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# Full Size U-10Mo Monolithic Fuel Foil and Fuel Plate Fabrication-Technology Development

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# FULL SIZE U-10MO MONOLITHIC FUEL FOIL AND FUEL PLATE FABRICATION-TECHNOLOGY DEVELOPMENT

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## ABSTRACT

Full-size U-10Mo foils are being developed for use in high density LEU monolithic fuel plates. The application of a zirconium barrier layer to the foil is performed using a hot co-rolling process. Aluminium clad fuel plates are fabricated using Hot Isostatic Pressing (HIP) or a Friction Bonding (FB) process. An overview is provided of ongoing technology development activities, including: the co-rolling process, foil shearing/slitting and polishing, cladding bonding processes, plate forming, plate-assembly swaging, and fuel plate characterization. Characterization techniques being employed include, Ultrasonic Testing (UT), radiography, and microscopy.

## 1. Introduction

U-10Mo based monolithic fuel plates are being developed for use in high power research and test reactors, as shown in Figure 1. Such plates consist of a metallic fuel foil having a bonded diffusion barrier-layer at the fuel-clad interface. Currently, a zirconium barrier layer is employed for the purpose of controlling UMo-Al interdiffusion at the fuel-meat/cladding interface during fuel plate fabrication and during irradiation.[1]. The cladding material utilized is Al 6061.

The fuel foil is prepared from a cast and machined coupon of U-10Mo via a hot “co-rolling” process. During the co-rolling process, a zirconium barrier layer, ~25μm thick, is bonded to each face of the ~0.3 mm thick U-10Mo fuel foil. Foils are subsequently cold rolled to the desired fuel meat thickness and sized to final dimensions via shearing or slitting.

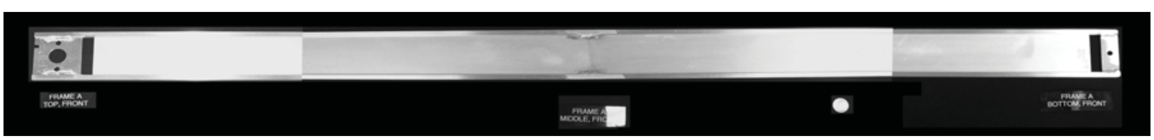



Figure 1. Monolithic fuel plate assembly containing two 57cm long fuel plates.

Currently, two processes for cladding monolithic UMo fuel foils are being developed at the Idaho National Laboratory (INL): (1) friction bonding (FB) and (2) hot isostatic pressing (HIP).[2] The FB process makes use of thermo-mechanical energy imparted via the application of a contacting rotary-tool. As the tool is traversed along the Al-foil-Al layup, down-force is applied to an extent that facilitates clad bonding. The HIP process involves the application of heat and pressure upon a hermetically sealed, evacuated sample canister containing a stack of cladding/fuel foil sheets.

The processing sequence developed at the INL for the preparation of U-10Mo monolithic foils having a Zr co-rolled diffusion barrier-layer is shown in Figure 2.

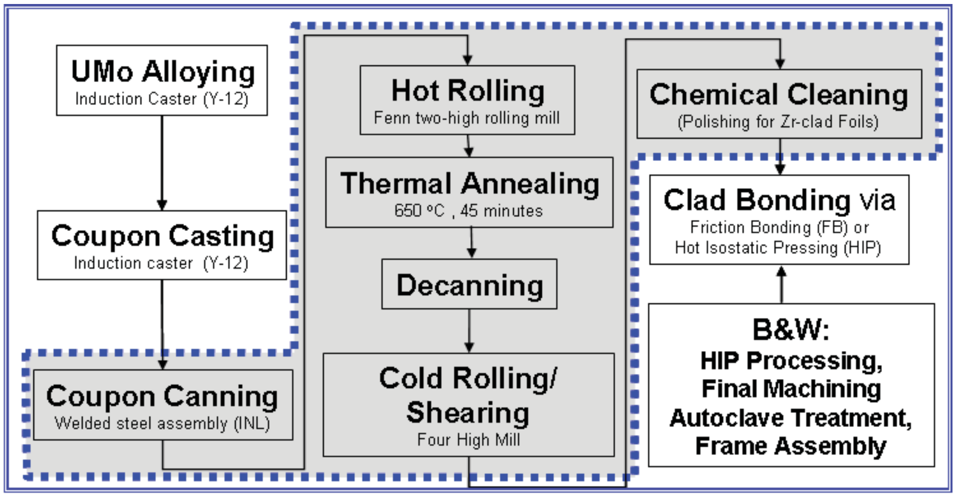



Figure 2. Monolithic fuel plate processing scheme.

## 2. Monolithic Fuel Foil Fabrication

The starting point for full size fuel foil fabrication at the INL is the preparation of cast U-10Mo coupons for co-rolling. Coupons were provided by the Y-12 National Security Complex, Oak Ridge, TN. Face-machined coupons, ~75 mm x 100 mm x 3.25 mm, were filed to remove sharp edges and chemically cleaned using a ~30% nitric acid solution, to remove surface oxide contamination.

