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UPDATE ON FRICTION BONDING OF MONOLITHIC U-MO FUEL PLATES

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ABSTRACT

Friction Bonding (FB), formerly referred to as Friction Stir Welding, is an alternative plate fabrication technique to encapsulate monolithic U-Mo fuel foils inside 6061-T6 aluminum alloy cladding. Over the past year, significant progress has been made in the area of FB, including improvements in tool material, tool design, process parameters, cooling capability and capacity and modeling, all of which improve and enhance the quality of fabricated fuel plates, reproducibility of the fabrication process and bond quality of the fuel plates. Details of this progress and how it relates to the observed improvements and enhancements are discussed. In addition, details on how these improvements have been implemented into the last two RERTR mini-plate irradiation campaigns are also discussed.

1. Introduction

Friction Bonding (FB), formerly referred to as Friction Stir Welding, is an alternative fabrication technique to encapsulate monolithic U-Mo fuel foils inside 6061-T6 aluminum alloy cladding [1]. The basis for the nomenclature change is two-fold. The first involves substitution of the term bonding for welding since welding implies movement of material across a boundary or interface in the traditional sense, with frictional heat providing softening of the material. For the current application, material movement, traditionally speaking, is not allowed, since this would result in perturbation of the monolithic foil. Thus, bonding implies that the process is similar to hot isostatic pressing (HIPing) in that successful encapsulation is on a micro-diffusion scale with frictional heat serving as a driving force. The second basis is similar to the first, but involves the term stir. Once again, since this term is not desirable in the conventionally used terminology, as stirring would disturb the fuel foil, it has been omitted, leaving just friction bonding.

Terminology aside, significant progress has been made in the area of nuclear fuel plate fabrication employing FB. This progress is evidenced by plates fabricated for the past two RERTR irradiation campaigns: RERTR-9A and -9B. RERTR-9A involved a detailed analysis of process parameters, the most being applied down-force, and the relationship with the monolithic fuel. RERTR-9B involved investigations into how the FB process dealt with a modified fuel interface, i.e. thermal spray or thin refractory metal sheets that serve as a diffusion inhibitor during irradiation [2].

2. Experimental Set-Up

Fuel fabrication for the RERTR-9A campaign involved placing a series of three 254 μm thick monoliths, each 8.26 cm long by 1.91 cm wide, in a staggered configuration. The bottom piece of 6061-T6 Al was nominally 8.64 mm thick, with milled pockets 279 μm deep to accommodate the foils. The top piece of 6061-T6 Al was nominally 6.10 mm thick. In the paper, "top" refers to the thin piece of cladding that is subjected to FB first, while "bottom" refers to the thicker piece of cladding that is subjected to FB once the top side is bound. The Al cladding is mechanically cleaned using a rotating wire brush on a milling machine to remove any significant oxidation. The monolithic fuel, composed of 58% ^{235}U – Mo, was chemically cleaned by immersion in nitric acid for a matter of seconds, followed by immersion in de-ionized water and drying. Monoliths were placed in the milled pockets immediately following cleaning. The top piece of cladding was placed on top of the monoliths, clamped in place, and the assembly was subjected to the FB process. The tool configuration remained unchanged as explained in previous papers [1,3]. Two different tool alloys were investigated, the first a low-thermal conductivity alloy, referred to as Alloy A and used in all previous campaigns, and a high thermal conductivity alloy, referred to as Alloy B. Process parameters remained largely unchanged, i.e. low rpm and high table feed rate, but applied down-force was allowed to be dictated by visual surface finish during the process. Four mini-plates were fabricated employing the Alloy A tool and three mini-plates employing the Alloy B tool for irradiation, along with a sufficient amount of DU-10Mo archive plates used for both destructive and non-destructive analysis, to be presented separately.

