Demonstration of Friction Stir Welding (FSW) Technology for Packaging of Used Nuclear Fuel – 15025

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ABSTRACT

With uncertainty surrounding the disposal of US Used Nuclear Fuel (UNF), the nuclear industry is making an effort to identify an interim storage solution. One of the alternatives is to simply manage UNF on-site until a permanent repository can be established – extended storage. In an effort to provide a technical basis for extended storage, the Department of Energy (DOE) performed a gap analysis identifying several issues that need to be addressed. One of the issues relates to the performance of the UNF dry storage container (DSC). DSC container welds (fabricated using conventional fusion welding processes) are sensitive to Stress Corrosion Cracking (SCC), and their extended-term performance is questionable.

Fluor, the Pacific Northwest National Laboratory (PNNL) and the Savannah River National Laboratory (SRNL) believe that Friction Stir Welding (FSW) technology may be able to address the DSC issue. The Fluor team collaborated on a project to demonstrate feasibility of FSW for DSC packaging (closure-welding). This paper reports on a 2-year project in which FSW process conditions were established (for DSC container materials and dimensions) and used in the preparation of mechanical and corrosion specimens for testing and evaluation. In addition to FSW test specimens, fusion welded specimens were prepared and tested in like manner for comparative purposes. The results show excellent mechanical properties (meeting construction code requirements) and significant improvement in corrosion performance – over the fusion welded specimens.

It is believed these findings will be of significant value to efforts underway to provide a technical basis for DSC extended storage performance. FSW technology appears to be an acceptable alternative or candidate process, capable of addressing the SCC sensitivity issues associated with fusion-welded DSC fabrication welds.

In addition, as an alternative to on-site, extended storage of UNF, the DOE has proposed the development and construction of a Consolidated Interim Storage Facility (CISF). UNF would be accepted from the many, local sites for consolidation at one or more CISFs until a permanent repository could be established. A recent CISF study indicates that UNF currently packaged into DSCs will likely be re-packaged into containers suitable for permanent storage. The study also indicates that re-packaging is best performed under water in a pool. FSW technology has several specific advantages for this application, 1) because it utilizes machine-tool equipment, a welding station can easily perform a cutting operation, and 2) FSW has been successfully demonstrated capable of joining container materials under water.

INTRODUCTION

With uncertainty surrounding the disposal of US Used Nuclear Fuel (UNF), the nuclear industry is making an effort to identify an interim storage solution. One of the alternatives is to simply manage

UNF on-site until a permanent repository can be established – extended storage. In an effort to provide a technical basis for extended storage, the Department of Energy (DOE) performed a gap analysis identifying several issues that need to be addressed. One of the issues relates to the performance of the UNF dry storage container (DSC). DSC container welds (fabricated using conventional fusion welding processes) are sensitive to Stress Corrosion Cracking (SCC), and their extended-term performance is questionable.

Fluor, a global Engineering, Procurement and Construction company, has significant experience with packaging of radioactive materials into containers and believes that a potential solution to poor DSC weld corrosion performance is to fabricate the containers using Friction Stir Welding (FSW) technology. FSW is a relatively new, solid-state welding process that can produce consistent, high-quality welds in the materials of construction currently specified for DSC container fabrication. To demonstrate FSW technology for this application, Fluor assembled a project team to include the Pacific Northwest National Laboratory (PNNL) and the Savannah River National Laboratory (SRNL). The PNNL has an experienced staff of researchers with over 40 years of combined research experience in FSW technologies. Facilities include one of the largest gantry style “high precision spindle” FSW machines in North America. The SRNL has significant experience and facility capability necessary to evaluate / assess corrosion performance of the materials and fabrication processes associated with DSC fabrication, to include FSW fabrications.

This paper reports on a 2-year project in which FSW process conditions were established (for DSC container materials and dimensions) and used in the preparation of mechanical and corrosion specimens for testing and evaluation. In addition, fusion welded specimens were prepared and tested in like manner for comparative purposes. The results show excellent mechanical properties (meeting construction code requirements) and significant improvement in corrosion performance of the FSW specimens when compared to the fusion-welded specimens.

