HYBRID LASER ARC WELDING OF A USED FUEL CONTAINER

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Abstract

The Nuclear Waste Management Organization (NWMO) has designed a novel Used Fuel Container (UFC) optimized for CANDU used nuclear fuel. The Mark II container is constructed of nuclear grade pipe for the body and capped with hemi-spherical heads. The head-to-shell joint fit-up features an integral backing designed for external pressure, eliminating the need for a full penetration closure weld. The NWMO and Novika Solutions have developed a partial penetration, single pass Hybrid Laser Arc Weld (HLAW) closure welding process requiring no post-weld heat treatment. This paper will discuss the joint design, HLAW process, associated welding equipment, and prototype container fabrication.

1. Introduction

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management [1] for the long-term care of Canada's used nuclear fuel. The program's objective is to create a socially acceptable, environmentally responsible, and economically feasible used fuel solution. The creation of a Deep Geological Repository (DGR) was proposed and accepted. The used nuclear fuel is encapsulated in long-lived Used Fuel Containers (UFC), then emplaced at a reference depth of 500m underground in a suitable rock formation, and surrounded with bentonite clay, as shown in Figure 1. The DGR method is consistent with the preferred approach from many countries around the world [2, 3, 4, 5].

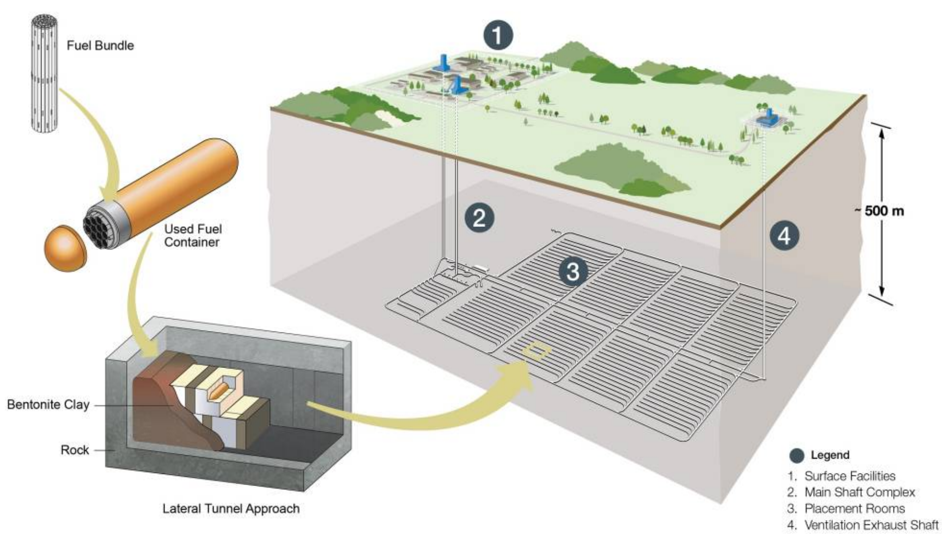

Figure 1 NWMO Deep Geological Repository (DGR) Concept

The DGR represents a multi-engineered barrier system designed to prevent radioactive material from reaching the biosphere. The container is a unique component of that system, as it is the only one designed specifically for containment. There are several different container concepts internationally. The KBS-3 repository container, developed by the Swedish (SKB) and Finnish (POSIVA) nuclear waste management organizations, is a dual-vessel design [6]. It consists of a cast-iron structural insert, with channels to separate and emplace the used fuel. This insert is contained within a large 50mm thick copper overpack corrosion barrier. The Swiss (NAGRA) and French (ANDRA) organizations are investigating the use of large steel containers [7, 8]. A common element of all these programs is the size of the containers; measuring over 4 metres in length and 1 metre in diameter. This large size is necessitated by the use of large, enriched uranium, light water reactor fuel bundles. The resulting containers weigh more than 25 tonnes with fuel.

In contrast to light water reactors, Canada's CANDU pressurized heavy water reactors use natural uranium fuel bundles, which are significantly smaller. A CANDU bundle measures approximately a half metre in length and weighs 25kg. The NWMO has developed a container specifically designed for CANDU fuel, shown in Figure 2, with several novel design features:

1. Constructed using standard nuclear pressure vessel grade materials and sizes
2. Hemi-spherical heads for uniform distribution of external pressure loads
3. Smaller sized container, weighing less than 3 tonnes when loaded with fuel
4. Copper coating corrosion barrier integrally bonded to structural steel container
5. Partial penetration Hybrid Laser Arc Weld (HLAW) for container closure

