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Light Water Reactor Sustainability Program:

Report Detailing Friction Stir Welding Process Development for the Hot Cell Welding System

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Light Water Reactor Sustainability Program

Report Detailing Friction Stir Welding Process Development for the Hot Cell Welding System

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EXECUTIVE SUMMARY

Development of the advanced welding hot cell facility at Oak Ridge National Laboratory's Radiochemical Engineering Development Center (REDC), funded jointly by the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program and the Electric Power Research Institute, Long Term Operations Program, has continued. Following an extensive weld process research and development effort, along with subsequent system and component level design and construction, the primary elements of the facility were integrated into Building 7930 Cell C at REDC, and final weld subsystem adjustments are underway in preparation for welding irradiated materials. The facility will be a significant asset and key enabler of technology development in the effort to identify and validate welding technologies capable of repairing highly irradiated materials for existing nuclear power plant operational lifetime extension beyond 60 years.

This report details the effort to complete the process development of Friction Stir Welding (FSW), a solid-state welding technique housed in the advanced welding cubicle that has been deemed promising for repair of highly irradiated materials. A primary focus of this effort was finalizing the transition from a force-based robotic control system, under which much initial FSW process development was performed, to a displacement-based control system utilized in the advanced welding cubicle. The specific objectives of this work included:

- Characterization of the behavior of the cubicle friction stir welder under varying axial loading conditions and identification of the factors that influence FSW tool-workpiece engagement and defect formation
- Implementation of weld parameter modifications, or initiation of FSW control system software modifications, within the capabilities of a displacement-based control paradigm, to mitigate issues with inconsistent tool-workpiece engagement and defect formation
- Confirmation of the functionality of the cubicle friction stir welder in performing Friction Stir Cladding (FSC), or the novel process for highly irradiated materials, and initiation of any necessary cladding process refinements as identified through further cold testing

FSC is a FSW variant technology that has been developed in this program to clad layers of unirradiated material to irradiated substrates. FSC is currently proprietary and under patent application; therefore, care has been taken to protect intellectual property in the drafting of this report. The specific objectives of FSC refinement under this milestone included the integration of FSC tooling and the adjustment of software parameters, along with the identification of welding parameters, required to produce quality cladding layers on unirradiated, representative stainless steels.

The completion of each of these objectives is detailed herein. System performance for both FSW and FSC was validated, with refinements made as necessary to enable the creation of continuous, defect-free welds on unirradiated, representative materials. This represents a significant milestone in the preparation for welding irradiated materials.

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1. Introduction

In order to address the growing need for weld repairs of degraded reactor internals to extend existing nuclear power plant operating lifetimes beyond 60 years of service, the Department of Energy Office of Nuclear Energy, through the Light Water Reactor Sustainability Program, and the Electric Power Research Institute, through the Long Term Operations Program, collaborated to develop advanced welding processes and a unique research and development facility within a hot cell that would allow the performance of the processes to be evaluated directly on highly irradiated material. The challenges associated with repairing highly irradiated reactor internals are complex. Not only are traditional detrimental effects from welding, such as residual stress, a concern, but reactor component damage, sustained from decades of stress, thermal, chemical, and irradiation effects, is further complicated by the accumulation of helium gas due to the transmutation of alloy constituents, boron and nickel, through neutron capture. During weld repairs, helium bubbles can coalesce and grow at grain boundaries, leading to cracking in the weld heat affected zone (HAZ). As nuclear power plants age, He levels in structural components can reach levels (exceeding 10 appm He) at which conventional welding process can no longer be used successfully.

In recent years, demand has grown for welding process capable of mitigating the problem of He-induced cracking. Research has determined that the keys to preventing He-induced cracking include limiting local temperature, limiting plastic deformation, and controlling the stress state of the material, and accordingly, the welding process that will initially be evaluated in the advanced welding cubicle at Oak Ridge National Laboratory Building 7930 incorporate these principles. The capabilities of the cubicle include Friction Stir Welding (FSW) and advanced Laser Beam Welding (LBW) with cold filler metal deposition. These are the processes that have been deemed most promising in the quest to demonstrate successful repair of highly irradiated materials with He concentrations exceeding 10 appm He and reaching levels as high as 30 appm He. The present milestone was directed toward the completion of process development for conventional FSW in the advanced welding cubicle, as well as refinement of a novel FSW variant technology, in preparation for welding irradiated materials. A primary focus would be completing the transition from a force-based control system, under which much initial FSW process development was performed, to the displacement-based control system utilized in the advanced welding cubicle.

1.1 Background

FSW is a solid-state joining process that has proven to offer numerous advantages overall conventional fusion welding processes in a multitude of applications. In many cases, the most significant advantage of FSW is that alloys are joined without melting, which mitigates the potential deleterious effects of melting and re-solidification on the strengthening mechanisms of many alloys. Lower heat input, in general, is often desired and can lead to a reduced likelihood of cracking, particularly in the HAZ of welds. This process characteristic is principal among those which make FSW attractive as an advanced repair technique for highly irradiated materials, which as previously discussed, are susceptible to He-induced cracking in the weld HAZ.

FSW involves a rotating tool, consisting of a probe and shoulder, that plunges into the workpiece and traverses the joint line, generating heat and softening material through both friction and plastic deformation, and mechanically stirring and forging material together. FSW tools are considered nominally non-consumable, i.e. tool consumption is not a mechanism of the FSW joining process, but in the welding of relatively high melting point materials, tool wear is a significant concern and an aspect of the process that must be well understood to design sustainable, efficient joining operations. Figure 1 displays a Polycrystalline Cubic Boron Nitride (PCBN) tool that is of the same type that will be used for welding of irradiated stainless steels in the advanced welding cubicle.

Figure 1: PCBN FSW Tool for Welding Stainless Steels

A critical aspect of the FSW process is the engagement of the FSW tool with the workpiece, i.e. proper relative position between the two components that is maintained throughout the welding process. This aspect of the process can effect heat generation, material softening, material flow characteristics, defect formation, surface finish, and tool wear, among other things. And, because that the FSW process, particularly when steels are joined, can generate large process forces (it is not uncommon for the axial force (F_z) which is directed through the axis of the FSW tool, to meet or exceed 35 kN, or approximately 8000 lb_f), maintaining proper tool-workpiece engagement is not trivial aspect of welding equipment and process design.

In order to perform FSW well, particularly in the presence of relatively high forces, specialized welding equipment is typically required to possess at least one of two characteristics: (1) very high rigidity, if a displacement-based control system without feedback is used for machine positioning, or (2) a force or torque feedback control loop that manipulates Z-axis positioning throughout the welding process to control axial force or torque to a desired value and maintain proper tool-workpiece engagement in the presence of machine compliance to high weld forces. The latter option is common, especially given recent efforts to apply FSW using standard industrial, articulated-arm robots, which can experience significant joint position deviation and link deflection under high loading scenarios. Typical control architecture is depicted in Figure 2.