Fuel fabrication for the RERTR-9B campaign involved a similar fabrication sequence as that explained for the -9A campaign, except that foils were placed in a straight configuration as opposed to a staggered configuration. Only Alloy B was used in this configuration, since Alloy A has a larger and somewhat prohibitive history. The RERTR-9B campaign also included plates that had a thin thermal spray layer consisting of Al-2Si. The powder used for the thermal spray process was Al-12Si eutectic downblended with elemental Al to an Al-2Si composition. Cladding plates were prepared using the same process described above, followed by vacuum sealing until the thermal spray process was carried out. Two different thicknesses of thermal spray were investigated: 12.7 μm thick and 25.4 μm thick. These thicknesses were selected since previous PIE analysis suggests a Al recoil zone of 13.7 μm, meaning that the modifications for these plates would be roughly equivalent and double what PIE suggests is needed [4]. All other conditions and parameters were held constant, in addition to attempts to hold the applied down-force constant during the process. A target load of 46.7 kN was used.

Process outputs, including applied down force, coolant temperature above the tool face, coolant inlet and coolant outlet temperatures, were recorded for each fabrication experiment. Data was collected via a 66.7 kN load cell (HiTec Corporation) and Type K thermocouples (Omega Engineering) to an Agilent 34970A data acquisition unit at a frequency of 10 Hz. An example of data collected from an FB run is provided in Figure 1 for applied down force and coolant temperature above the tool face, and Figure 2 for the coolant inlet and coolant outlet temperatures.

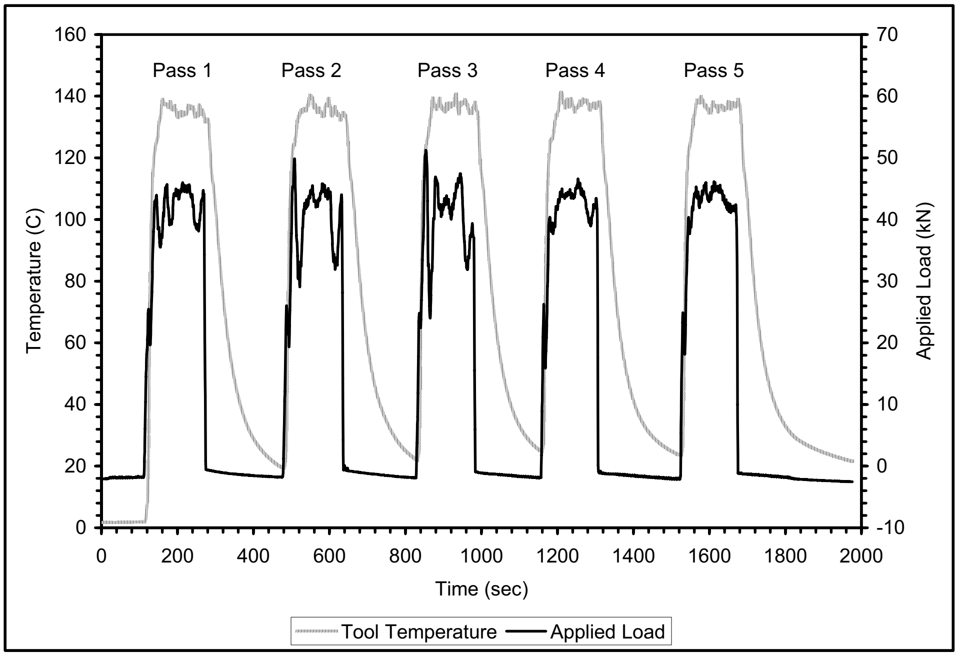

Figure 1. Typical data profile obtained from the load cell measuring applied down force of the tool and coolant temperature measured by the thermocouple placed directly above the tool face.