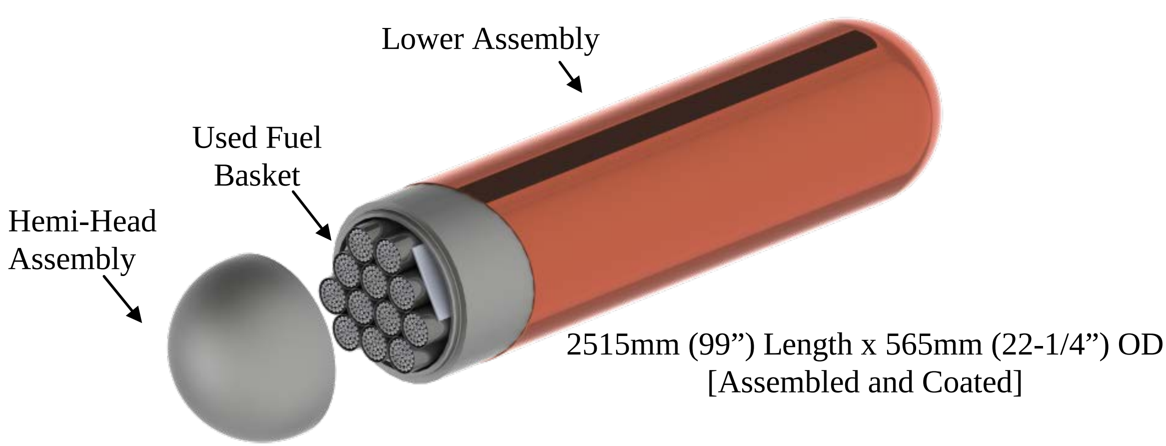

Figure 2 NWMO's Mark II Used Fuel Container

The partial penetration HLAW seal weld is a departure from the international designs. The SKB/POSIVA dual-vessel container features a bolted lid inner container, which provides temporary containment via elastomeric seal. The long-term containment boundary is the copper overpack vessel, which is welded closed using full-penetration, single pass Friction Stir Welding (FSW). The NAGRA/ANDRA steel containers also propose full-penetration welds requiring multi-pass arc welding or high-penetration Electron Beam Welding (EBW).

2. Method

2.1 Hybrid Laser Arc Welding

Conventional arc welding processes such as Shielded Metal Arc (SMAW) and Gas Metal Arc (GMAW/MIG) operate on a similar principle. Electric current creates an arc between the base metal and filler wire. The arc plasma heats the base and filler metal reaching the materials melting point resulting in a weld pool. The penetration depth and welding speed is limited due to the low energy density; that is, the arc and weld pool quickly lose heat to the surrounding base materials limiting weld depth. In order to create deep welds, groove joint preparation and / or multiple passes are required.

Alternatively, high energy density welding processes such as Electron Beam Welding (EBW) and Laser Beam Welding (LBW) use focused energy on very small areas to both melt and vaporize the metal. The beam is focused on the joint and vaporizes the surface material creating a vapour cavity, known as the keyhole. Once the keyhole develops, the beam can penetrate deep into the joint, displacing the molten metal at the joint surface. This allows for deep single pass welds up to 16mm for LBW and 150mm for EBW [10]; however, joint preparation, position, and tolerances are critical for weld quality.

Hybrid Laser Arc Welding (HLAW) combines both LBW and GMAW into a single process, as shown in Figure 3. The laser beam is aimed at the leading edge of the weld pool and is closely followed by the GMAW, which move together simultaneously. The hybrid process uses the advantages of each individual process: laser provides deep penetration and high-speed single pass welds. Joint tolerance sensitivity is eliminated as the GMAW produces a wide and shallow bead filling any residual gap.

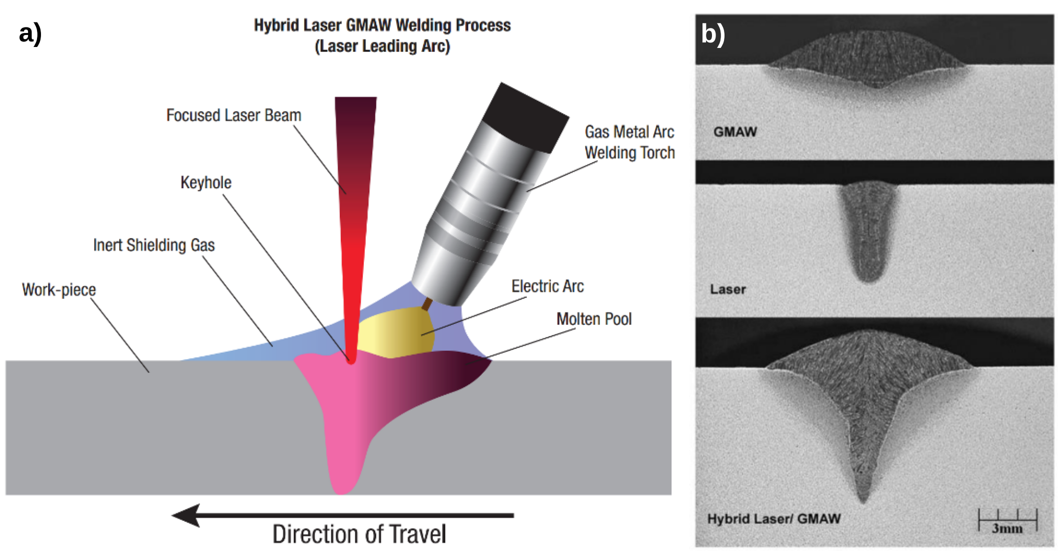

Figure 3 (a) Hybrid Laser Arc Welding Process Schematic [9] (b) Weld cross-sections from Gas Metal Arc Welding, Laser Beam Welding, and Hybrid laser Arc Welding [10]

2.2 Joint Design for Used Fuel Container

Partial penetration welds are not suitable for conventional, internally pressurized nuclear vessels and containments. As a result, they are not permitted by relevant design codes and standards, such as CSA N285.0 and the American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section III [11] under most circumstances (the code will be referred to as ASME for the reminder of the paper). The NWMO is following industry best practice and all applicable design codes and standards; however at this time, no national or international standard exists for the requirements on used fuel disposal containments. The closest appropriate code is the ASME Section III, Division 3, "*Containments for the Transportation and Storage of Spent Nuclear Fuel and High Level Radioactive Material and Waste*". Sub-section WC provides rules for interim used fuel storage containments only (Class SC vessels). A key difference with sub-section WC is that partial penetration welds are permitted for vessel closure for flat head designs, as shown in Figure 4 (b) and (c). NWMO's current approach is to follow the intent of ASME Section III Division 3, augmented as required for disposal containments.