It is believed these findings will be of significant value to efforts underway to provide a technical basis for DSC extended storage performance. FSW technology appears to be an acceptable alternative or candidate process, capable of addressing the SCC sensitivity issues associated with fusion-welded DSC fabrication welds.

PROJECT WORK

Project Description

The overall project is multi-phased and consists of the following elements:

Phase I	Process Development and Weldment Characterization – Mechanical and Corrosion Performance
Phase II	Fabrication of DSC Mockup Containers using the Developed Process Conditions
Phase III	Demonstration of DSC Container FSW Weld Start / Stop, Repair of DSC Fusion Weld Defects and Healing of DSC Fusion Weld HAZ – Sensitized Material
Phase IV	Characterization of DSC FSW Weld Stress Corrosion Cracking Performance

This paper reports on Phase I activities and describes FSW weld process (weld parameters) development and characterization activities along with mechanical and corrosion test protocols and results. In addition, test specimens using a standard DSC fusion welding process (GTAW) were prepared and tested for direct comparative analysis to the FSW specimens. All test coupons were welded using Type 316L stainless steel plate material and joint configuration common to current DSC container designs.

The development approach consisted of identifying process conditions required to produce sound (consolidated) welds in the test materials – soundness was characterized through metallographic evaluation and visual examination. Having established a Process Window (parameter mapping) for making sound welds, an iterative process to isolate preferred corrosion properties within the window was conducted. Selected parameter conditions were evaluated for corrosion performance and based on their results, other conditions (suspected to further improve corrosion results) were identified for additional evaluation. This iterative process led to the identification of FSW process conditions that produced significantly improved corrosion performance, when compared to that of the fusion-welded specimens.

The weld process development and preparation of weld coupons was conducted at the PNNL. All corrosion testing and evaluation was performed at the SRNL.

Phase I

Task 1: Development of Robust Process Conditions / Window for FSW Joining of 316L Material

A process window was developed for which multiple combinations of welding parameter sets produced a weld that resulted in 100% consolidation with no volumetric defect in the cross section or visual defect on the crown or root of the weld. A range of process parameters, including weld speed, tool rotation and forge force were evaluated for their ability to produce defect free welds. Additionally, several other criteria were considered in the determination of an appropriate weld window, including tool overload (no more than 2000 lbs. force in the x direction) and weld stability roughly measured by stability in the load output plots made during welding.

Numerous iterations of tool design, pin length, and weld process parameters were experimentally investigated. Once the criterion for stable weld loads and good surface appearance were met, the coupons were sectioned for metallographic examination and evaluated for volumetric defects. Weld conditions that produced wormhole or other volumetric defects were designated outside the acceptable process window. In addition, weld conditions that produced a significant amount of second phase particles (coarse carbides) in weld micrographs were also defined as outside the acceptable window.

Figure 1 represents the process window for which acceptable welds, as defined above, were made. The process space defined by this window was developed using a specific tool design and a specific forge force (33.4 kN). The window (RPM and IPM) is a 2-dimensional representation of process space that is actually multidimensional. Other factors such as tool load or forge force can be added as other axes. The process window shown here can be thought of as the RPM / IPM slice through the process space at a fixed forge load. Within limits, other tool designs and forge loads will produce