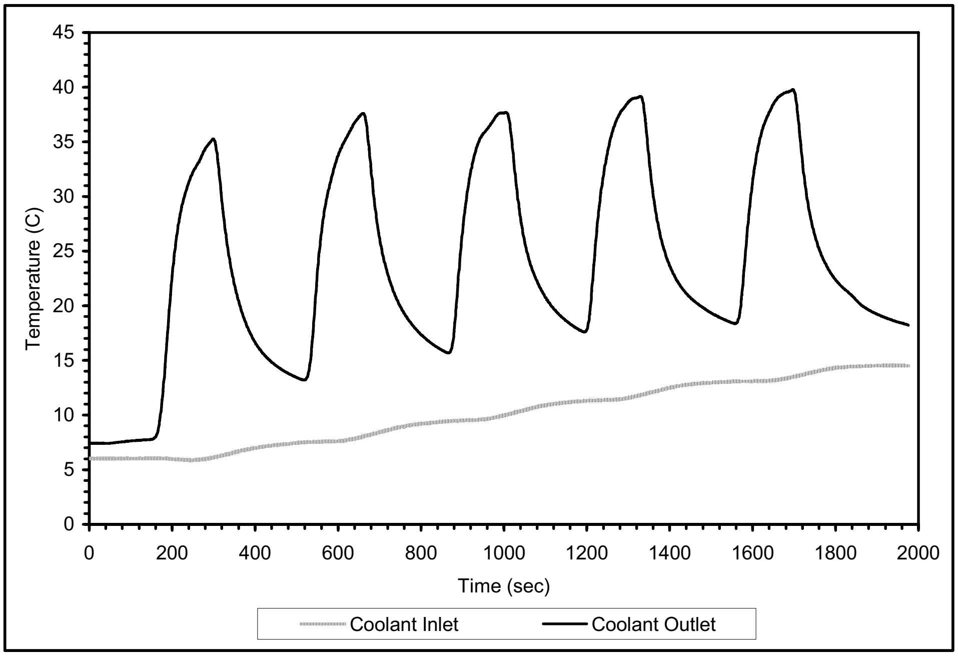

Figure 2. Typical data profile measured from in-line thermocouples for the coolant temperature into the tool and coolant temperature out of the tool.

3. Results

Ultrasonic test (UT) scans of the assemblies containing three HEU-10Mo mini-foils for the RERTR-9A campaign employing Alloy A and Alloy B faced tools are provided in

Figure 3. Observation of the top scan in Figure 3 (Alloy A) shows three relatively straight, intact and well bound mini-foils. The foil to the right of the figure shows some small pieces of fuel that have been carried out into the aluminum by the tool. Observation of the bottom scan in Figure 3 (Alloy B) shows three mini-foils with slightly more deflection in the direction of the bond passes. For the most part, the foils appear to be well bound, with the exception of a small area on the farthest end of the right foil. The left foil has a piece of fuel that has been removed and carried well out into the aluminum by the tool. Figure 4 shows the effect of tool thermal conductivity measured by a thermocouple placed in the coolant directly above the tool face. Observation of Figure 4 reveals that the average coolant temperature increases with the bond pass as a result of residual heat not removed from the cooling system, i.e. the ΔT of the coolant inlet and

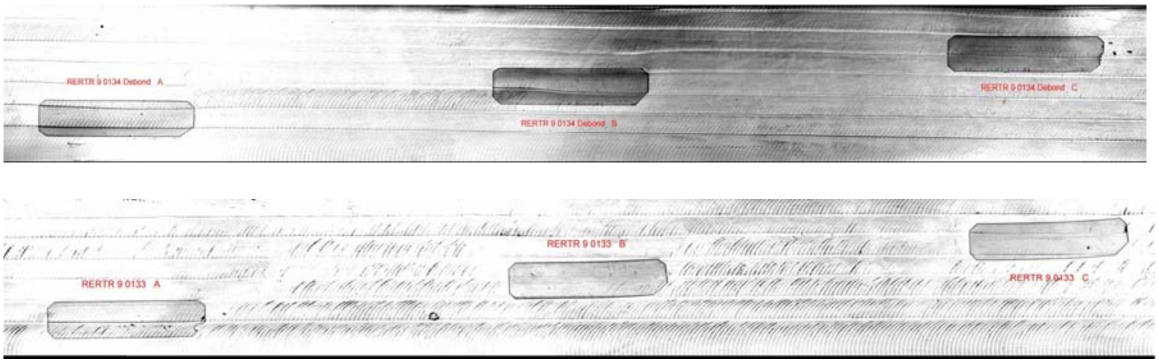

Figure 3. UT scans of assemblies fabricated employing a tool face from Alloy A (top) and Alloy B (bottom).