Used fuel containers, whether interim or disposal, are designed to withstand external loads – internal pressurization is limited and a non-issue. The Mark II container joint design utilizes an integral backing in the cylindrical shell, as shown in Figure 4 (a). This backing supports the thinner hemi-spherical head and provides a locating feature suitable for automation in a radiological environment. With this design, the weld experiences limited tension and shear under external pressure. The weld's role in structural integrity is vastly diminished and its core function is reduced to an air-tight seal. The NWMO's current structural analysis shows that an 8mm partial penetration weld is more than sufficient for long-term containment.

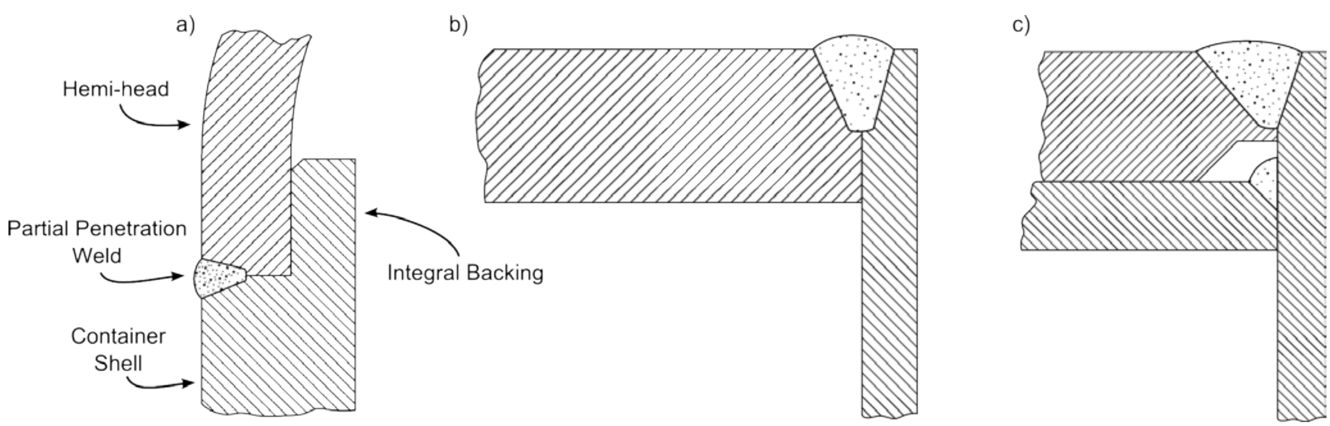

Figure 4 Partial penetration joint designs (a) NWMO's Mark II container with hemi-spherical heads (b) Typical ASME BPVC Class SC containers with single closure flat head (c) Double closure flat heads (adapted from [11])

2.3 HLAW Process Development and Demonstration for the Used Fuel Container

The NWMO investigated several different methods for welding the container based on the following weld requirements:

1. Metallurgy and Mechanical Properties
   a. Tensile strength and ductility equivalent to base material properties
   b. No martensite present (Hardness <22 Rockwell C as preliminary target)
   c. Must meet ASME Section III impact toughness at lowest service temperature of -5°C
   d. Weld penetration > 8mm
2. Quality
   a. Must meet ASME Section III ultrasonic inspection requirements with more restrictive criterion (3mm max flaw length)
   b. Cracks, lack of fusion, or incomplete penetration are unacceptable regardless of length
   c. High repeatability
3. Manufacturability
   a. No post-weld heat treatment
   b. Ability to perform localized weld repair
   c. Suitable for remote welding using automated equipment (nuclear application)

After completion of the feasibility and scoping studies, summarized in Table 1, HLAW emerged as the preferred technology. NWMO and Novika Solutions [12] began a comprehensive HLAW process development and demonstration program for the Mark II container closure weld. The work program involved investigation and proof testing of:

1. Weld joint design and preparation
2. HLAW procedure, parameters, and draft qualification
   a. Weld pre-heat
   b. Laser (power, spot size, weld speed, ...)
   c. GMAW (current, voltage, angle, wire feed rate, ...)
3. Metallurgical and mechanical properties testing to meet ASME Section III requirements
4. Non-destructive Examination
5. Defect repair

As mentioned, the NWMO is following the intent of the ASME code including applicable fabrication rules. Specific weld qualification rules are required for compliance. The primary objective of weld qualification is to ensure that materials and techniques being utilized result in consistent, quality welds with acceptable mechanical properties. Beginning with the 2013 code edition, ASME allows the use of HLAW for fabrication of nuclear pressure vessels including storage containments.

Table 1 Scoping Study: Comparison of Welding Processes

Welding Process	**Process Advantages**	**Process Disadvantages**
Arc-Welding (GMAW, GTAW)	- Low Equipment Cost - High Reliability - Well-understood - Rough joint position and fit-up required	- Lower penetration - Groove joints and multi-pass required for thick welds
Laser Beam Welding (LBW)	- Low distortion - Small Heat Affected Zone (HAZ) - Fast Weld Speed - No filler metal - Flexible fiber optic cables for beam delivery from laser source - Easily automated, robot friendly	- Accurate joint position and fit-up required - High equipment costs - Beam alignment and focus critical
Electron Beam Welding (EBW)	- Low distortion - Small Heat Affected Zone (HAZ) - Fast Weld Speed - No filler metal - Highest Penetration	- Very accurate joint position and fit-up required - High equipment costs - Beam alignment and focus critical - Requires vacuum (chamber or local seal) - X-rays generation (safety hazard) - Larger electron gun unit required for beam delivery
Friction Stir Welding (FSW)	- Low distortion - Small Heat Affected Zone (HAZ) - No filler metal - Solid state process	- Very accurate joint position and fit-up required - High equipment costs - Weld termination (exit hole) requires run off tab - Automation difficult
Hybrid Laser Arc Welding (HLAW)	- Low distortion - Fast Weld Speed - Simple joint preparation - Easily automated, robot friendly	- High equipment costs