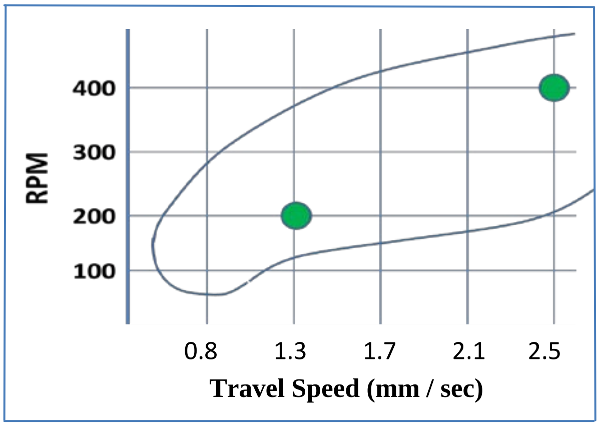
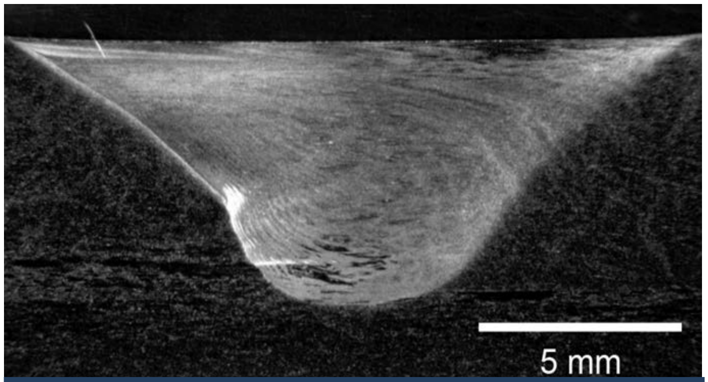


Figure 1. Process parameters that produce fully consolidated welds using the selected tool design and 3402 kg forge force fall within the open boundary above. Circled conditions represent welds subjected to mechanical and corrosion testing

different RPM / IPM process windows.

Figure 2 is a photomicrograph of a weld made within the window showing full consolidation and good surface finish.



All welds made during Task 1 weld trials were done under fixed weld process conditions that did not change during the course of the nominal 203 mm long welds. The parameters of RPM, IPM and Forge force were held steady during the full length of the weld (after a short startup sequence from the weld start). Weld temperature profiles recorded from a thermocouple embedded in the tool indicate that although adjustable parameters were held constant during any given weld, weld temperature fluctuated over the length of the weld – See Figure 3. Under some process conditions, the weld would begin at a relatively high temperature (900C) and then cool over the length of the weld; other conditions would cause the temperature to increase. These temperature fluctuations are the result of changing boundary conditions and were noted to be more pronounced near the edges of the process window.

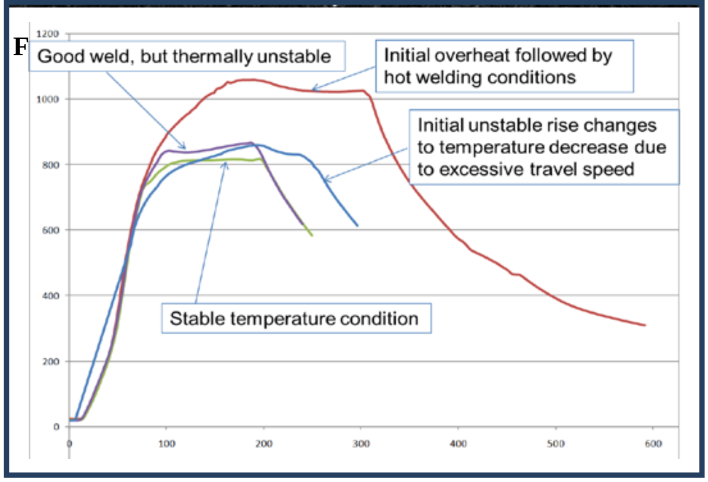


Figure 3. Weld Temperature Fluctuation

Weld conditions that led to excessive carbide formation, a phenomenon associated with austenitic stainless steel, were defined to be outside the window. These conditions or parameters were those that produced the highest temperatures - over 1000 C. A cross section of one of these welds (Figure 4) shows a zone of coarse 2nd phase particles that develop near the bottom on the advancing side of the weld nugget. This 2nd phase particle had an EDS signature very high in chrome