Material preparation for the hot co-rolling process entails encapsulating a Zr-foil/ U-10Mo coupon/Zr-foil layup in a three piece carbon steel plate picture-frame assembly, as hown in Figure 3. A colloidal graphite paint “Neolube” was applied to the rolling assembly cover plates in order to establish “no-stick” surfaces; allowing the foil to be removed after co-rolling. The rolling assembly was edge-welded inside of an argon atmosphere glove box to produce a “canned” rolling assembly.

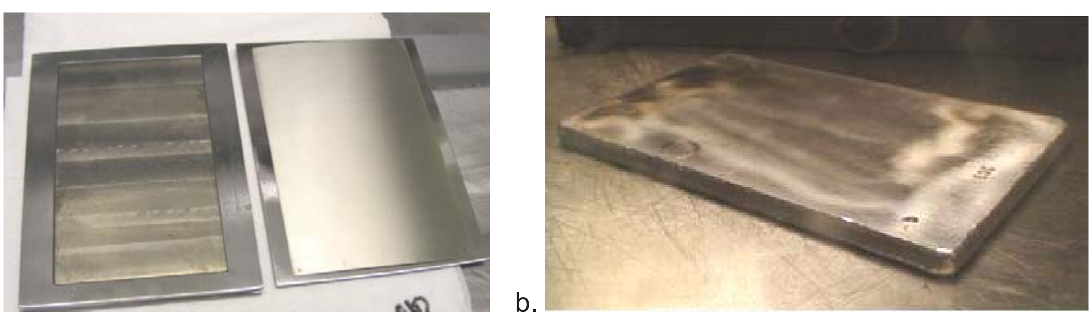
a.  b.

Figure 3. (a) Full size U-10Mo coupon hot rolling assembly lay-up, and (b) welding hot rolling assembly

Rolling assemblies are placed on edge (in a plate-rack) inside a preheated box furnace at 650°C for 30 minutes prior to rolling. The rolls on the FENN® two-high rolling mill were preheated overnight, prior to hot rolling, to 80°C using heating blankets.

The rolling schedule used was based on the thickness of the rolling assembly, which can be directly measured throughout the hot rolling process. The percent reduction is based on per-pass thickness reduction and limited to less than 100,000 lbs load force on the mill. The per-pass reduction range generally used was 5 to 20%. Assembly reheating, 5-15 minutes, was typically performed every 2-3 passes at 650°C. An example rolling reduction plot is shown in Figure 4.

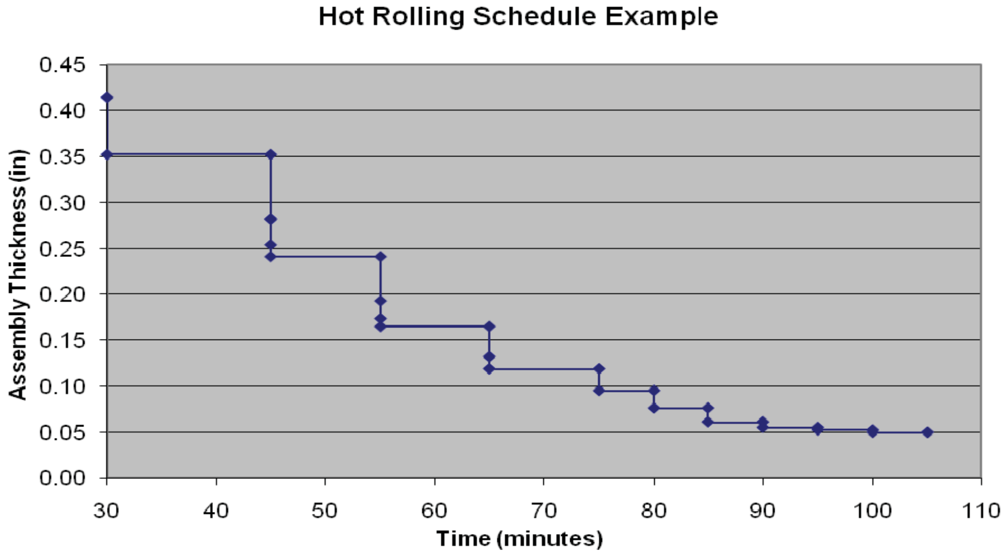



Figure 4. Plot of rolling assembly thickness versus time during hot co-rolling.

After hot co-rolling reduction was complete, the canister assemblies were placed back in the furnace at 650°C for 45 minutes. Heat treated foils were then de-canned by removing the perimeter of the rolling assembly using a hand-held power shear, as shown in Figure 5. Next, Zr bonded U-10Mo co-rolled foils were cold rolled to achieve final thickness using a four high rolling mill. This step was employed in order to precisely establish the fuel meat thickness, typically 0.38 mm, and to smooth out fuel meat thickness variations imparted via the hot co-rolling process. A cross sectional image of a co-rolled U-10Mo fuel foil after final cold rolling is shown in Figure 6.

a.  b. 

