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Revision 0

Assessment of UTP A 2133 Mn as a Matching Filler Metal for Alloy 800H in Section III, Division 5 Applications

September 2023

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Idaho National Laboratory

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ABSTRACT

Six alloys are qualified in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) for elevated-temperature nuclear components. Due to reactor design alloy restrictions and motivation to improve operational efficiency and plant lifetimes, it is necessary to maximize the usefulness of qualified alloys. One of these alloys is Alloy 800H, which is qualified for a maximum temperature of 760°C and a maximum 300,000-hour service life. However, the welding filler metals qualified to join Alloy 800H have stress rupture factors that reduce the allowable weldment strength by factors as low as 0.59 times the Alloy 800H base metal. In an effort to improve the weldment creep-rupture performance, or to increase the stress reduction factor, non-code qualified filler metals are under investigation by the Department of Energy's Advanced Reactor Technologies program. For this investigation, UTP A 2133 Mn filler metal (Fe-Cr-Ni-Mn-Nb) was used to join 0.5-in. thick Alloy 800H plate to demonstrate passing an ASME BPVC Section IX weld qualification. The multi-pass, pulsed gas tungsten arc welding process showed successful weld qualification results, and additional property measurements were conducted to compare previous analyses of Alloy 82 and Alloy 617 filler metals. Future work will evaluate the cross-weld creep-rupture performance of the UTP A 2133 Mn in comparison to Alloy 82 and Alloy 617 filler metals.

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ACRONYMS

ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BPVC	Boiler and Pressure Vessel Code
CTE	coefficient of thermal expansion
DOE	Department of Energy
EDS	energy dispersive spectroscopy
FM	filler metal
GCR	gas-cooled reactor
GTAW	gas tungsten arc welding
HAZ	heat affected zone
INL	Idaho National Laboratory
MTR	material test record
NE	Office of Nuclear Energy
NRC	nuclear regulatory commission
SEM	scanning electron microscope
SMAW	shielded metal arc welding
SRF	stress reduction factor
UNS	unified numbering system
US	United States
UTS	ultimate tensile strength

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Assessment of UTP A 2133 Mn as a Matching Filler Metal for Alloy 800H in Section III, Division 5 Applications

1. INTRODUCTION

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) regulates elevated-temperature nuclear components in Section III, Division 5 [1]. Only six alloys are qualified in Division 5 for welded (non-bolted) Class A metallic pressure boundary components for high-temperature service. One of these alloys is Alloy 800H (33Ni-42Fe-21Cr), which is qualified for service temperatures up to 760°C and a maximum service life of 300,000 hours. Division 5 also specifies the filler metals for welding each alloy. For Alloy 800H, only one bare wire filler metal is permitted in Division 5, which is nickel base alloy ERNiCr-3 (UNS N06082), also known as Alloy 82 or filler metal (FM) 82 [1]–[3]. Only one other filler metal is permitted for welding on Alloy 800H. This filler metal is ENiCrFe-2 (UNS 86133), also known as Alloy A, which is a flux-coated electrode for shielded metal arc welding (SMAW) [3], [4]. ENiCrFe-2 filler metal is in the form of a flux-coated stick electrode commonly used for field fabrication and repair welding.

Due to weldment cracking in the Clinch River Breeder Reactor, the Nuclear Regulatory Commission (NRC) expressed concerns about weldment design procedures. Thus, ASME introduced weldment design limits within ASME BPVC Section III, Division 5, Subsection HB, Subpart B (HBB). These limits are referred to as stress reduction factors (SRFs) to account for the potential of creep strength reduction across weldments. The SRFs range from zero to one, where one indicates the weldment performs as good or better than the base material. These SRFs are for a specific material and filler metal combination and depend on the service temperature and operational lifetime. Further details on SRF determination and calculations can be found in Sham's 2021 report [5]. SRFs for Alloy 800H welded with ERNiCr-3 ranges from 1.0 at 475°C to 0.59 (lowest) at 750°C for a 300,000 hr service life [1]. Therefore, welds using Alloy 82 exposed to the maximum temperature and lifetime permitted for Alloy 800H are reduced to 59% of the base metal elevated-temperature properties.