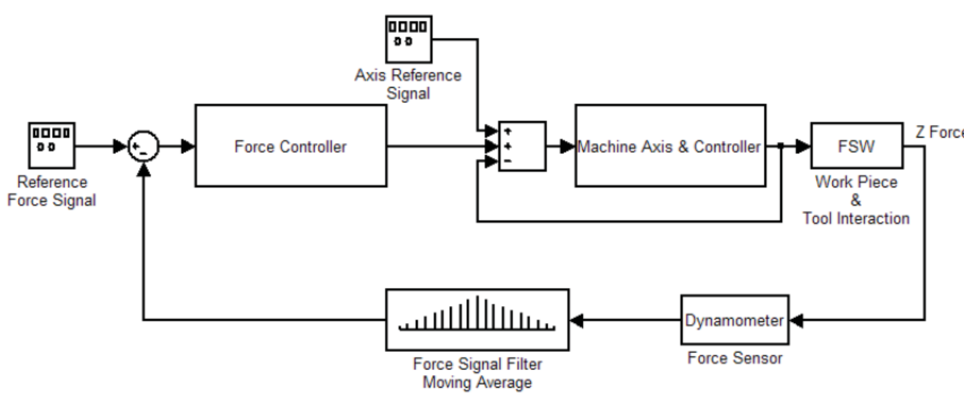

Figure 2: Typical FSW Robot Force Control Architecture [1]

The control architecture depicted is nested loop control. It is common for machines to have closed-loop positioning systems for individual axes, in which displacement is controlled with feedback, but this is not universal. This is the inner loop in Figure 2, and it is surrounded by a force-feedback loop, in which process forces are sensed and compared against a reference force signal to provide an error signal to the force controller. This enables a continual adjustment of axis position in order to control axis force, which in the case of FSW is related to tool-workpiece engagement. There are drawbacks to the utilization of force control however, such as increased system complexity and cost. In particular, one or more force sensors are required which can be expensive, subject to thermal influence, and damage prone due to unexpectedly high force or thermal loading events.

Displacement based control for individual axes or an entire system can be either open or closed loop, with locations of position measurement potentially varying from axis motors or actuators to the robot end-effector. The Z-axis of the FSW machine in the advanced welding cubicle operates under an open-loop displacement based control system, depicted in Figure 3, which contains an industrial motor and controller along with gearboxes and power screws for translating rotational to linear motion.

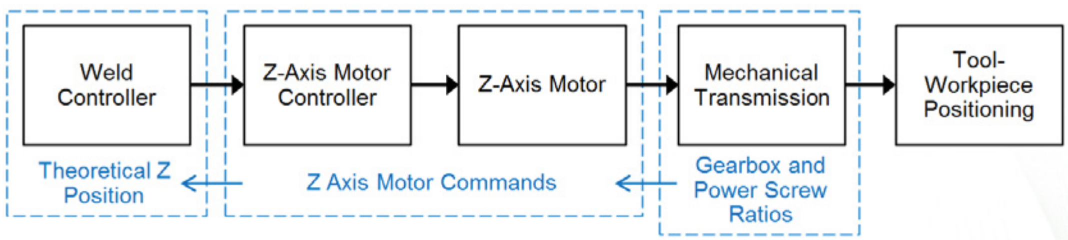

Figure 3: Open Loop Z-Axis Positioning System of the Cubicle FSW Equipment

Theoretical Z-axis positioning is determined based on the motor command or actual position along with gearbox ratios and power screw theory. Downstream of the motor, however, positioning error can arise from deflection and backlash in the mechanical linkages, and, if there is overall machine structural compliance to high weld forces, there is no recourse to correct improper tool-workpiece engagement during welds. Benefits associated with this type of system, however, are simplicity, reliability, and low cost, qualities that were attractive during the design phase of a machine that would ultimately be placed in the harsh environment of a hot cell for welding irradiated materials.

Despite the limitations of a displacement-based control system, there are variables in the welding process that can be controlled to influence better weld performance. Welding speed and tool rotation rate both can be selected to facilitate reduced axial force, and tool shoulder design can offer flexibility in relative tool-workpiece positioning while maintaining adequate engagement, particularly when a convex shoulder design, like the one pictured in Figure 1, is selected for use. These aspects would be examined in further weld process development activities for the advanced welding cubicle.

2. Prior Work and Motivation

Initial weld process development for FSW of irradiated stainless steels was carried out on unirradiated, representative stainless steel material using the ORNL FSW Process Development System (PDS) in Building 4508 as a test bed. Through this work, baseline welding parameters were established. Then, following the integration of the advanced welding cubicle into ORNL Building 7930 Cell C, FSW of unirradiated, representative stainless steel material was demonstrated on the dedicated hot cell FSW equipment [2]. Initial testing was focused on confirming the basic operation of the PLC control system and verifying that all desired operations could be completed automatically and remotely from the 7930 operating room. The system performed as anticipated from both mechanical and controls perspectives, and baseline weld performance was established, with multiple continuous friction stir welds produced that were subsequently analyzed with a particular focus on macro-defect formation. Through this analysis, tool-workpiece engagement was identified as a critical factor in the creation of high quality welds and one that would likely be complicated by the displacement based control technique utilized in the FSW system of the cubicle. During initial start-up and cold testing, friction stir welds exhibited some degree of defect formation at the weld crown, or linear discontinuities at the weld surface for some fraction of the weld length. This behavior was observed to occur consistently in the latter portion of the welds, suggesting a departure from the desired welding conditions rooted in a machine misalignment or deflection that the open-loop displacement based control system was of course incapable of detecting or correcting as the welds progressed. Figure 4 displays a welded specimen from these trials with a near-ideal surface finish for the majority of the weld length, followed by the formation of a surface defect near the end of the weld.