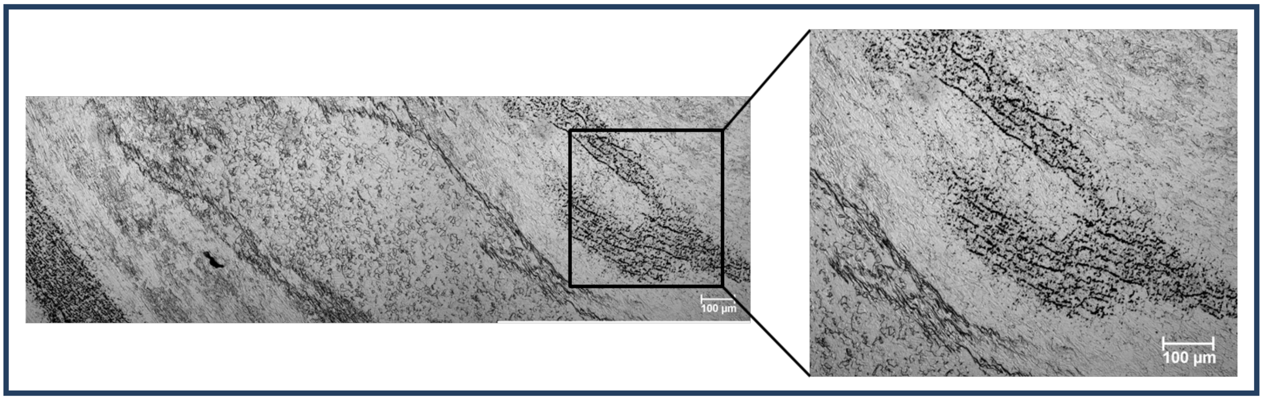


Figure 4. Chrome Carbide Phase

and is suspected to be a Cr-carbide phase. Coarse carbides of this morphology are commonly identified as sigma phase and considered to be deleterious to corrosion performance due to the Cr depleted zones that occur near them.
Using the criteria of full consolidation, stable weld loads, and minimum 2nd phase formation, two weld conditions were selected for additional testing (200 RPM, 3 IPM and 400 RPM, 6 IPM). Both conditions showed stable weld loads in the X and Y directions, full consolidation, smooth and flat weld crowns, and good penetration to the bottom of the joint. Both welds were run in load control with a Z-axis load set point of 33.4 kN. It was decided to evaluate these two conditions because they represented two different regions of the weld window and produced significantly different weld temperatures. Figure 5 shows the temperature profiles of the selected weld conditions.

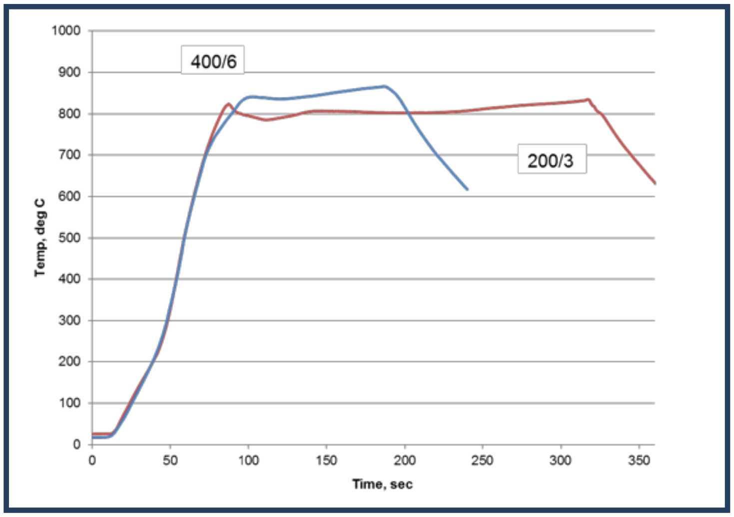


Figure 5. On average the 400/6 welds produced temperatures from 850 to 910 C, and the 200/3 welds averaged from 790 to 850 C.

Several additional coupons using the 200/3 and the 400/6 conditions were welded. Transverse tensile and corrosion specimens were prepared from these coupons. The tensile specimens were tested (Figure 6), meeting code-specified weld qualification requirements and the corrosion specimens were forwarded to the SRNL for corrosion evaluation.