2.4 Novika Solutions Laser System

Novika Solutions' HLAW system consists of four major components, as shown in Figure 5. The laser source is an IPG Photonics YLS-15000 15 kW fiber laser. The focusing optics encompass a 0.4mm core fiber optics process cable with a Precitec YW-50 processing head (150 mm collimator and 300 mm focal length). The GMAW system is a Lincoln Electric Power Wave 655R and a PowerFeed 10R wire feeder. Seam tracking was assured via a Servo Robot Quanta LF laser camera and Robo-Trac servo slides. A Fanuc Robotics R-2000iB 165F robot was used for handling the weld end effector system.

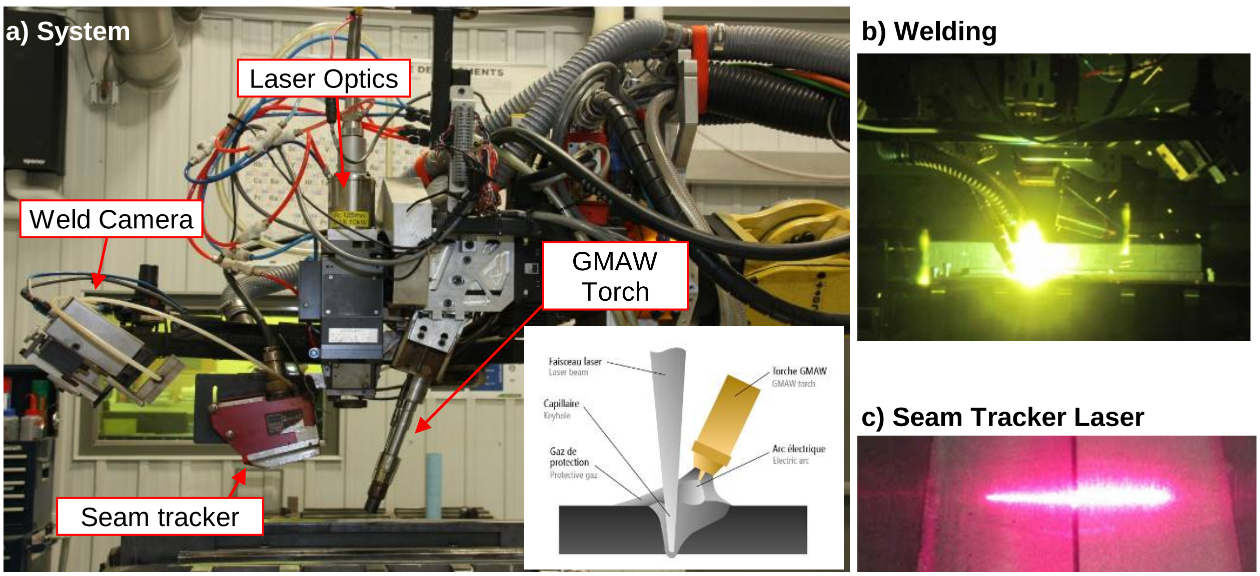

Figure 5 Novika Solutions' Hybrid Laser Arc Welding (HLAW) System

2.5 Used Fuel Container Rotation Equipment (ROTEQ)

To complete automated welds on full-scale Mark II prototype containers, a specialized piece of handling equipment was required. The Used Fuel Container Rotation Equipment, known as the ROTEQ and shown in Figure 6, was designed, fabricated, and tested by Novika Solutions in collaboration with the NWMO.

The container is rotated while the weld end effector remains stationary relative to the ground (1G weld position); therefore, the weld speed is directly controlled by the container's rotation speed. A conventional rotation method for welding steel pipe is to use motorized rollers in contact with the outer diameter. However, this is not suitable for the container as rollers can create high, localized contact pressures. The Mark II container is fully copper coated and a primary concern is to minimize the damage to this surface. Additionally, even if rollers were possible, the hemi-spherical head would still need to be secured in place for the welding operation.

To circumvent these issues, an end-clamping method was devised that simultaneously secures the hemi-heads and minimizes contact pressure with the container surfaces. Custom chucks, shown in Figure 6, were designed to clamp directly onto the two hemi-spherical heads and drive the rotation. This design provides several advantages over rollers:

1. The unwelded hemi-spherical head is securely clamped into place with over 27,000N force
2. Larger contact areas on the end chucks keep pressures low, eliminating damage from indentation
3. Limited potential for slippage compared to rollers. Allowing precise rotation positioning for circumferential welding.
4. Limited potential for vertical displacement (e.g. bouncing / vibration on rollers), which is critical for post-weld machining operations

