 9, 2006.[14]

The enrichment of the MZ plates was limited to <20% ²³⁵U/total U, about one-third of that used in most of the other monolithic plates in the test. These plates therefore operated at lower power densities and to lower fission densities, with total average ²³⁵U burnup of 37.5% and 33.1%, respectively. The estimated beginning-of-life (BOL) thermal conditions are described in Table 4.[14]

Table 4. BOL thermal conditions for MZ25 and MZ50 in RERTR-7A experiment.

Capsule-Position	Mini-plate	Average Heat flux	Average Fuel Plate Power	Coolant Temp.	Plate Surface Temp.	Fuel-Clad Temp.	Fuel Central Temp.
		W/cm ²	W/cc	°C	°C	°C	°C
B-8	MZ25	137	10773	61	82	86	90
C-4	MZ50	216	8494	64	97	104	133

The operating parameters, peak surface heat flux, power density generated at the beginning and end of irradiation, total burnup of ²³⁵U, and minimum and maximum clad-surface temperatures of the MZ25 and MZ50 plates are shown in Table 5.[14]

Table 5. Zry-4-clad plates in ATR test RERTR-7A—operating parameters.

Fuel Plate	Peak Surface Heat Flux W/cm ²	Peak Power Density W/cm ³		²³⁵ U BU %	Average Fission Density, 10 ²¹ f/cm ³	Peak Fission Density, 10 ²¹ f/cm ³	Clad surface T °C	
		BOL	EOL				Max	Min
MZ25	205	16160	12250	37.5	2.54	3.81	83	56
MZ50	336	13164	10600	33.1	2.05	3.18	97	58

5. POST-IRRADIATION CHARACTERIZATION

5.1 Plate Thickness

Plate-thickness measurements were performed, before irradiation, at 12 locations and after irradiation at 18 locations on each of the two mini-plates. The locations are shown in Figure 5. The pre- and post- irradiation plate-thickness data are shown in Figure 6 for MZ25 and in Figure 7 for plate MZ50. The difference between pre-irradiation (as-built) and post-irradiation measurements provides a measure of the swelling of the plate in reactor.

Note that for each plate, the left side has swollen more than the right side, as expected; the left edge of the plates faced the ATR core center, so that side experienced higher neutron flux. The fuel meat thickness for MZ50 was twice that of MZ25, but the cladding thickness was thicker for the MZ25 plate (0.37 mm vs 0.25 mm for MZ50). These factors bias this measurement of swelling based on total plate thickness change for MZ50, despite the slightly higher fission density in MZ25. If the thickness change is compared to the original meat thickness (i.e., not the plate thickness), then the average meat swelling (in the thickness direction) for MZ25 is 15% and 12% for MZ50. The higher swelling for MZ25 is consistent with its higher fission density.

Local fuel swelling values were calculated using the local post irradiation thickness as well as the average pre irradiation plate and foil thicknesses. The local fission density values were calculated using the plate average values shown in section 4 and the gamma scans which show relative fission density as a function of location. The local fuel swelling versus fission density is shown in figure 8.

Insert Figures 5–8.

5.2 Surface-oxide Thickness

The growth of an oxidation layer on the surface of the plate is important because it affects the operating temperature of the fuel by effectively lowering the thermal conductivity at the surface. As it grows very thick, it can further compromise fuel-plate integrity by both thinning the wall thickness of the cladding and reducing cooling-fluid flow. Oxide growth on aluminum-alloy-clad fuel is particularly important because the specific form of the oxide/hydroxide, its rate of growth, and its thickness are all important and dependent on fuel-cladding temperature, water pH and impurity content, and pre-treatment of the surface. The oxide layer growth on Zry-4 is also dependent on some of these same parameters and would, perhaps, be as important to the performance of the fuel in a research reactor as it is in light-water-reactor fuels, although the growth rates are likely different due to operating temperature.