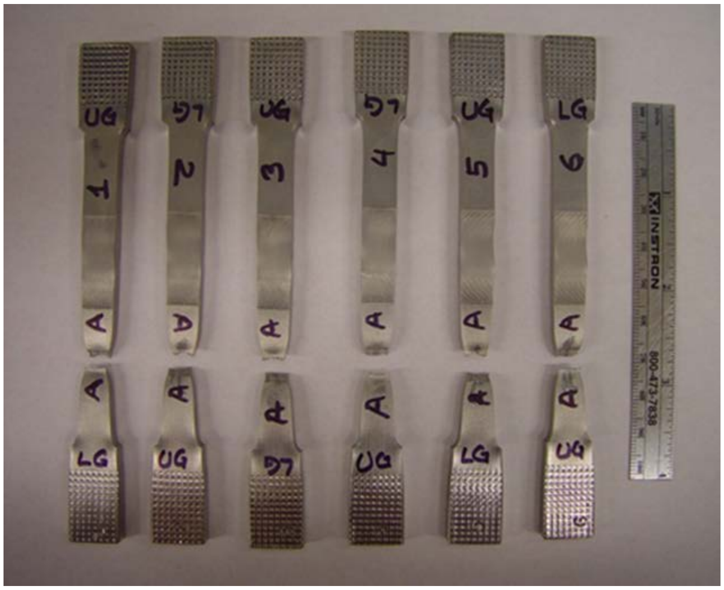


Figure 6. Transverse weld tension testing revealed all specimens failed in the base metal.

<u>Task 2:</u> Corrosion Evaluation of Task 1 Developed Process Conditions

The corrosion specimens noted above were sent to SRNL for evaluation. FSW Coupons representing the lower temperature weld condition (200/3) were identified as Low Heat Input (LHI) and the higher temperature coupons (400/6) were identified as High Heat Input (HHI). In addition, a third set of coupons, prepared using a standard GTAW fusion welding process, were submitted for evaluation to provide comparative analysis.

Corrosion evaluation consisted of performing electrochemical measurements, including: (1) open circuit potential (OCP) monitoring, (2) linear polarization resistance (LPR) scans, and (3) cyclic potentiodynamic polarization (CPP) scans. Figure 7 is a plot of Corrosion Rate [in mils per year (mpy)] vs time of exposure to an aggressive corrosion media; corrosion rate is calculated from LPR scans. The plot shows that corrosion rates for the GTAW and HHI welds are similar. Corrosion rates for the LHI weld however, varied considerably from above 35 mpy (measured from the same weld) to a much lower rate.

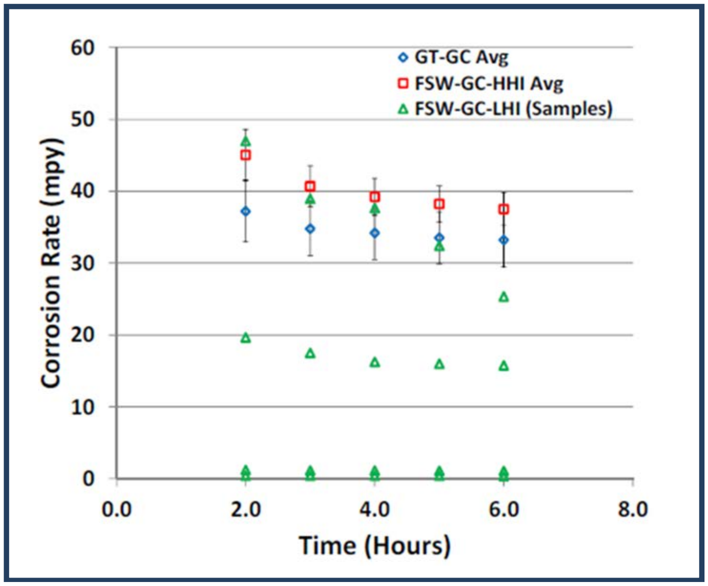


Figure 7. General corrosion rates for the HHI, LHI and GTAW weld specimens.