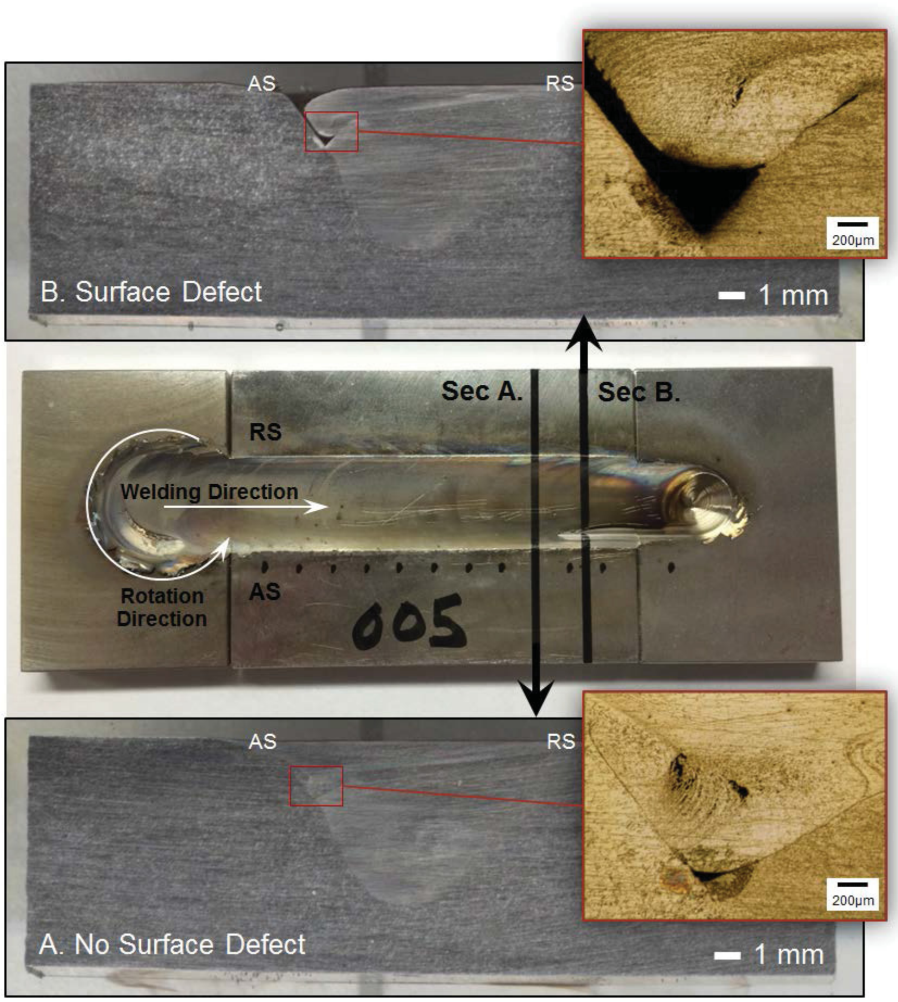

Figure 4: Macro Defect Analysis of a Friction Stir Welded Stainless Steel Specimen from Cubicle Start-Up Testing: Cross-Section A. Consolidated Surface Region, Cross-Section B. Surface Defect Region

The standard configuration of friction stir weld specimens for the welding cubicle includes a run-on tab, weld coupon, and run-off tab. The tabs allow for a longer overall weld and will increase the length of steady-state welding over the irradiated coupons that can be subsequently analyzed. Figure 4 also includes two YZ-planar cross sections from the weld, one from the welded region exhibiting a surface defect, and one from the consolidated region immediately preceding it. It is shown from this examination that it is possible for volumetric defects to initiate under a weld crown of desirable appearance prior to the start of a surface defect and that this is an aspect of the process that would have to be monitored closely in further cold testing that followed. Overall, the goals for further cold testing, to be completed before the start-up of welding activities on irradiated stainless steels, included the following:

- Characterize the behavior of the cubicle friction stir welder under varying axial loading conditions and identify factors that influence the tool-workpiece engagement and defect formation
- Implement weld parameter modifications, or initiate FSW control system software modifications, within the capabilities of a displacement-based control paradigm, to mitigate issues with inconsistent tool-workpiece engagement and defect formation
- Confirm the functionality of the cubicle friction stir welder in performing Friction Stir Cladding, or the novel process for highly irradiated materials, and initiate any necessary cladding process refinements as identified through further cold testing

These activities would be carried out with the intention of finalizing weld parameter selections and operating procedures and making other final preparations for welding irradiated stainless steel specimens.

3. Current Status

Friction stir weld testing on unirradiated, representative stainless steel materials has continued, with a focus on process improvement through weld parameter modification, in order to improve overall weld performance and specifically to create continuous, defect-free welds along the entire length of the coupon plus tabs workpiece configuration. Successful completion of this task would demonstrate the final transition from force controlled FSW to a displacement based control system for welding of irradiated materials in the advanced welding cubicle.

3.1 Completion of the Friction Stir Weld Process Development for the Dedicated FSW System in the Welding Hot Cell: Transition from Force Based Control to Displacement Based Control

Performing successful friction stir welds in the absence of force control capabilities, the benefits of which are enjoyed on the ORNL FSW PDS, requires having an understanding of FSW machine rigidity and its dynamics within the relatively high axial force regime associated with FSW of stainless steels. An understanding of this behavior can potentially allow for compensation within the weld parameter selections to mitigate undesirable weld characteristics that may result from significant machine deflection and inconsistent or inadequate tool-workpiece engagement, such as surface and sub-surface volumetric defects.

3.1.1 Experimental Methods

To quantify the behavior of the FSW machine from a rigidity perspective, two additional sensors were placed in the welding environment, a cantilever-style extensometer and a standard dial indicator, for monitoring the displacement between the FSW head assembly, through which the large axial force is transmitted during welding, and the specimen clamp, which moves with the machine table. Figure 5 displays the experimental setup of the extensometer.

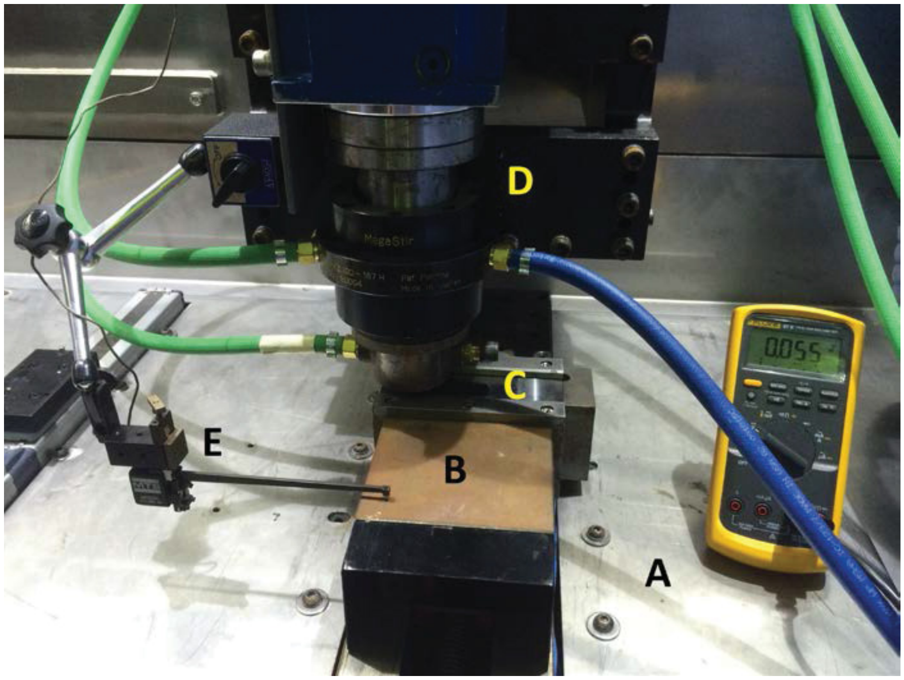

Figure 5: FSW Experimental Setup with Extensometer: A. FSW Machine Table, B. FSW Clamp, C. FSW Specimens (Run-on Tab, Coupon, Run-off Tab), D. FSW Head Assembly, E. Extensometer

Extensometer displacement data was recorded, while the dial indicator (not shown in Figure 5, but pictured in the appendix) was monitored visually and with video through the shield window of the hot cell during welding operations. In order to create different loading scenarios, dry runs, in which the machine is run without producing welds to create zero-load situations, were performed along with welding of both 304 stainless steel and aluminum, which generates relatively low weld forces. Welds were initially inspected visually between trial runs, and subsequent weld analysis included x-ray non-destructive evaluation (NDE) followed by metallographic cross-sectioning and optical microscopy. Tooling and weld parameters were varied to improve performance in the initial visual inspections as trials progressed. Variables for the most recent round of welding experiments are listed in Table 1.