Surface-oxide thickness was measured using a handheld eddy-current probe, manufactured by HELMUT FISCHER, model DeltaScope MP30, modified for hot-cell use. The technique allows for the measurement of oxide thickness on all plates, whereas previous measurements were only

made on plates that were destructively examined, measuring the thickness in metallographic images of the plate cross-section. The current technique has been shown to be accurate to $\pm 0.5 \mu\text{m}$ when the substrate is flat, the oxide layer is uniform, and the probe is perpendicular to the plate surface. The zero calibration of the oxide-layer thickness measurements was done using the remaining side pieces of the final-sized mini-plate cutting operation.

Figure 9 shows the measurement locations on the plate surfaces for oxide thickness, nine on each side of the mini-plate. Figure 10 and Figure 11 show the results of the oxide-thickness measurement for plates MZ25 and MZ50, respectively.

Insert Figures 9–11.

The average oxide-layer thickness measurements for mini-plates MZ25 and MZ50 after irradiation were 2.6 and 3.2 μm , respectively. This oxide-layer thickness on the Zircaloy cladding was slightly smaller than for the pre-filmed aluminium clad plates irradiated in same capsules (which averaged 4 μm).

5.3 Metallographic Characterization

5.3.1 MZ25

Plate cross-sections, cut perpendicular to the long direction of the plates, were polished for metallographic observation. Figure 12 shows a montage of metallographic images that were taken of such a cross-section through the MZ25 plate. The direction in which the plate was oriented relative to the ATR core center is arrowed. The fuel at that end of the plate received a higher neutron flux and achieved a higher burnup. The burnup gradient across the width of the plate was 1.85 (max/min).

A higher magnification optical image of the interface is shown in Figure 13. The appearance of the fuel/cladding interface is evidence that bonding between the fuel and clad remained intact. However, no significant depth of interaction between the Zry-4 cladding can be observed optically (500x magnification) that might have been created during fabrication and/or irradiation. Fuel swelling, as is often noted by fission-gas bubbles near the fuel-foil/cladding interface, was minimal. Therefore, the swelling observed by plate-thickness measurement should be considered low and uniform for this plate geometry.

Insert Figures 12 and 13.

5.3.2 MZ50

Error! Reference source not found. 14 shows a high-magnification optical image of the fuel/cladding interface in plate MZ50. This is the width end, or edge of the plate that faces the ATR core centerline, so this part of the plate operated with the highest fission rate and at the highest temperature and fission density. No fuel/Zry-4 cladding interaction layer was found in the plate using optical metallography, the swelling was uniform, and the bonding between fuel and cladding appeared to be intact. Few or no fission-gas bubbles were visible in the fuel.

Insert Figure 14.

5.4 DISCUSSION

Several difficulties had to be resolved for the fabrication of these two U-7Mo monolithic mini-plates. An adequate strategy for handling different coefficients of thermal expansion of U-7Mo and Zry-4 was developed. This central feature of this strategy was not allowing significant cooling of the plate in between roll-bonding steps, using quick operating procedures until total welding/bonding of clad to fuel was accomplished. The hot co-laminated fabricated plates surely had residual stresses remaining at the interface, but no complications were noted in further

operations. The residual stresses were likely partially eliminated during the final polishing and in the irradiation field. Other problems that had to be resolved included the necessity to tightly fit the U-7Mo in the Zry-4 frame to avoid blistering.

Finally, a straight forward picture-and-frame process of hot-rolling and roll-bonding of Zry-4/ U-7Mo/ Zry-4 stacked, side-welded plates was successful. The steps of this process included the conformation of frame and covers of Zry-4 and the U-7Mo coupon, peripherally welding them together in a sandwich, hot rolling to a co-laminated fuel plate and achieving complete bonding, flattening, oxide removal and polishing, cutting and indenting. Since the hot roll bonding is performed at temperatures where the gamma phase is stable no metallurgical transformations should be expected, although short heating times are needed to avoid excessive growth of a fuel/cladding inter-diffusion layer and surface oxide on the cladding. The mechanical properties of Zry-4 allowed cladding thicknesses of 250 microns (10 mils) to be attained, as in MZ50, and thinner cladding could likely have been achieved.