Creep-rupture across a weldment, where the base metal, heat affected zone, and fusion zone all have distinct variations in microstructure, is a result of damage accumulation based on the local properties and material interaction. According to Corum [6], weldment creep-rupture depends on the relative yield strength and creep deformation. It was believed that different filler metal properties may improve high-temperature cross-weld creep strength and SRFs. Because of this, Rupp [7], evaluated Alloy 617 filler metal in comparison to Alloy 82 [7], [8]. Alloy 617 is an overmatched alloy and creep-rupture lives did not show improved performance [8]. All failures with the Alloy 617 filler welds occurred at or near the heat affected zone (HAZ), and creep test temperatures below 950°C failed in the HAZ directly adjacent to the fusion boundary [7], [8]. Due to the Alloy 617 showing no improvement in creep-rupture strength compared to FM 82, Rupp [7] initiated evaluation of an alternative filler metal, UTP A 2133 Mn, used for welding Alloy 800H in other industries [9]. It was reported by Grooten et al. [10] and Van Zyl et al. [11] that the difference in creep-rupture strength may be a result of stresses caused by the variation in tensile strength and coefficient of thermal expansion between the base metal and filler metal. Literature has shown that Alloy 800H welded with a near-matching filler metal may improve creep-rupture performance [12], [13]. These results were the basis for the UTP A 2133 Mn filler metal analysis.

This report contains the gas tungsten arc welding (GTAW) parameters that were developed to pass an ASME BPVC Section IX, "Welding, Brazing, and Fusing Qualifications" [14], weld qualification for Alloy 800H plate welded with UTP A 2133 Mn filler metal. Parameter optimization and microstructure evaluation was reported in previous work [9], [15], but this report contains the specific variables and test results to perform a weld suitable for Section IX qualification [14]. Future work will evaluate the cross-weld creep-rupture performance using identical weld parameters to pass weld qualification. The UTP A 2133 Mn filler metal will then be compared to Alloy 617 and Alloy 82 creep-rupture properties.

2. EXPERIMENTAL METHODS

The following subsections include the material compositions, material test record (MTR) information, GTAW parameters, and microstructure examination procedures. These methods were to examine the ability to pass an ASME Section IX weld procedure qualification for GTAW of Alloy 800H plate welded with UTP A 2133 Mn filler metal. Additional mechanical and microstructure analysis was performed to better understand weld metal properties of UTP A 2133 Mn in comparison with Alloy 800H and the previous Alloy 617 and Alloy 82 weld trials [7], [8].

2.1 Materials

The composition of the 0.5-in. thick Alloy 800H (UNS N08811) is shown in Table 1. The Alloy 800H was in the solution annealed condition with a minimum annealing temperature of 2100°F (≈1150°C). Table 1 also contains the chemical composition of the UTP A 2133 Mn filler metal. Both compositions are from the MTRs. The filler metal wire diameter was 0.047-in. The UTP A 2133 Mn filler material does not have an associated F-number defined in ASME BPVC Section IX [14].

Table 1. Chemical composition in weight percent of Alloy 800H and UTP A 2133 Mn filler metal. Reported compositions are from the manufacturer's MTRs.