Table 1: Friction Stir Welding Parameters for Cold Testing [*New Condition Tool]

Weld No.	Material	Tool	Welding Speed (IPM)	Rotation Rate (RPM)	Lead Angle (°)	Weld Path Z Travel (inch)
006	Stainless Steel	1	1.8	400	0	0.329
007	Aluminum	1	1.8	400	0	0.329
008	Stainless Steel	1	1.8	400	0	0.329
009	Stainless Steel	3*	1.8	400	0	0.329
010	Stainless Steel	3	1.8	400	0	0.334
011	Stainless Steel	3	1.8	400	0	0.339
012	Stainless Steel	3	1.8	400	0	0.339
013	Stainless Steel	3	1.8	400	0	0.339
014	Stainless Steel	3	1.8	400	0	0.339
015	Stainless Steel	3	1.8	400	0	0.339

The Weld Path Z Travel represents the tool plunge depth from its pre-weld home position, in which the tool is positioned very close to the run-on tab without actual, physical contact.

3.1.2 Results

Results of FSW system testing on stainless steel and aluminum, along with corresponding machine dry runs, indicate that varying axial loading scenarios had significant impacts on machine behavior from a deflection standpoint. Figure 6 displays the FSW machine Z-axis commanded position along with extensometer data for a dry run, an aluminum weld, and two stainless steel welds. The Z-axis commanded position displayed corresponds to a Weld Path Z Travel of 0.339 inch, or a 0.010 inch greater plunge depth than that used for the dry run or cold weld 007 (aluminum). The end of the plunge phases and weld starting times for varying plunge depths are denoted on the figure.

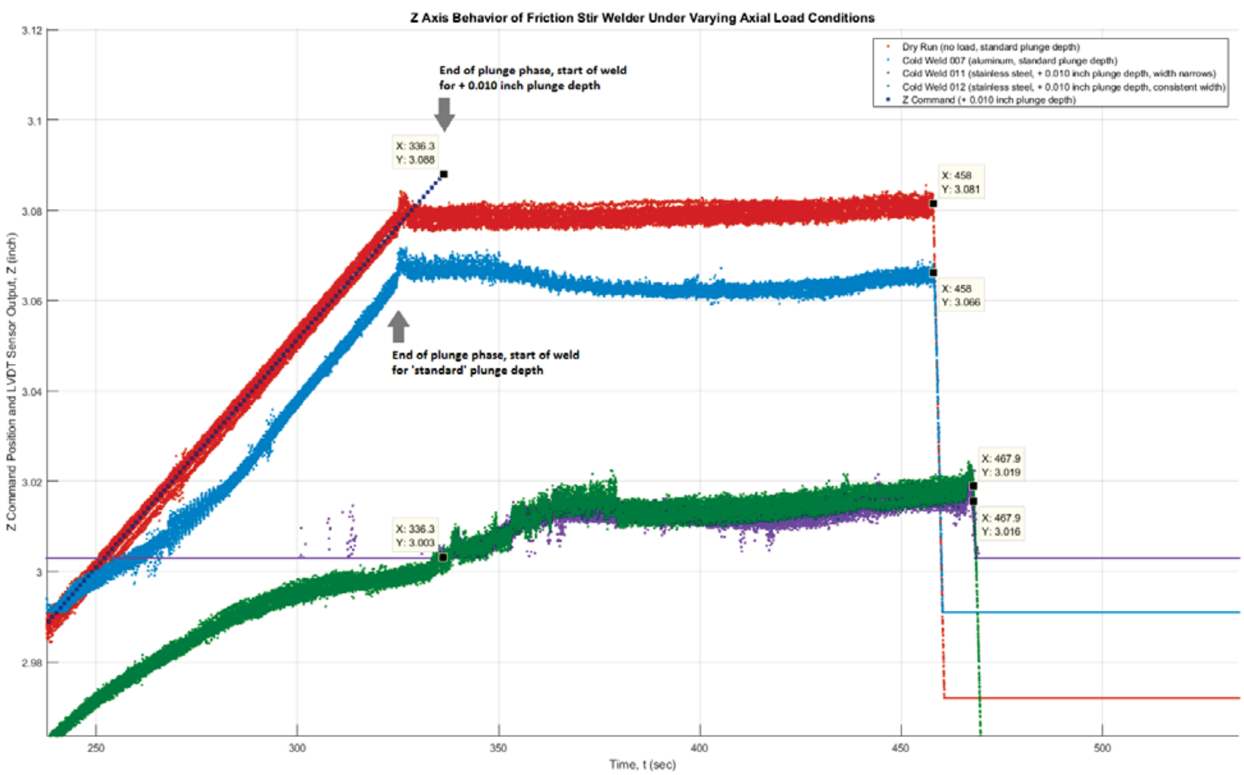

Figure 6: Extensometer Data for Varying Loading Conditions

It is observed that during a dry run, the actual FSW machine table Z position corresponds well with the commanded Z position. The plunge phase is comprised of a linear increase in Z position over time, followed then by an assumed constant Z position during the welding phase. The measured welding phase Z position shows only a slight, approximately 0.002 inch, deviation from the desired value. During the welding of aluminum (weld 007), a significant deviation in actual Z position from the commanded Z position is evident in the plunge phase, beginning approximately around 250 seconds. A corresponding increase in FSW spindle motor current indicates that this deviation occurs when the shoulder of the FSW tool contacts and plunges into the workpiece. An increase in weld forces, including torque, which is related to spindle motor current, would be expected at this time. All machine data, including commanded

Z position and spindle motor current, for welds with extensometer data in Figure 6 can be found in the appendix. Least-squares linear regressions of spindle motor current for select analysis windows are included as well, to provide insight into the consistency of tool engagement with the workpiece throughout the length of the welds. Extensometer data for stainless steel welds 011 and 012 is displayed in Figure 6 as well. It is evident from these welds that the higher axial force regime of stainless steel welding has a significant impact on the machine's ability to reach the commanded Z positions. For instance, extensometer data indicates that the machine table Z position is 0.085 inch below the expected value at the completion of the plunge phase and start of weld 012. This is likely a consequence of machine structure compliance and an inability of an open-loop displacement based control system to sense and correct for actual Z position deviations from the commanded values. These observations were confirmed with dial indicator data that was compiled from video and displayed in Figure 7. Additional dial indicator data for welds 006 – 008 can be found in the appendix.