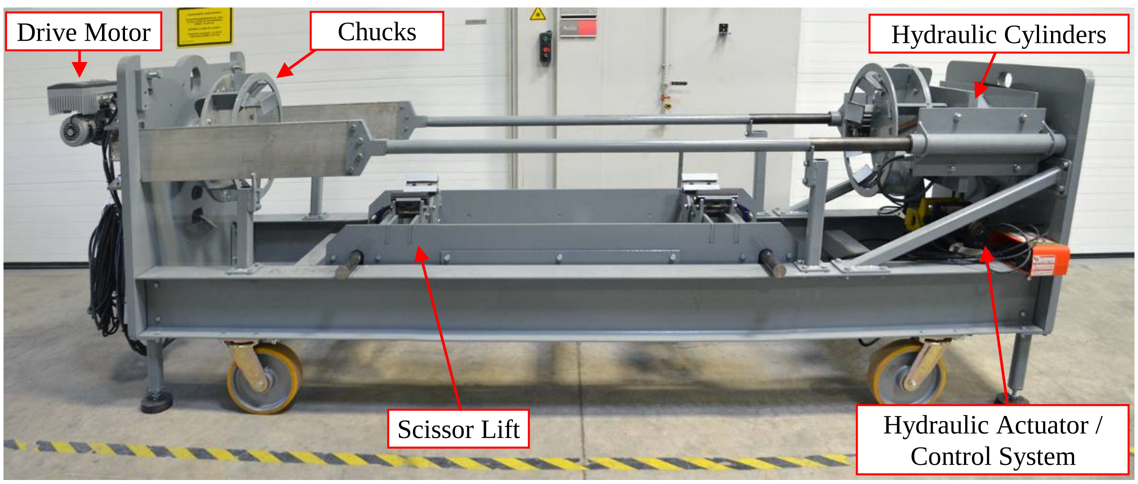

Figure 6 Rotation Equipment (ROTEQ) for Mark II Used Fuel Container welding

3. Results

3.1 HLAW Process Development and Demonstration for the Used Fuel Container

3.1.1 Joint Design and Preparation

An initial study investigated NWMO's proposed integral backing joint design by determining the achievable penetration depth while maintaining weld quality using various preparation techniques. As shown in Figure 7 (a), a simple square butt joint achieved quality welds of 8mm-11mm depth (averaging 9mm). Depths of >13mm were achieved; however, root cracking occurred. To achieve quality welds at greater depths, a V-groove joint prep was added. This allowed depths up to ~20mm, as shown in Figure 7 (b), in a single pass with the filler metal providing ~10mm of penetration.

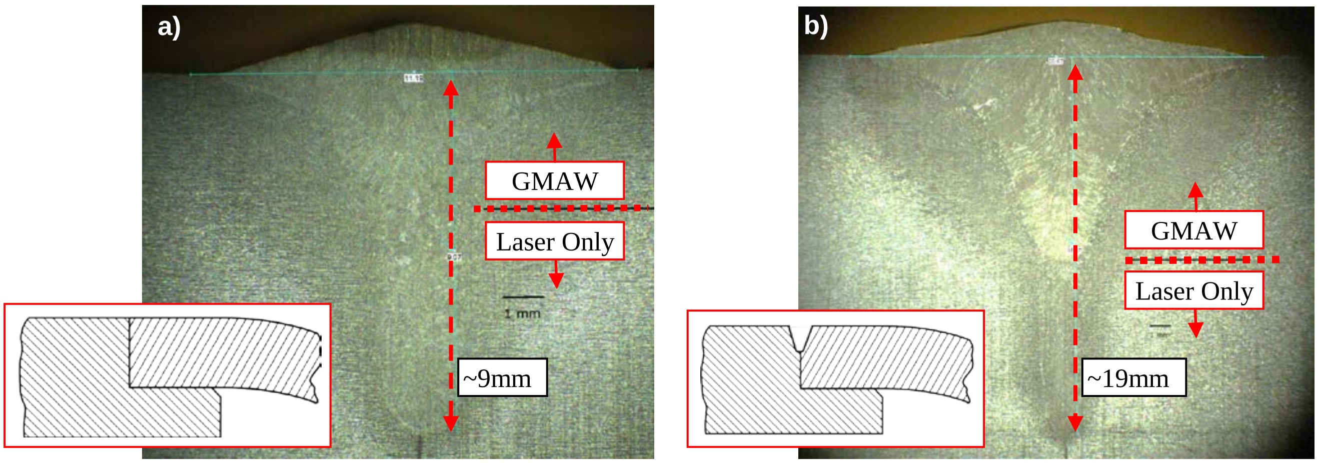

Figure 7 Typical Hybrid Laser Arc Weld Micrographs (a) Butt joint (no preparation) (b) ~8mm V-groove joint preparation

The sensitivity of joint position and fit up was also examined. The axial gap between the head and shell were varied from 0.0mm up to 1.0mm. The surface mismatch was tested up to ~1.6mm. As shown in Figure 8, the GMAW weld filler metal accommodates for up to 0.5mm of gap and 1.6mm of mismatch while still producing quality welds. The NWMO has set preliminary tolerances that ensure that the maximum gap and mismatch are below these values.