This same trend was seen in the CPP scans. CPP scans were performed to evaluate localized corrosion performance. CPP subjects specimens to conditions that can initiate localized corrosion, using high electrochemical potential to disrupt the passive layer. As the potential returns to zero, the ability of the passive layer to heal can be measured. CPP scans for the LHI specimens exhibited significantly different behavior from the GTAW and HHI specimens, See Figure 8. These specimens showed an active-passive transition that was much less pronounced than for the GTAW and HHI specimens. The LHI specimens also showed negative hysteresis where the current was lower during the reverse scan indicating a very stable surface.

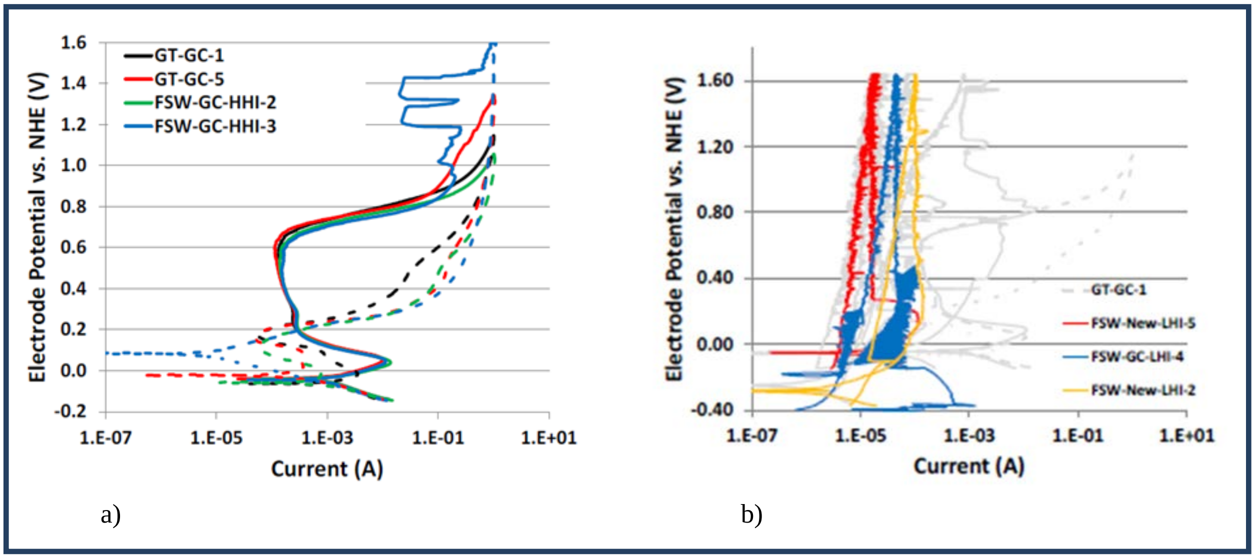


Figure 8. a) CPP of GTAW and HHI scans, b) CPP of LHI scan, showing a very a stable and passivated surface.

Differences in corrosion behavior can be seen in the photos in Figure 9. In the top photo, the GTAW specimen, the weld appears to be relatively free of pitting – this is due to alloying from the filler material making the weld more noble than the base material. The middle photo, the HHI specimen, shows pitting over the entire surface (FSW is an autogenous process). The LHI photo displays very little pitting which is corroborated by the LPR and CPP scan data.

The variable corrosion rate of the LHI specimens when compared to the HHI specimens (shown in Figure 7), led to speculation that there may be a weld temperature threshold, below which corrosion mechanisms are inhibited. In both the LHI and HHI coupons the temperature recorded increased substantially over the length of the weld. It was hypothesized that some of the LHI test specimens could have been cut from regions of the weld that experienced temperatures below this speculated corrosion threshold. Weld temperatures from 790C to 850C were seen in the LHI weldments.