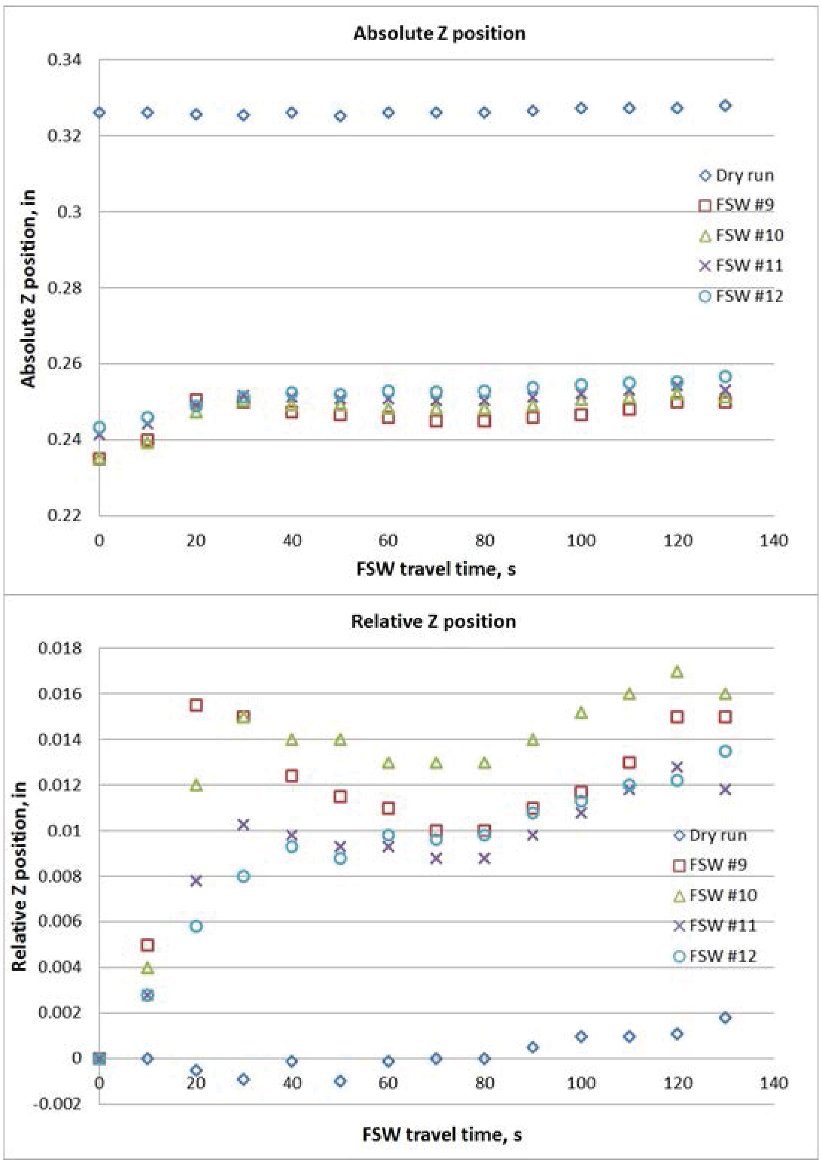

Figure 7: Dial Indicator Data Showing the Absolute and Relative Z-Axis Position Variations during a Machine Dry Run and Welds 009 - 012

In order to compensate for the observed machine deflection, and therefore unexpected or inconsistent engagement between the FSW tool and the workpiece, the Weld Path Z Travel, or tool plunge depth relative to the pre-weld home position, was increased incrementally between weld trials until, through post-weld visual examination, it became clear that surface defects from inadequate tool-workpiece engagement were being eliminated. Figure 8 displays weld surface finish and X-ray NDE results for welds 009 through 012. Weld 009 exhibits a surface defect like those of prior tests, but welds 010 through 012, with increased plunge depths, have defect-free surfaces. Measurements of weld crown width as a function of weld length for welds 009 through 012 are included in the appendix. X-ray NDE captured the significant defect of weld 009, as expected, and no indications of defects in welded coupons 010 through 012 were identifiable. Metallographic cross-sectioning and optical microscopy confirmed these results, with the exception that a relatively small volumetric defect at the root of weld 012, likely attributable to tool wear based on its location, was identified. These results are shown in Figure 9.