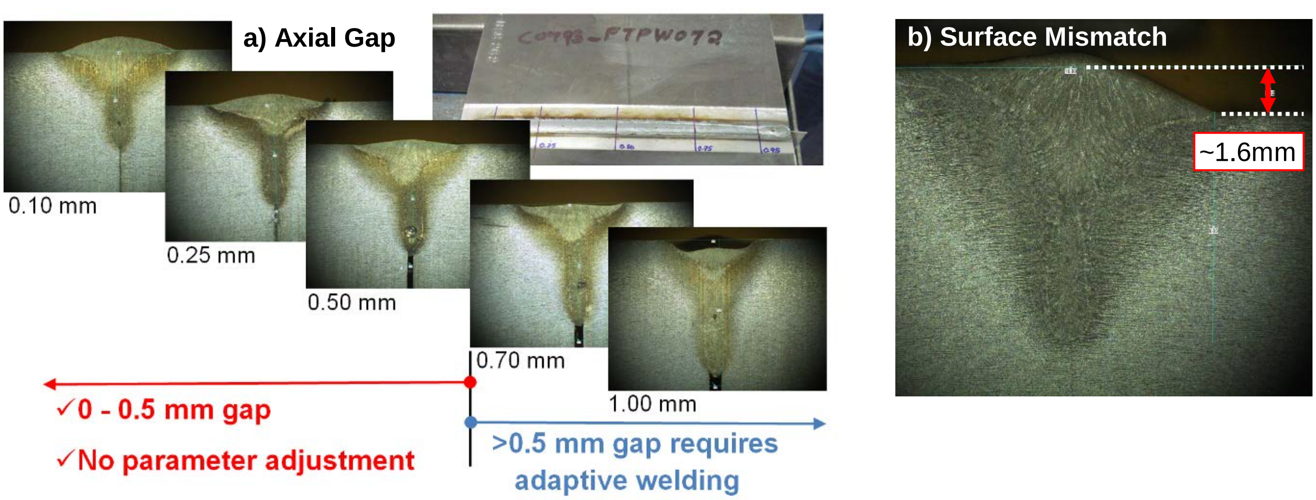

Figure 8 Joint tolerance for acceptable welds (a) Axial gap < 0.5mm (b) Surface mismatch < 1.6mm

3.1.2 Metallurgical and Mechanical Properties

A key metallurgical requirement is no untempered martensite after welding; additionally, the NWMO wishes to avoid a post-weld heat treatment operation. Novika Solutions determined that pre-heating was necessary to achieve these requirements and performed parameter trials at 100°C to ~500°C. The study concluded that a minimum pre-heat of 400°C produces hardness less than 22HRC (250 Vickers); measurement values and locations are summarized in Figure 9. To consistently ensure low hardness, a reference pre-heat value of 450°C is applied and maintained on the container prior to and during welding. The key mechanical properties were also tested on the qualification samples. All specimens exceeded the ASME Section III requirements, summarized in Table 2.

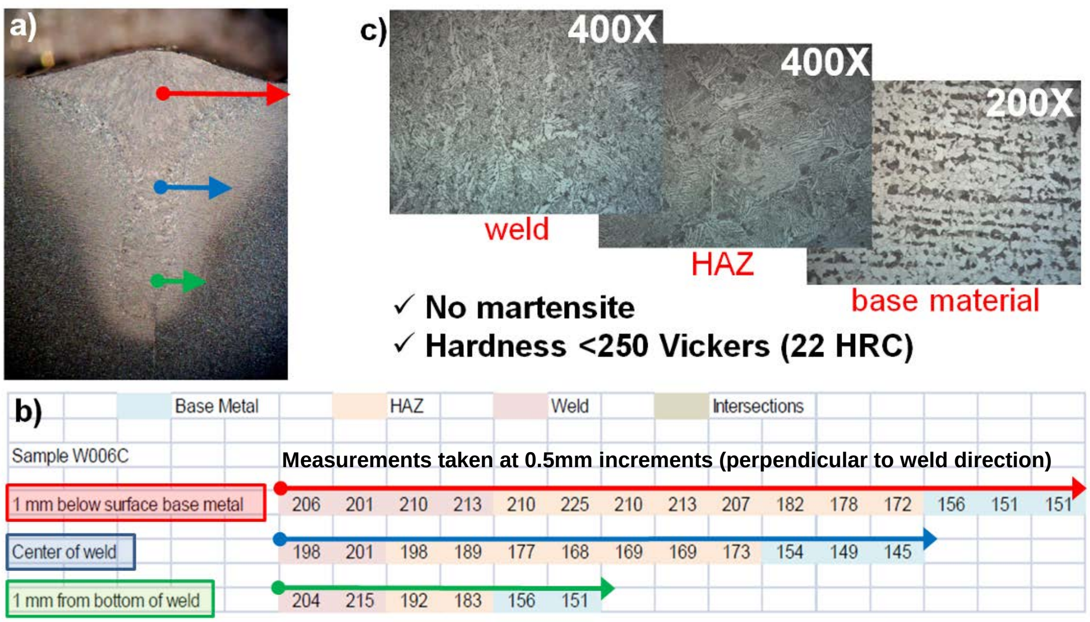

Figure 9 Metallurgical Analysis (a) Micrographic cross-section (b) Hardness measurements < 250 Vickers (22 HRC) (c) Micro-structure of weld, Heat Affected Zone (HAZ), and base material - no martensite visible

Table 2 Mechanical Properties Analysis

Property	**Requirement**	**Result**	**Comments**
Tensile Strength	≥ 483 MPa	496 MPa avg.	All specimens passed. Ductile failure in base material, except for one specimen in weld at 502 MPa.
Ductility (side bend test)	No open discontinuities	No open discontinuities	All eight specimens passed
Charpy Impact Toughness @ -5°C	≥ 27J	105J avg.	All six specimens passed.

3.1.3 Non-destructive Examination

Non-destructive examination was completed by ultrasonic inspection using both phased array and pulse echo methods. These methods provide a full volumetric examination of the weld and HAZ zone detecting porosities, lack of fusion, and penetration depth.