	Fe	**Ni**	**Cr**	**Mo**	**Nb**	**Ti**	**Al**
800H	46.2	30.6	19.7	-	-	0.54	0.56
UTP A 2133 Mn	Balance	32.1	21.6	<0.1	1.23	-	-
	Co	**Cu**	**Si**	**Mn**	**C**	**P**	**S**
800H	0.10	0.20	0.42	1.27	0.061	0.024	0.001
UTP A 2133 Mn	-	<0.1	0.2	4.8	0.16	0.008	0.001

2.2 Welding Parameters

The welding process was a semi-automated, pulsed gas tungsten arc welding (GTAW-P) using direct current electrode negative polarity. The shielding gas was inert argon (99.99%) meeting the requirements of AWS A5.32/A5.32M, "Welding Consumables – Gases and Gas Mixtures for Fusion Welding and Allied Processes" [16]. The joint design used a 30-degree included angle, a backing plate, and an approximately 3/16-in. root opening, as shown in Figure 1. These dimensions were based on prior work that analyzed Alloy 617 and Alloy 82 filler metals [7], [8]. Table 2 contains the weld parameters for the successful weld qualification of Alloy 800H welded with the UTP A 2133 Mn filler metal. Wire feed speed was varied for the root, fill, and cap passes. These speeds were 60-, 70-, and 45-in./min, respectively. A total of five passes were used to fill the joint, resulting in three fill passes. The welds were tested in the as-welded condition (i.e., no post weld heat treatment).

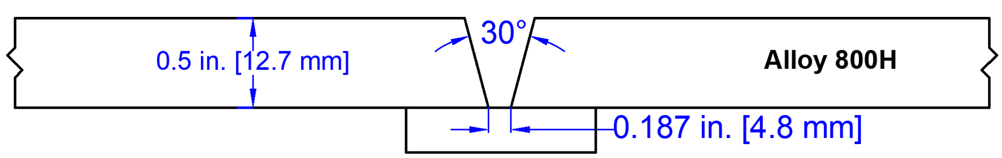


Figure 1. Full penetration butt joint, V-groove geometry with backing plate used for weld qualification analysis.

Table 2. Welding parameters, excluding the wire feed speeds, for all weld passes.

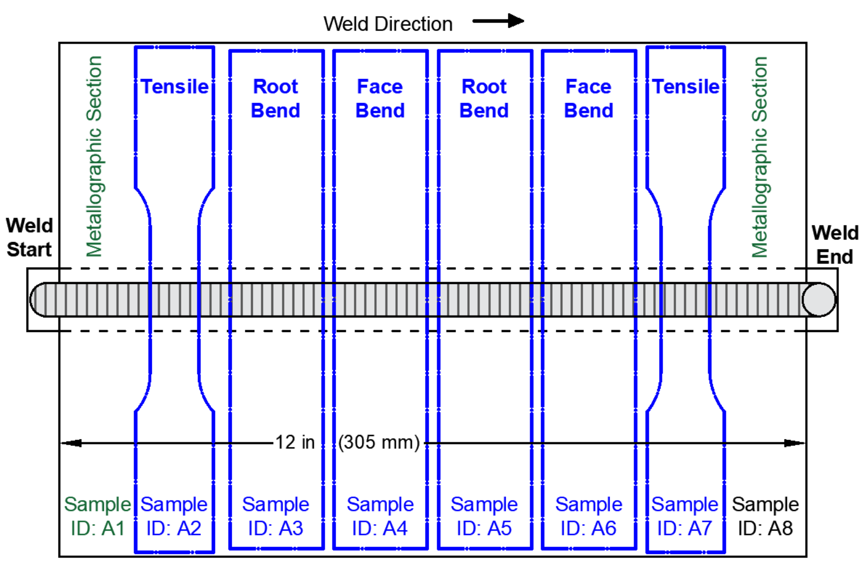
Peak Current (A)	Peak Pulse Time (s)	Background Current (A)	Background Pulse Time (s)	Voltage (V)	Travel Speed (in/min, [mm/s])	Heat Input (kJ/in, [kJ/mm])
325	0.2	225	0.2	11	4.5, [1.9]	40.3, [1.59]

2.3 Microstructure Characterization

Sample preparation involved typical metallography procedures such as sectioning and hot mounting in a thermosetting polymer. Grinding followed successive steps from 400- to 800-grit silicon carbide abrasive paper. Electrochemical etching was performed using 10% oxalic acid at 6 V. The etch time was approximately 20 seconds for light optical microscopy. For scanning electron microscopy, the transverse cross-section was analyzed in the unetched condition. Scanning electron microscopy was performed using a FEI Quanta FEG 650 scanning electron microscope (SEM). The accelerating voltage was 20kV at a 6.0 spot size, and the working distance was 10 mm. Energy dispersive spectroscopy (EDS) was performed using an Octane Elect Plus C5 detector and EDAX TEAM software, Version 4.6.