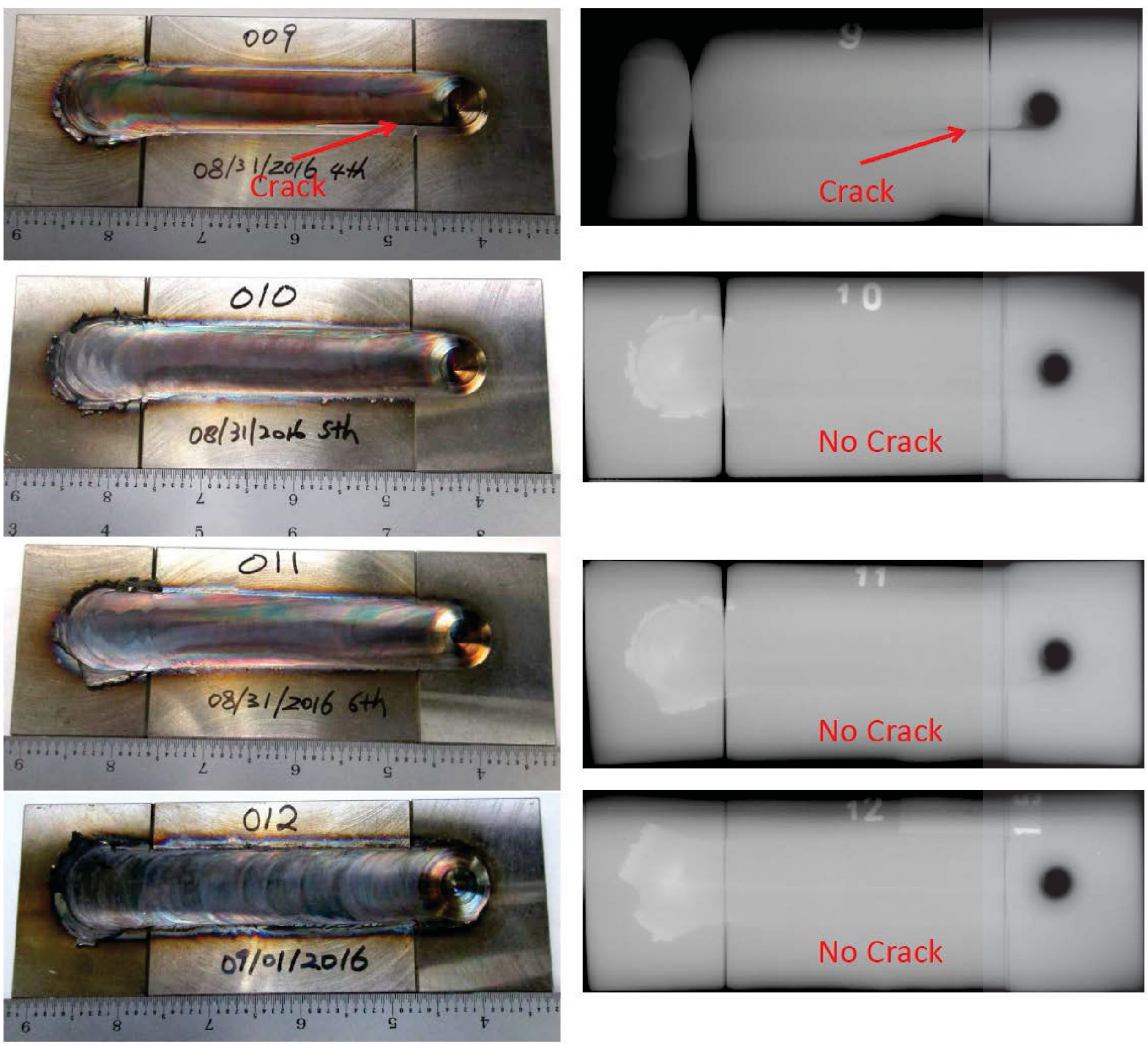

Figure 8: Visual and X-Ray NDE Examinations of Cold Welds 009 – 012

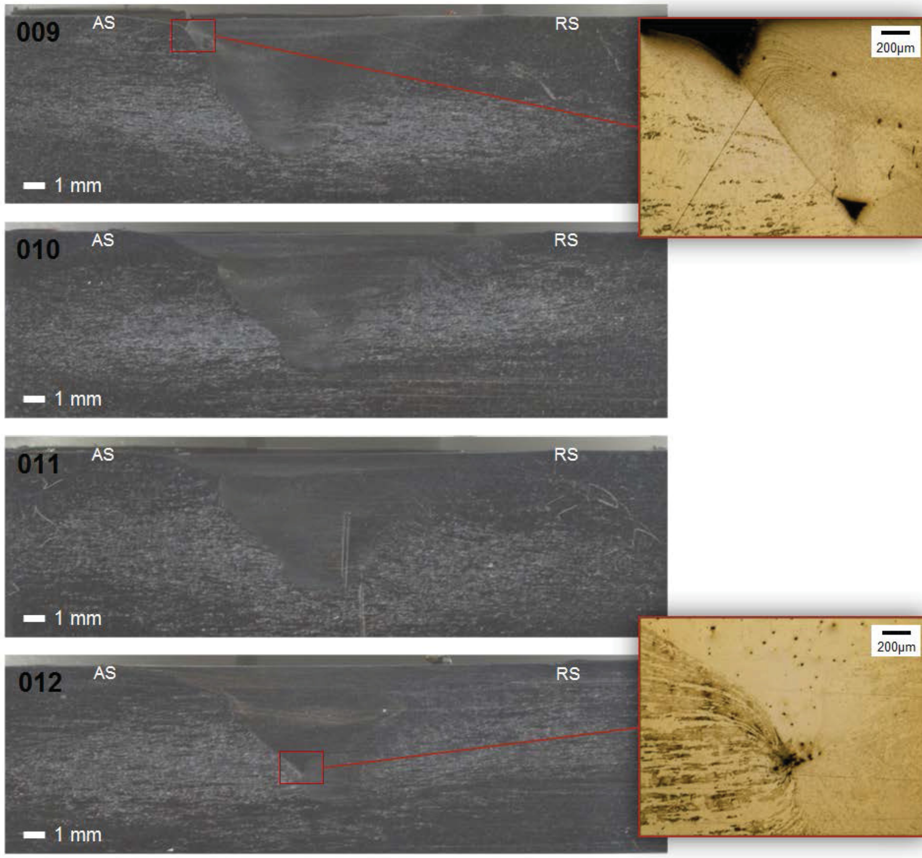

Figure 9: Metallographic Cross-Sections of Cold Welds 009 - 012

The indication of tool wear, significant enough to result in the formation of a volumetric defect, in the fourth weld after a tool change may be a consequence of compensation for machine deflection through increased plunge depth; prior tool wear investigations performed with axial force control indicated a longer tool life for this application. Nevertheless, weld parameters were identified that yielded surface and sub-surface defect-free results that could be applied using a displacement-based control system. This was a significant step forward in the preparations for beginning weld repair R&D work on irradiated materials.

3.2 Refinement and Confirmation of the Novel FSC Process for Highly Irradiated Materials on the Dedicated FSW System

In addition to transitioning from one control technique to another and identifying target weld parameters for conventional FSW, the novel Friction Stir Cladding (FSC) process was performed on the dedicated FSW system for the first time since the system was installed in Building 7930 Cell C, and the process was further refined in preparation for welding irradiated materials. FSC is currently proprietary and under patent application; therefore, care has been taken to protect intellectual property in the drafting of this report. Specific objectives of FSC refinement under this milestone included the integration of FSC tooling and the adjustment of software parameters, along with the identification of welding parameters, required to produce quality cladding layers on unirradiated, surrogate stainless steels.

3.2.1 Results

Performance of the dedicated hot cell welding equipment in the proper execution of the FSC process was confirmed. Parameters were successfully refined to achieve the desired results. The repeatability of the system was observed to be very good in terms of creative successive clads of similar appearance. FSC sample sectioning and metallurgical analysis are on-going to confirm the quality of the clads, but the system performance in the execution of the FSC process was found to be excellent by the metrics evaluated.

4. Summary

The advanced welding facility at Oak Ridge National Laboratory's Radiochemical Engineering Development Center will be a significant asset and key enabler of technology development in the effort to identify and validate welding technologies capable of repairing highly irradiated materials for existing nuclear power plant operational lifetime extension beyond 60 years. The major components of the facility have been installed and the final adjustments to the weld process subsystems are underway. Specifically, the transition from a force-based control system for FSW, under which initial process development was performed, to an open-loop displacement-based control system utilized on the dedicated FSW machine in the hot cell cubicle was completed. The performance of the machine positioning system is critical for achieving and maintaining proper tool-workpiece engagement during welding, and it was found that weld parameter modifications were required in order to create defect-free welds. These modifications were made successfully, and multiple defect-free welds were produced to demonstrate acceptable functionality of the system ahead of welding irradiated materials. Additionally, the performance of the dedicated welding hot cell equipment in executing the novel FSC process was confirmed. The dedicated welding system of the hot cell met the demands of performing both FSW and FSC on unirradiated, representative materials and is well positioned for the next program phase of initial welding of irradiated specimens.

Acknowledgements

The authors thank Kathryn Kinney and Allen Smith, along with Scott White and the personnel of the Radiochemical Engineering Development Center, for their significant contributions to the development, installation, and initial testing of the advanced welding cubicle and supporting equipment.