The irradiation performance showed stable fuel swelling under the conditions tested similar to previous U-Mo irradiations and no evidence of bubble nucleation or growth of the U-7Mo/Zry-4 interlayers. Optical metallography indicated a very thin and uniform interaction layer between the fuel foil and the Zry-4 cladding. When compared to U-10wt%Mo monolithic fuel clad with aluminum and irradiated under similar conditions, a significant difference can be seen. Plate L2F030 was irradiated to $2.4\text{E}+21$ fissions/cm² as part of the RETR-6 experiment. Optical examination of this plate indicate interaction layers 5–10 µm thick and resulting delamination of the fuel and cladding on one side of the plate. Figure 15 shows a cross section through the width of the plate and delamination is clearly visible. Figure 16 shows a high magnification of the aluminium and U-Mo interface where an interaction layer and porosity have started to form.

5.5 Conclusions

The fabrication procedure, quality control tests and irradiation performance of monolithic U-7Mo fuel with Zry-4 cladding is a concept demonstrated at the mini-plate scale. The simple picture-and-frame technique was successfully used in this case without the need to introduce alternative, sophisticated methods. Successful irradiations of the resulting test plates, MZ25 and MZ50, in the RERTR-7A experiment opens the possibility of a new design concept with a currently understood fabrication technology. No problems were encountered so long as the thermal expansion mismatch (Zry-4 and U-7Mo) was accommodated during fabrication. Accommodation was provided by limiting the range of thermal cycles during hot rolling (not allowing the plate to cool between passes) and relatively low rolling temperatures (650–675°C). The interaction zone U-7Mo and Zry-4 resulting from fabrication was very small. The irradiation performance of the MZ25 and MZ50 test plates to 2.7×10^{21} f/cm³ and 2.3×10^{21} f/cm³, respectively, was acceptable, with low fuel swelling comparable to Al-alloy-clad plates.

5.6 References

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6. ACKNOWLEDGEMENTS

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8. FIGURE CAPTIONS

Figure 1. Bonded interface between U-7Mo and Zry-4. Optical metallography.

Figure 2. U-7Mo/Zry-4 broken interface after diffusion testing. The irregular surfaces may indicate that they were torn during cooling after being bonded by diffusion. SEM image.

Figure 3. Nominal dimensions of miniplate for a typical RERTR experiment.

Figure 4. Frame dimensions (in mm) for constructing the MZ25- and MZ50-stack sandwiches.

Figure 5. Positions where post irradiation plate thickness was measured.

Figure 6. MZ25 pre- and post-irradiation plate thickness.

Figure 7. MZ50 pre- and post-irradiation plate thickness.

Figure 8. Local fuel swelling versus local fission density

Figure 9. Schematic of oxide-thickness measurement locations, nine on each side.

Figure 10. Oxide thickness on plate MZ25 following irradiation.

Figure 11. Oxide thickness on plate MZ50 following irradiation.

Figure 12. MZ25 full-plate metallographic montage of a polished transversal cut. Arrow points to direction of ATR core center.

Figure 13. MZ25 metallographic cross-section showing fuel (bottom) and clad (top) bond line.

Figure 14. MZ50 fuel-plate metallographic cross-section showing hot end/edge of plate. Arrow points to direction of ATR core center.

Figure 15. Metallographic cross section of aluminum clad U-10Mo fuel plate with similar burnup.

Figure 16. Metallographic image of porosity forming in the aluminum U-Mo interaction layer.

9. FIGURES

Figure 1.

Figure 2

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

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Figure 11.

Figure 12.

Figure 13.

Figure 14.

Figure 15.

Figure 16.

9.1 Submission Checklist

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