The inspection procedure followed applicable ASME Section III Division 3 and Section V methodology. All imperfections which produced a response greater than 20% of the reference level were investigated to determine the shape, identity, and location of all such imperfections and evaluate them in terms of the acceptance standards given in (a) and (b) below.

a. For weld procedure development purposes, unacceptable imperfections are those indications which exceed the reference level amplitude and have lengths exceeding 3 mm.
b. Indications characterized as cracks, lack of fusion, or incomplete penetration are unacceptable regardless of length.

All qualification welds passed ultrasonic examination using both phased array and pulse echo methods; all indications were less than 20% of the reference standard signal (i.e. non-relevant).

3.1.4 Weld Repair

Weld repair was performed on several different types of intentional defects including porosities, lack of penetration, missed joint, and lack of filler material.

Repair was completed by re-applying the welding procedure in the affected area with an additional ~20mm overlapping start and stop regions in existing "good weld". In these regions, the laser power is ramped from zero to full welding power (or vice versa) to prevent abrupt collapse of keyhole / weld pool. Ultrasonic examination was completed before and after the weld repairs to confirm successful repair of all weld defects.

The largest challenge for weld repair is re-locating the weld joint. Once the weld cap is machined flush, there is no identifying feature on the surface of the container for the seam tracker to locate the joint. To overcome this limitation, the weld system records the weld joint positions during the initial weld. All subsequent repair welding is completed in "playback" mode, where the positioning corrections are made on an elapsed-time basis or as a function of container radial position.

3.2 Leading Container Welding and Machining

The ROTEQ successfully welded and machined the prototype Mark II container. The operation of the ROTEQ is summarized below with key steps shown in Figure 10 and Figure 11:

1) The container is loaded into the moveable scissor lift for initial positioning of the container
2) Once located, the upper hemi-spherical head is positioned onto the container shell integral backing.
3) Two linear hydraulic cylinders securely clamp the hemi-head and container shell. A hydraulic accumulator is used to prevent loss of pressure and clamping force. The scissor lift is retracted and the full container weight is supported solely by the end chucks.
4) A circular induction heating coil slides over the container weld zone with a uniform ~1/4" standoff distance and begins pre-heating.
5) An encoded, high torque gear motor rotates the container ensuring uniform pre-heat at all locations.

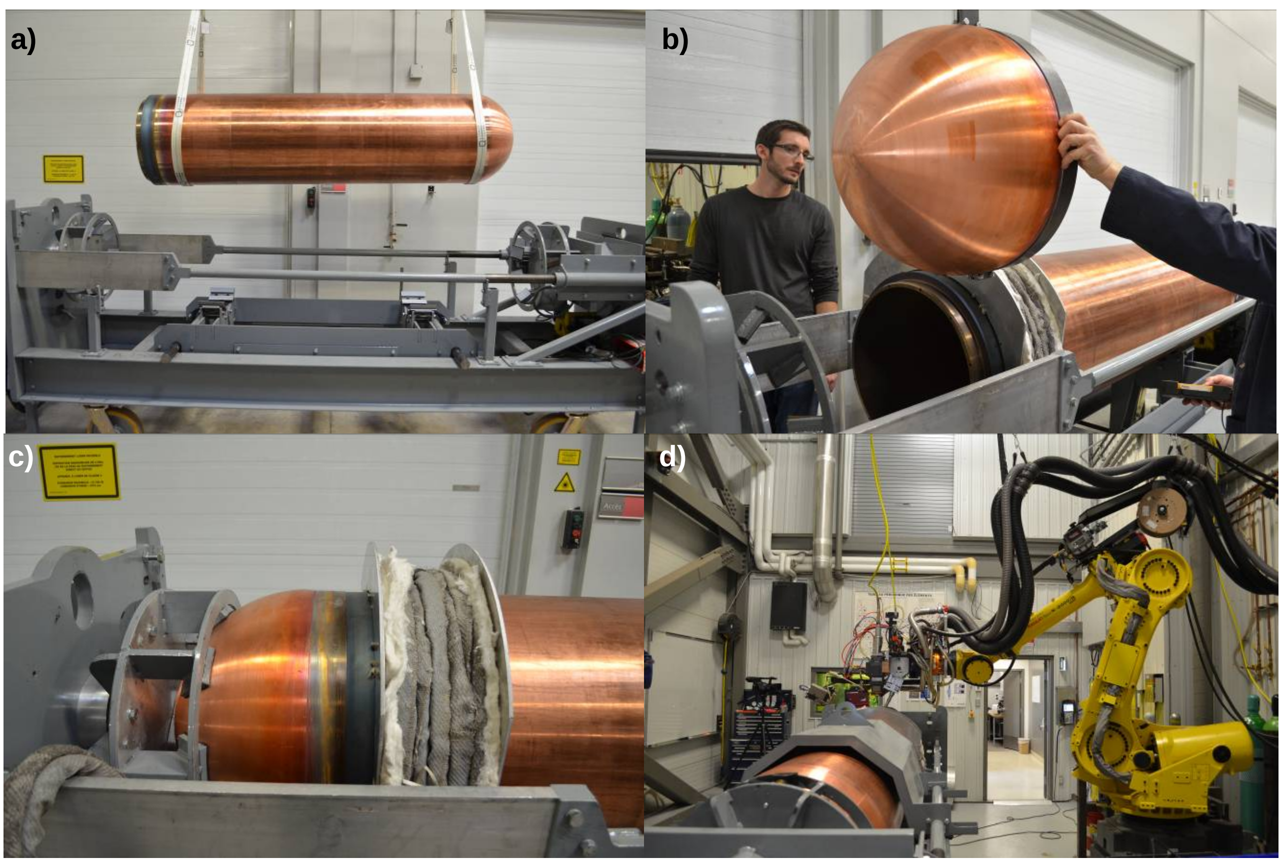

Figure 10 Mark II Used Fuel Container Welding (a) Loading container into scissor lift (b) Loading upper hemi-head into position (c) End-clamping of container and positioning of non-contact induction heater (d) Welding with splatter guards in place