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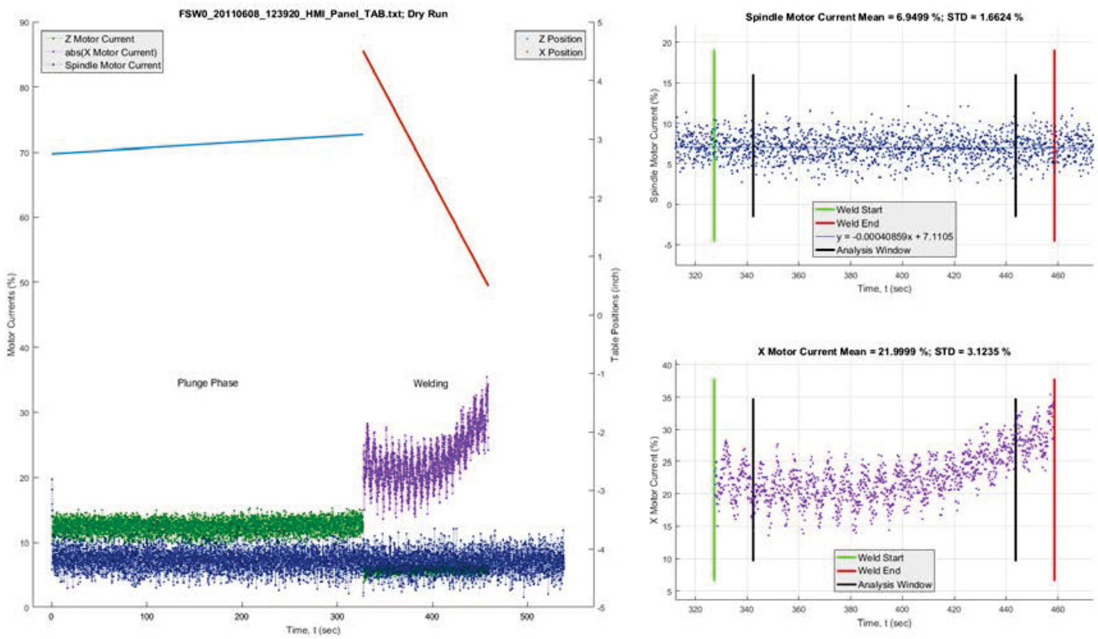
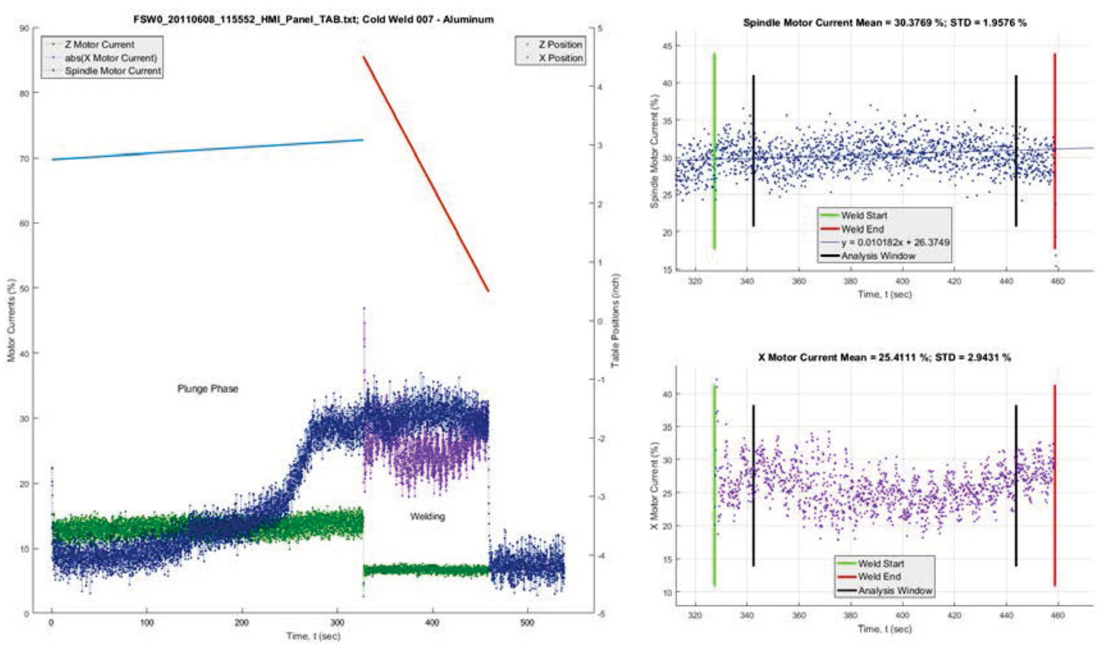
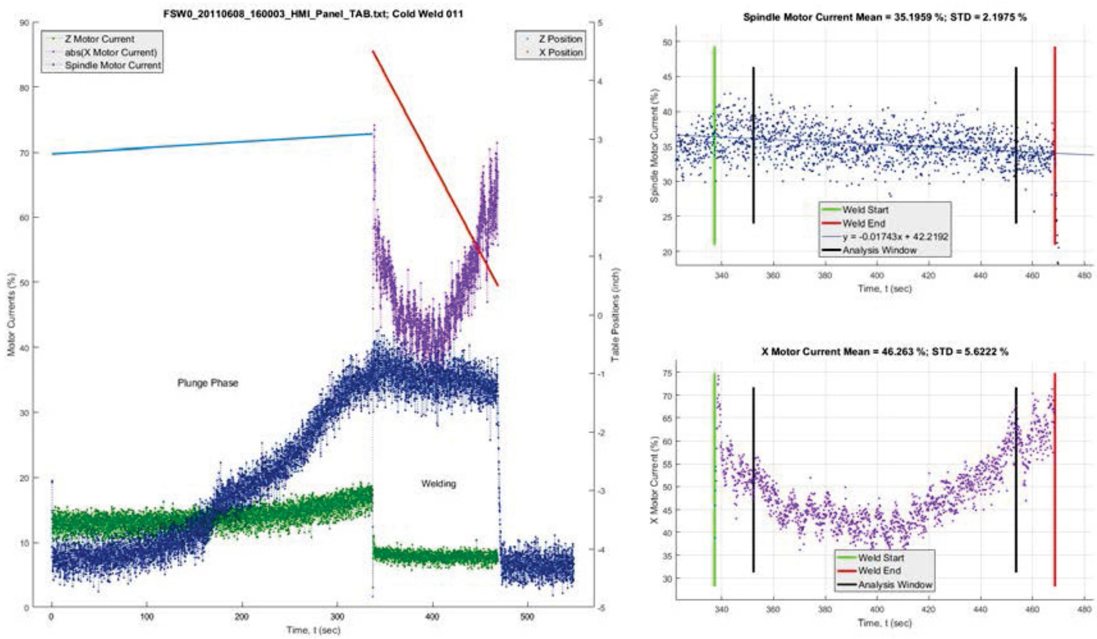
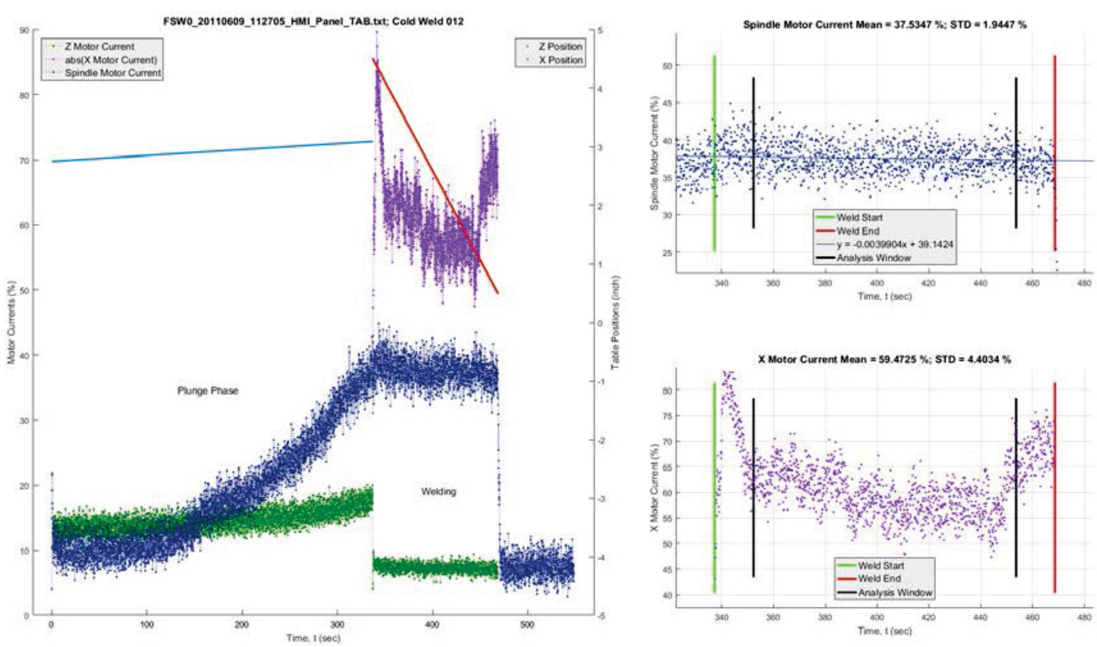
Appendix