To test this hypothesis, a second set of weld coupons were prepared in which process conditions were developed to maintain weld temperatures below 780C.

Task 3: Optimization -Weld Temperature Control for Low Corrosion Rates

Process conditions were developed that produced "low" and stable weld temperatures over the length of the weld. Coupons were prepared (identified as New LHI), in which weld temperatures were held below 780C. Specimens from these coupons were sent to the SRNL for repeat corrosion evaluation. The Figure 10 plot shows the corrosion performance of the New LHI specimens as calculated from the LPR scans. The corrosion rate is consistent and below 1 mpy, which is significantly lower than that of the GTAW and HHI welds reported previously.

Phase I Conclusions

Phase I objectives were to demonstrate feasibility of FSW technology for the joining of common DSC materials using a standard joint design, along with weldment characterization of mechanical

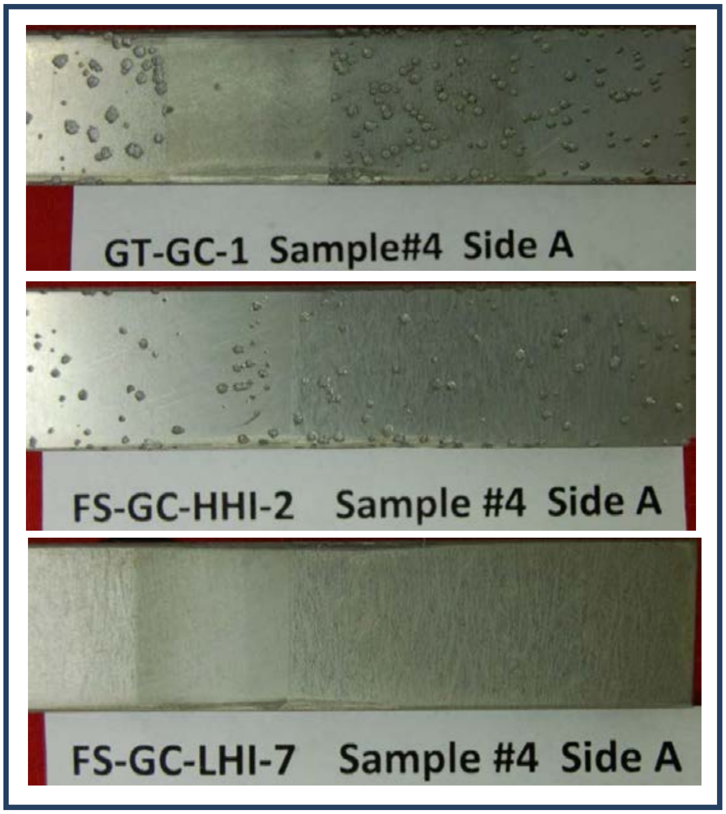


Figure 9. CPP Corrosion Specimens

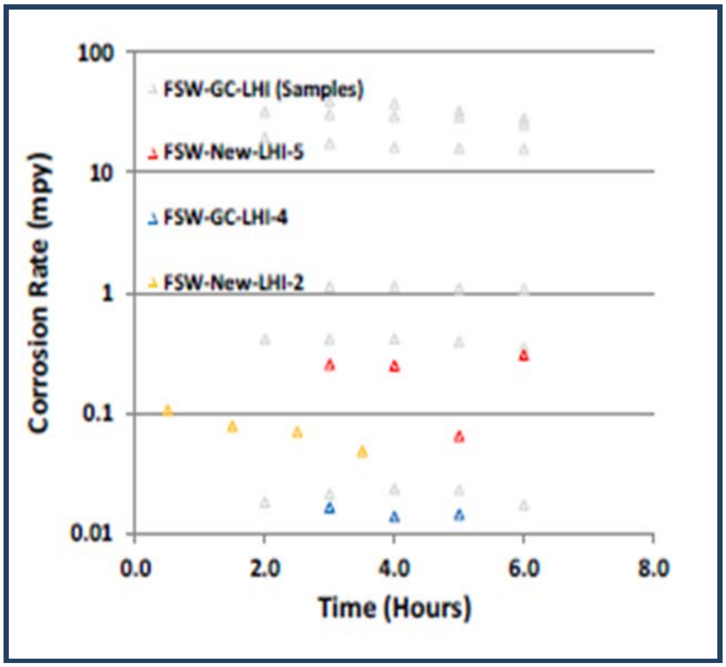


Figure 10. General corrosion rates for the New LHI weld specimens.