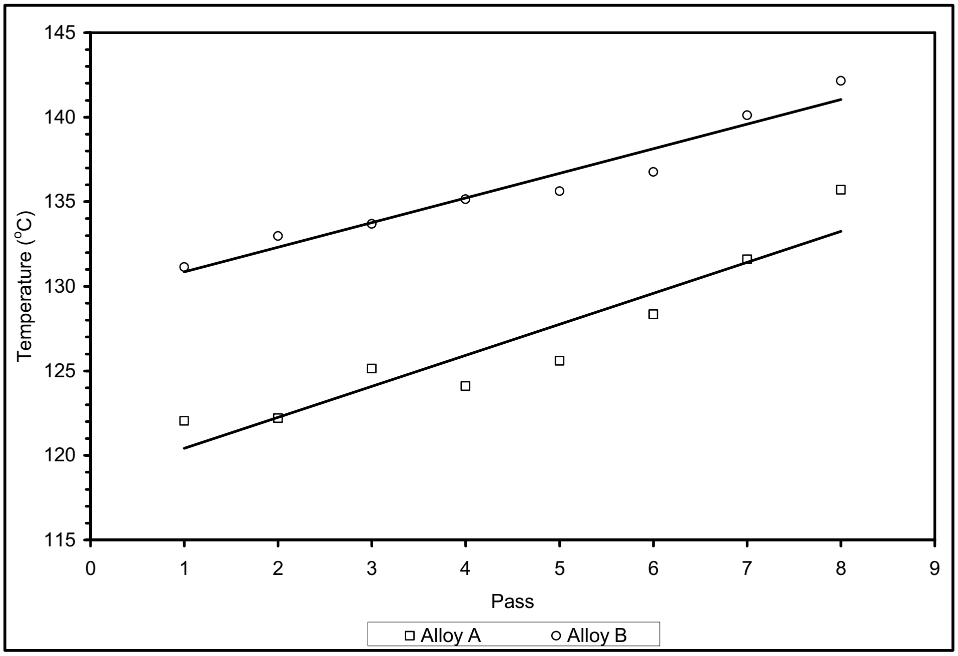

Figure 4. Average coolant temperature as a function of bond pass made on the top side of the fuel plate assembly as measured by a thermocouple placed in the coolant directly above the internal tool face.

outlet decreases with an increasing number of bond passes, albeit relatively small, <15°C. In addition, the figure reveals that Alloy B has a higher average coolant temperature relative to Alloy A, independent of the bond pass, on the order of 6-11C.

UT scans of the assemblies containing two HEU-10Mo mini-foils for the RERTR-9B campaign employing an Alloy B faced tool are provided in Figure 5. Observation of the figure reveals that the first HEU foil encountered by the tool is unacceptable. There are multiple small pieces removed from the upper edge of this mini-foil and a large section separated from the bulk foil at the bottom right corner. The second HEU mini-foil in the assembly reveals a significantly straighter foil than those produced for RERTR-9A. There is a single suspect debond region over the middle of the foil, but whether or not such defects are acceptable for fuel plates has yet to be determined. An SEM photomicrograph of a cross-section from a DU-10Mo archive fuel plate, fabricated in the same manner as those described above, is presented in Figure 6. Observation of the photomicrograph reveals that there is sufficient bonding between the fuel and cladding with no observable reaction layer, owing to the rapid temperature rise and decay of friction bonding.

An SEM photomicrograph of a typical downblended Al-2Si thermal spray coating on the 6061-T6 Al cladding is provided in Figure 7. Observation of the photomicrograph reveals that there is a significant amount of porosity in the thermal spray coating, but there appears to be an adequate mechanical bond between the coating and cladding, allowing transfer of the assembly, loading of the foil and ensuing fabrication with FB. UT scans of mini-foils fabricated employing an Alloy B faced tool with a 12.7 μm thick and a 25.4 μm thick thermal spray coating are provided in Figure 8. Observation of the

Figure 5. UT scans of an assembly fabricated employing a tool face from Alloy B for the RERTR-9B irradiation campaign.

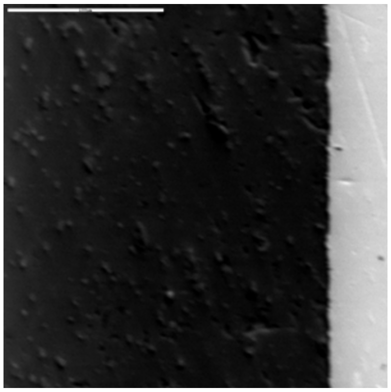

Figure 6. SEM photograph of a fuel-clad interface for a mini-plate fabricated for the RERTR-9B campaign employing an Alloy B faced tool. The dark region is the Al cladding and the light region is the monolithic fuel.