FSW Hot Cell Cubicle Equipment Output Data; Dry Run and Welds 007, 011, 012

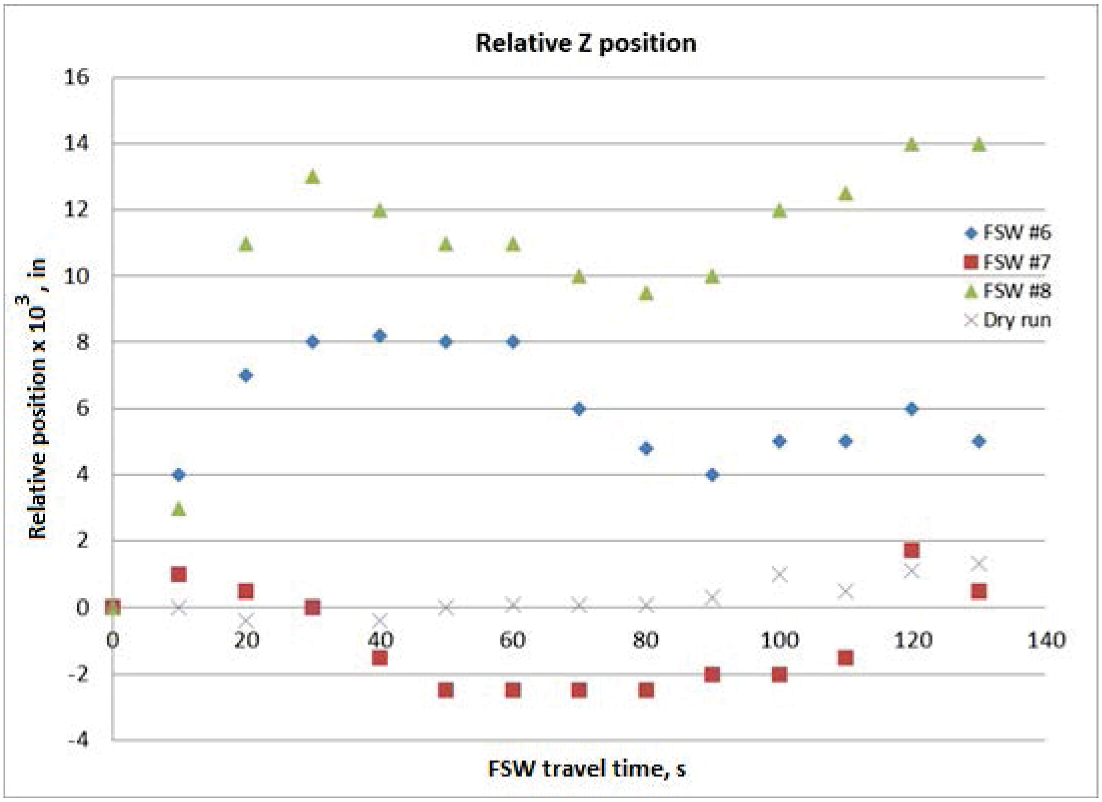




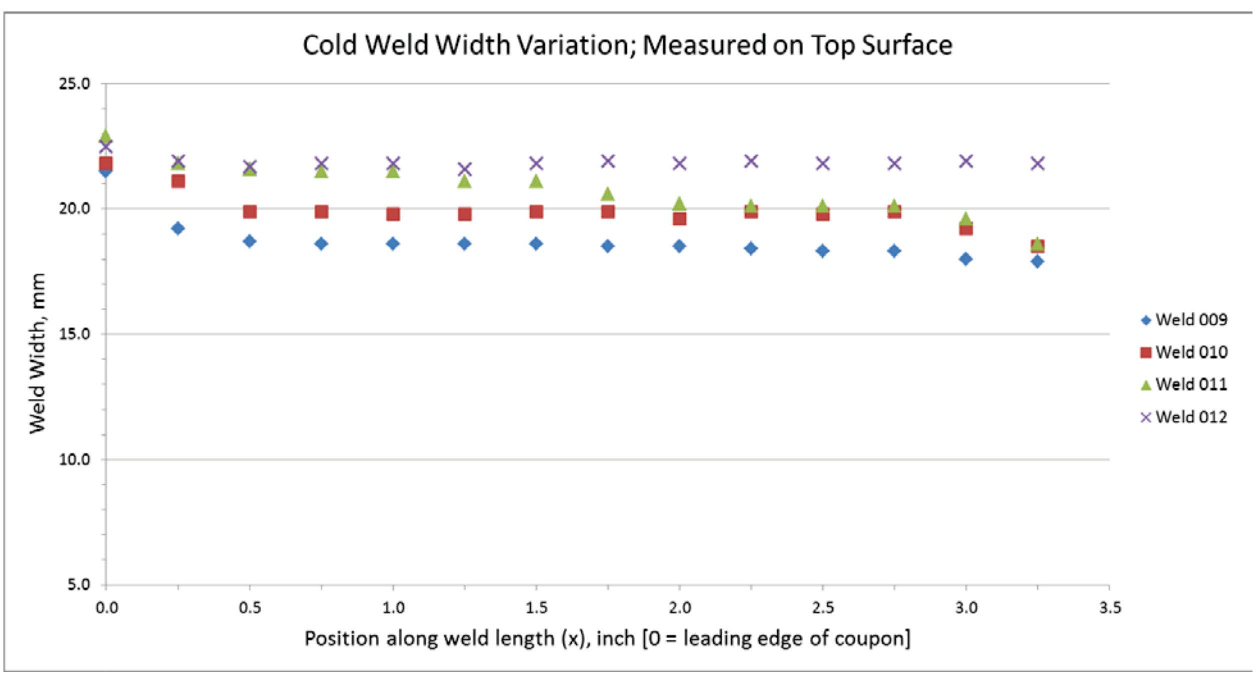

FSW0_20110608_160003_HMI_Panel_TAB.txt; Cold Weld 011
Z Motor Current
abs(X Motor Current)
Spindle Motor Current
Z Position
X Position
Plunge Phase
Welding
Motor Currents (%)
Table Positions (inch)
Time, t (sec)
Spindle Motor Current Mean = 35.1959 %; STD = 2.1975 %
Weld Start
Weld End
y = -0.01743x + 42.2192
Analysis Window
Spindle Motor Current (%)
Time, t (sec)
X Motor Current Mean = 46.263 %; STD = 5.6222 %
Weld Start
Weld End
Analysis Window
X Motor Current (%)
Time, t (sec)


FSW0_20110609_112705_HMI_Panel_TAB.txt; Cold Weld 012
Z Motor Current
abs(X Motor Current)
Spindle Motor Current
Z Position
X Position
Plunge Phase
Welding
Motor Currents (%)
Table Positions (inch)
Time, t (sec)
Spindle Motor Current Mean = 37.5347 %; STD = 1.9447 %
Weld Start
Weld End
y = -0.0039904x + 39.1424
Analysis Window
Spindle Motor Current (%)
Time, t (sec)
X Motor Current Mean = 59.4725 %; STD = 4.4034 %
Weld Start
Weld End
Analysis Window
X Motor Current (%)
Time, t (sec)

Relative FSW Machine Z-Axis Position for a Dry Run and Welds 006 – 008



Weld Width for Welds 009 - 012



Dial Indicator Positioning as Viewed Through the Cell C Shield Window