and corrosion performance. In addition, comparison to current DSC fusion welding processes was to be evaluated. Conclusions are summarized as follows:

1. FSW welds met code-required mechanical properties, and
2. After some weld process optimization, FSW weld performance (general and localized) was shown to perform significantly better than that of current DSC fusion welding processes (GTAW).
3. General and localized corrosion behavior can have a significant influence on the propensity for SCC to occur (in DSC weldments). The corrosion results observed herein would suggest that results of the Phase IV SCC evaluation will also show a much improved performance over current DSC welding processes.

DISCUSSION

As described in the Introduction, industry is preparing to store UNF locally (at commercial nuclear facilities) for a much longer term than originally planned; much of the current fuel is being stored dry, in DSCs. A technical basis to support this "extended", dry storage is being prepared. One of the primary challenges to this basis is the corrosion performance of current DSC welds, which are fabricated using conventional, fusion welding processes. These welds are sensitive to SCC and there is significant uncertainty about their long-term performance. The Nuclear Regulatory Commission released an Information Notice in 2012 [1] identifying through-wall failure of austenitic stainless steel (same materials used for DSC fabrication) components resulting from SCC.

Current efforts to establish this technical basis center on the characterization of atmospheric exposure, residual weld stress and DSC temperatures. This however, will at best be a very difficult task and may prove unfeasible. As a potential solution to the DSC weld issue, the authors of this paper believe that FSW technology may provide suitable answers.

The overall objective of the multi-phase project described above, is to demonstrate feasibility of FSW technology to produce DSC welds that provide acceptable, long-term corrosion performance – necessary to support extended storage requirements. At the conclusion of this project, there should be sufficient data and understanding to warrant commercialization activities necessary to qualify / certify FSW for this application. The Phase I results, reported herein, provide good reason to believe that the overall project objectives can be met. Work is currently underway for Phases II and III and Phase IV is scheduled to begin mid-2015.

A commercially qualified FSW process (assuming weld corrosion performance meets storage requirements) could potentially benefit the following UNF container fabrication activities:

1. New DSC fabrication – in addition to required corrosion performance, FSW offers significant economic and worker safety advantages over conventional welding processes (Phases I, II and IV),
2. FSW could potentially be used to repair corrosion defects and remediate SCC sensitive microstructures in current DSC welds (Phase III), and
3. Repackaging of UNF from existing DSC into disposal containers (for placement into a national repository). The DOE has proposed development and construction of a Consolidated Interim Storage Facility (CISF). UNF would be accepted from the many, local sites for consolidation at one or more CISFs until a permanent repository could be established. A recent CISF study indicates that UNF currently packaged into DSCs will likely be re-packaged into containers suitable for permanent storage. The study also indicates that re-packaging is best performed under water in a pool. FSW technology has several specific advantages for this application, 1) because it utilizes machine-tool equipment, a

welding station could easily also perform a cutting operation, and 2) FSW has been successfully demonstrated capable of joining container materials under water.

CONCLUSION

Phase I work is complete and is concluded to have successfully met the stated objectives. Phases II, III and IV work should continue. Industry is invited to consider the work reported herein and how FSW technology may be used to help establish a technical basis for the extended storage of UNF.

REFERENCES

[1] US NRC Office of Nuclear Material Safety and Safeguards, *Potential Chloride-Induced Stress Corrosion Cracking of Austenitic Stainless Steel and Maintenance of Dry Cask Storage System Canisters*, NRC Information Notice 2012-20, November 14, 2012.