UT scans reveals that there is no residual porosity in the coating from thermal spray, and that the mini-foils are straight, uniform and well bound with no internal defects. In general, the thermal spray modification to the fuel-clad interface does not appear to have any significant impact on the FB process that needs to be addressed. Figure 9 shows an SEM photomicrograph and an EDX mapping of the monolithic fuel-clad interface with a 25.4 µm thick thermal spray coating after FB. Observation of the SEM photomicrograph reveals no significant debonds and no observable reaction layer between the fuel and cladding resulting from the FB process. Observation of the EDX elemental mapping reveals spherical Si regions appearing white in the map, along the interface of the fuel plate. There is no evidence that the Si has dissolved into solution during processing and diffused to the fuel-clad interface, suggesting that the process temperatures are not sufficient to do so.

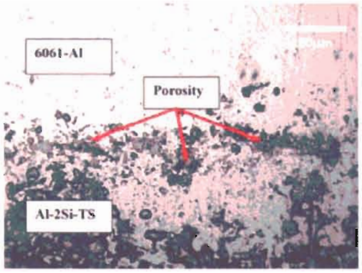

Figure 7. SEM photomicrograph showing typical downblended Al-2Si thermal spray coating on the 6061-T6 Al cladding, prior to FB.

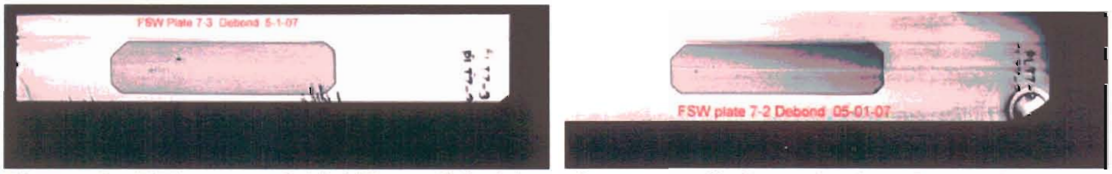

Figure 8. UT scans of Al-2Si modified interfaces, applied employing thermal spray, after FB with an Alloy B faced tool for coatings 12.7 µm thick (left) and 25.4 µm thick (right).

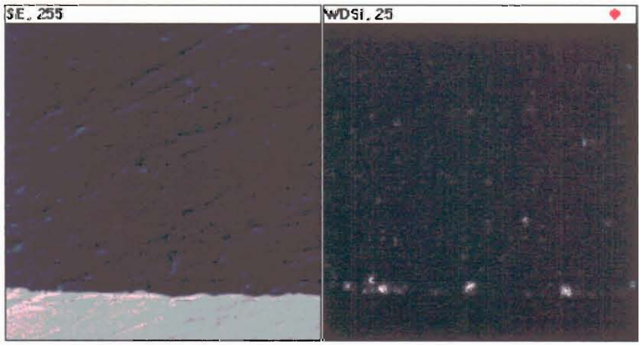

Figure 9. SEM photomicrograph (left) and EDX elemental mapping (right) of the monolithic fuel-clad interface of a 25.4 µm thick Al-2Si thermal spray coating after FB. The dark region is the Al cladding and the light region is the monolithic fuel.