6) Once the pre-heat temperature is reached, the induction coil is moved directly beside the weld zone on the shell side. It continues operating during welding to maintain the pre-heat temperature.
7) The Fanuc robot with Novika Solution’ custom weld end effector moves into position above the weld zone.
8) The rotation begins and the tacking sequence is initiated. A laser-only tack weld is completed every 45 degrees. After all 8 tacks are completed, the position is reset.
9) The rotation begins and the final welding sequence is initiated. The seam tracker leads the hybrid laser-GMAW and follows the position of the joint. The weld is completed in less than 3 minutes.
10) After cooling, the induction coil is moved out of the way and the weld cap machining attachment is installed.
11) The weld cap machining is initiated and the cap is removed in one or two passes.

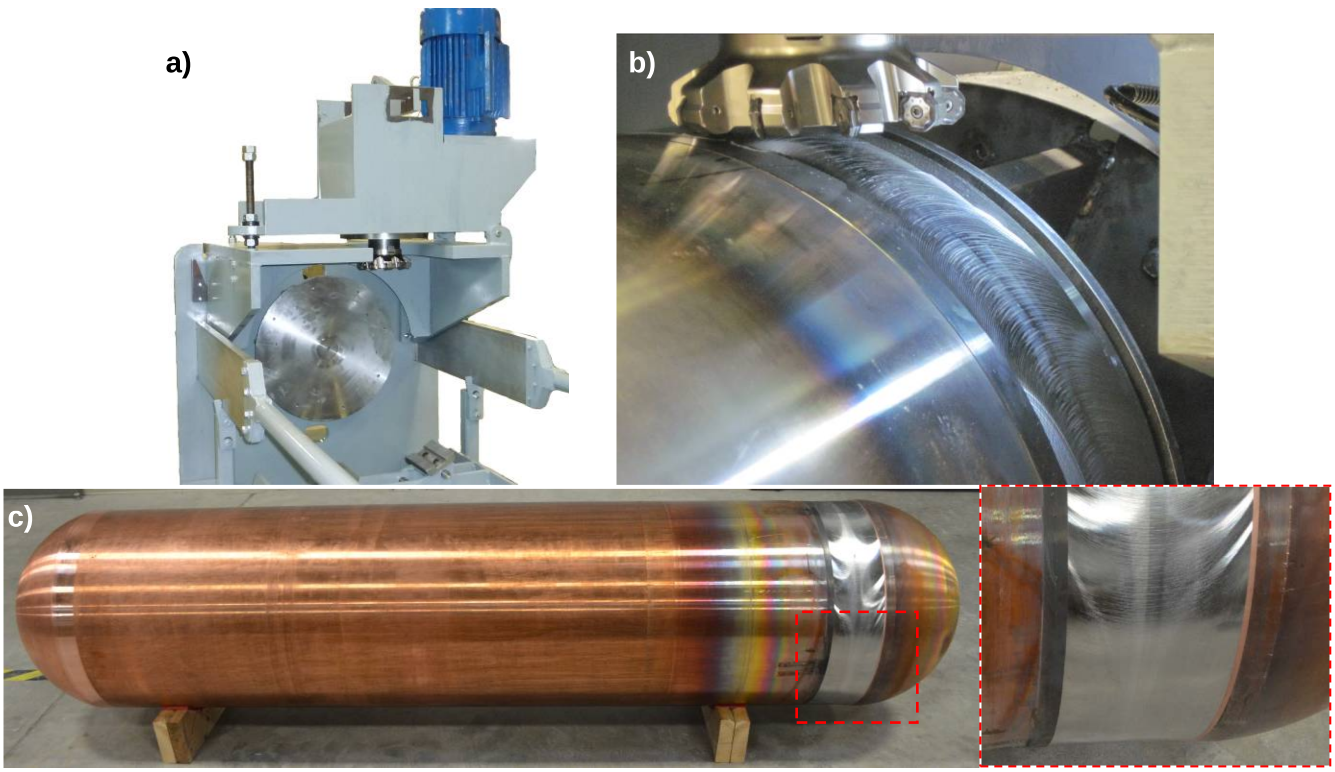

Figure 11 Mark II Used Fuel Container Machining (a) ROTEQ with weld cap removal attachment installed (head chuck removed for clarity) (b) Close-up of face mill cutting tool (c) Post-machining surface finish

4. Conclusions and Future Work

NWMO and Novika Solutions have demonstrated that Hybrid Laser Arc Welding is a viable process for closure welding of the Used Fuel Container. It is a fast, repeatable, and repairable process meeting all NWMO requirements. A draft weld procedure specification has been produced, tested, and analyzed on plate and pipe specimens with all metallurgical, strength, and quality properties meeting the ASME Section III requirements. A custom piece of equipment for welding the Mark II container was designed, fabricated, and tested successfully on full-scale Mark II container prototypes.

As part of future work, Novika Solutions is investigating weld parameter sensitivity and its effect on weld quality. After this investigation, a final weld procedure specification will be created for the normal and repair weld scenarios. The ROTEQ equipment will be upgraded to incorporate automation features, such as non-contact pre-heat temperature control and rigid coil induction heating system that does not need to be manually re-positioned prior to welding.

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