Figure 5. (a) Decanning of co-rolled assembly, and
(b) Zr co-rolled U-10Mo monolilthic fuel foil

Prior to foil sizing operations, foils are cleaned/polished using a paste comprising 30 μm diamond powder suspended in a water soluble binder. Polished Zr co-rolled foils were typically free of radiological contamination. Foil shearing was used to establish the final length and width of each fuel foil. Shearing was performed using either a bench-top shear or a hydraulic squaring-shear, depending on the length of the foil.

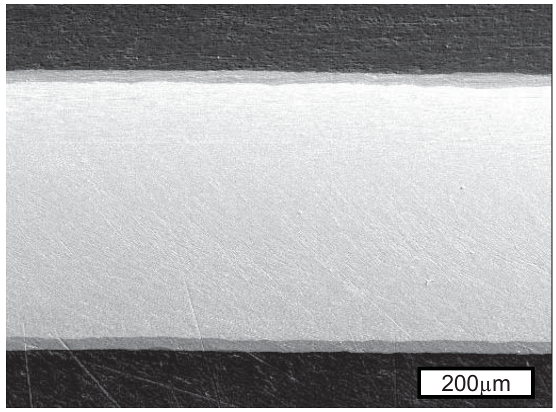



Figure 6. Cross sectional scanning electron microscope (SEM) micrograph of a Zr co-rolled U-10Mo fuel foil

## 3. Cladding Application

The cladding material used for both the HIP and FB processes was Al 6061 sheet stock supplied in the T6 condition. Two cladding sheets were prepared for each fuel plate assembly, i.e. a top/cover plate (~0.6 mm) and a bottom/pocket plate (~1.0 mm). Both sides of each cladding sheet were brushed using a stainless steel bristle brush mounted in a milling machine tool holder. A foil retention pocket was machined in the bottom cladding sheet to prevent foil shift during processing. For HIP plate processing, cladding sheets were additionally chemically cleaned using a sodium hydroxide bath, followed by a nitric acid dip, and finally a two-step rinse in cold then hot de-ionized water.

Cladding was bonded to the fuel foils using the Friction Bonding (FB) process developed at INL. The process utilizes a water cooled rotating tool configured in a commercial friction bonding workstation (Transformation Technologies, Inc., Elkhart, IN). FB run set-up consisted of laying up a cladding/foil "pack", comprised of the polished fuel foil and two sheets of 6061 aluminium. Overlapping bonding passes were performed on both sides of the clad/fuel/clad layup.

Fuel plate samples are HIP processed at the INL and also Babcock & Wilcox Nuclear Operations Group - Lynchburg. HIP processing assemblies consist of an evacuated stainless steel "can" containing clad/fuel-foil/clad plate layups; each layup being separated by a "strong back/steel plate" and Grafoil™ sheets. HIP can preparation has been previously reported.[3, 4] HIP runs were conducted at 560$^{o}$C for a period of 90 minutes and 100 MPa.

## 4. Fuel Plate Final Processing and Characterization

Following clad application operations, the fuel plates were non-destructively evaluated for clad/foil bonding and cladding thickness using an Ultrasonic Testing (UT) workstation. Once the initial cladding thickness over the fuel zone was established, an end mill was used to machine fuel plates to final thickness, 1.25 mm thick, and maintaining a minimum cladding thickness of 0.15 mm, over the fuel region. Once machined to thickness, final plate dimensions were established via shearing.

An oxide film "boehmite" was applied to dimensioned fuel plates using an autoclave treatment consisting of a four hour treatment at 185 °C and ~160 psi (1.1 Mpa) in pH 6-8 adjusted de-ionized water. Prior to autoclaving, fuel plates were chemically cleaned using the sodium hydroxide solution etching process described above; including the nitric acid dip and water rinse steps.

## 5. Development Activities

Over the course of the last four years, RERTR fuel plate sample size has increased from 25 mm x 100 mm, to 55 mm x 1100 mm. As such, efforts are underway to facilitate fabrication of full size fuel plates that are conducive to having a radius of curvature established via a “press-forming process”[5]. Supporting this objective are a series of on-going development activities including: (1) precise-width foil preparation using a slitter machine, (2) preparation of D U-10Mo surrogate HIP fuel plates for press-forming studies, (3) tooling and method development for a force-feedback or semi-automated fuel plate-to-rail swaging system, (4) demonstration of a digital radiography system for mapping the fuel meat thickness of in-process fuel foils and HIPed fuel plates, and (5) demonstration of a UT workstation for curved fuel plates.

## 6. Acknowledgements

Work supported by the U.S. Department of Energy, Office of Nuclear Nonproliferation and Security Affairs (NNSA) under DOE-NE Idaho Operations Office Contract DE AC07 05ID14517. This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

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