4. Discussion

Mini-plates fabricated for the RERTR-9A irradiation campaign employing two different tool face materials were relatively successful. Motivation for fabricating plates employing two different tool face materials was initiated by preliminary pull tests of previously fabricated archive DU-10Mo mini-plates [5,6]. Results of these preliminary pull tests are provided in Figure 10. These tests revealed that the strength of the bond normal to the fuel-clad interface for Alloy A was surprisingly low, whereas that of Alloy B was on par with the hot isostatic pressing (HIP) method. These results seemed to be confirmed by PIE examination of the RERTR-7 irradiation campaign, from which all FB plates were fabricated employing an Alloy A faced tool. Plates in this campaign de-laminated during PIE metallographic sample preparation, not during irradiation, but the fact that bond strength was significantly affected by tool material warranted further investigation [7]. The RERTR-9A campaign provided an ideal opportunity to investigate the relationship of bond strength and tool material in a side-by-side environment. It has been hypothesized that the dissimilarity in bond strength as a function of tool material is a direct result of thermal conductivity of the tool, and thus the amount of load, and thus temperature, that can be applied for a given tool material. The effect of thermal conductivity in the tool is observed in Figure 4, where the higher thermal conductivity material (Alloy B) correlates to a higher measured coolant temperature, since more heat is being conducted away from the bond surface and into the coolant for a given load. One drawback of the RERTR-9A FB fabrication campaign was the staggered foil layout that ultimately resulted in foils that had a counterclockwise deflection as a result of the tool rotation. Mini-plates containing foils with such a deflection could contain additional and undesired residual stress that could potentially contribute to de-lamination of the fuel-clad interface, either during irradiation or PIE metallographic sample preparation. The hypothesis behind this observation is that since all three foils were not clamped down at the same time during the process, the mini-foils may have had a tendency to come out of the milled pocket, resulting in the counterclockwise deflection as the tool passed over the foil. This hypothesis is proved by the fact that the deflection worsens from the first foil (on the left) to the last foil (on the right), as the first foil is the first to be clamped down and subjected to the FB process, while the last foil is the last to be clamped down. The observed effect is much less pronounced with the Alloy A tool material than the Alloy B tool material, most likely because of higher internal temperatures with the Alloy A material, meaning that the aluminum is softer and more plastic thus being more capable of deforming around the foil.

Consequently, results from the RERTR-9A campaign gave rise to the modified fabrication configuration, i.e. fewer mini-foils in a fabrication assembly placed in a straight line, so that all mini-foils could be clamped down and subjected to the FB process at the same time, resulting in more uniform mini-plates. This configuration also permitted better control over the process parameters than did the staggered configuration. As such, effects of the process parameters on the resultant mini-plate were revealed, especially in terms of the applied load. This fact is illustrated by the left foil presented in

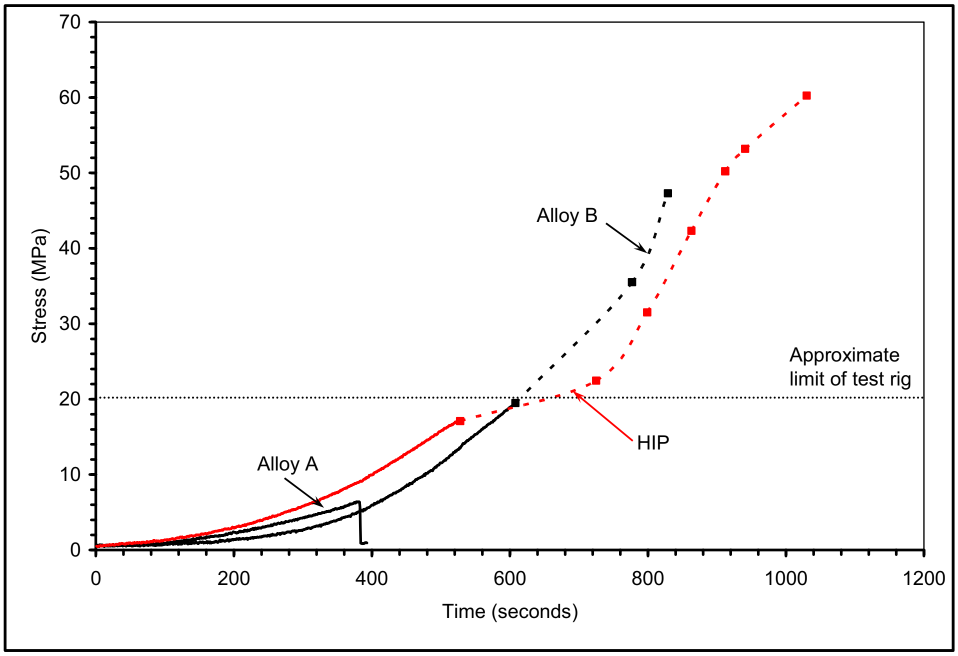

Figure 10. Normal bond strength of FB fuel plates employing Alloy A and Alloy B faced tools and the HIP process.

Figure 5 that has obviously been disturbed by the tool face, whereas the right foil, placed only 20.3 cm away from the left foil, does not experience any perturbation. Average applied load was found to significantly increase over the edge of the right foil on the bottom side, while the other passes were much closer to the target load, as shown in Figure 11. Such a high applied load, i.e. >53.3 kN, and large standard deviation over the pass results in destruction of the mini-foil and the “halo” effect observed at the top edge of the mini-foil. This effect has also been observed with basic tungsten particle tracer tests for loads of ≥53.3 kN, and will be presented in a future paper. When the applied load was held closer to the target load of 46.7 kN with smaller deviations, better success with mini-plate fabrication was obtained.

Finally, results of the modified, Al-2Si thermal spray fuel-clad interface were encouraging, but refinement of the method is required. The interface modification did not affect the FB process or bond integrity as determined by UT scans. However, the FB process does not provide sufficient kinetics to promote diffusion of Si to the fuel-clad interface owing to the much more rapid temperature rise and decay when compared to the HIP process. As a result, since the downblended Al-2Si feedstock was not homogenized prior to thermal spray, particles of Al-12Si eutectic are observed at the fuel-clad interface, evidence by the light regions in Figure 9. Potentially, coverage of the fuel during irradiation may not be sufficient to inhibit reaction layer formation if the Al-12Si particles have a large distance between them. This hypothesis, however, can not be proved or rejected until PIE is performed on these plates. Nonetheless, modifications to the thermal spray process are currently underway to ensure sufficient coverage over the fuel after fabrication and during irradiation. These modifications will be incorporated into upcoming full-size plate tests and future mini-plate irradiation campaigns.

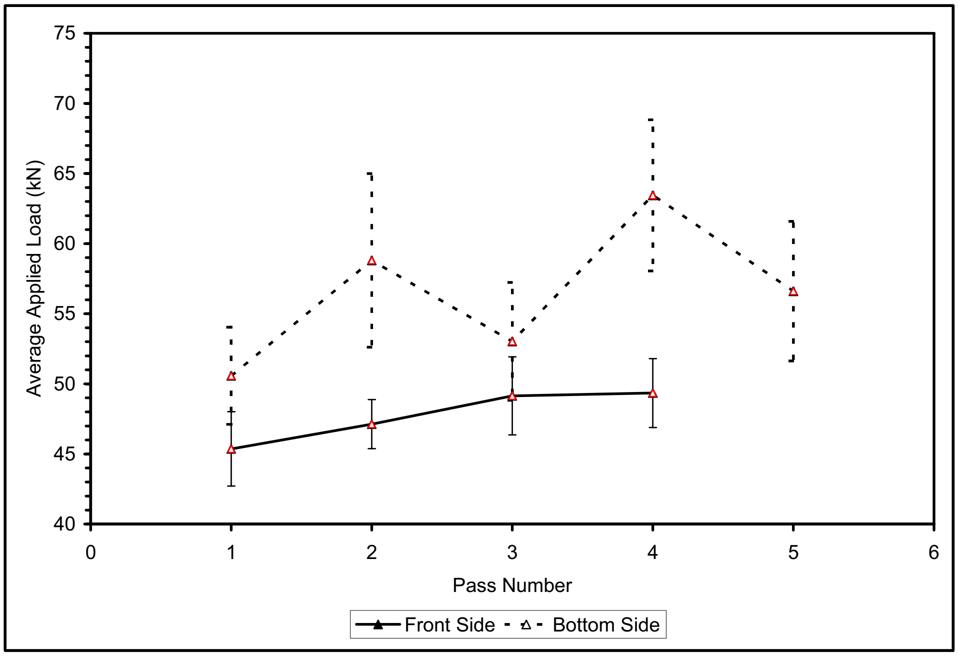

Figure 11. Average peak load as a function of pass over the fuel foil for the top side (solid line) and bottom side (dashed line).

5. Conclusions

The RERTR-9A and -9B mini-plate irradiation campaigns have provided an opportunity to better understand the FB process and improve upon previously employed fabrication concepts of the formerly referred to FSW process. A number of mini-plates have been fabricated to statistically validate a number of parameters, including FB tool face material, applied load, fabrication assembly configuration and a modified fuel-clad interface, in these two irradiation campaigns. PIE results of these campaigns will aid in a more educated selection of process and fabrication parameters for full-size plate fabrication. These slections will ultimately aid in downselection of the fabrication process and whether or not and which type of fuel-clad modification is employed during fabrication for the RERTR program.

6. Acknowledgements

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