2.4 Mechanical Testing

Figure 2 shows the tensile and bend test specimens as extracted from the weld test coupon according to ASME Section IX [14]. Property measurements of a weld metal deposit, which contained no base metal (Alloy 800H) dilution, was also analyzed via laser ultrasound and laser-based coefficient of thermal expansion (CTE) measurements to better understand the properties of the UTP A 2133 Mn filler metal.



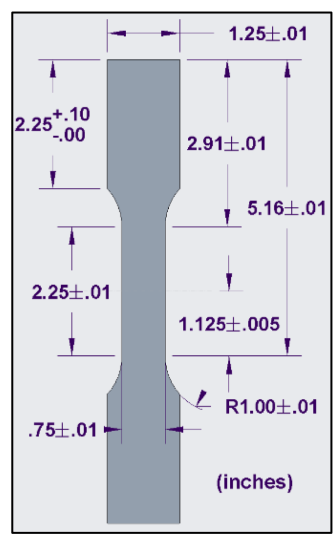


Figure 2. Schematic of extracted mechanical test specimens (left) and dimensions of the full thickness tensile specimens (right).

2.4.1 Bend Testing

Bend testing was performed using a plunger type bend test machine according to ASME Section IX with a 1.5-in. diameter bend radius. Two face bend (top side of weld) specimens A4 and A6, and two root bend (bottom side of weld) specimens A3 and A5 were tested. The respective sides were placed on the outer side of the bend radius, so the respective face or root side was in tension as labelled in Figure 2. The results are discussed in Section 3.1.1.

2.4.2 Tensile Testing

Tensile testing was performed at ambient temperature using an Instron 5984 load frame with 150-kN maximum capacity load cell. An extensometer with a 1.5-in. gage section was used until a total strain of 10%. Then, the extensometer was removed to pull the specimens to failure. The ultimate tensile strength (UTS) was determined from these two test specimens based on the measurements reported in Table 3. A strain rate of 0.05-in./in./min was used until 10% strain, and then, the strain rate was increased to 0.1-in./in./min until failure for conformance to ASTM E8/E8M-21, "Standard Test Methods for Tension Testing of Metallic Materials [17]. These results are discussed in Section 3.1.2.

Table 3. Full thickness tensile specimen reduced area measurements.

Sample Number	Width [in, (mm)]	Thickness [in, (mm)]	Area [in^2, (mm^2)]
A2	0.7488, (19.02)	0.4606, (11.70)	0.3449, (222.5)
A7	0.7504, (19.06)	0.4606, (11.70)	0.3456, (223.0)

2.4.3 Young's Modulus, Poisson's Ratio, and CTE Measurements

For using laser ultrasound to measure the Young's modulus, a weld metal deposit consisting of 12-layers of UTP A 2133 Mn filler metal were made on Alloy 800H plate. Cylinders, 10 mm in diameter, were machined from the weld metal deposit. Disks were created with approximately 1.5 mm thickness from the top portion of the weld deposit. Disks 10 mm in diameter and 1.5-mm in thickness were also extracted from the Alloy 800H. Time of flight measurements were made using laser pulses to determine the Young's modulus and Poisson's ratio using Idaho National Laboratory's (INL's) laser ultrasound system. The specific information regarding the laser ultrasound theory, measurement system, and previous data can be found in Hurley and Spicer's 1999 article and Rees et al.'s 2021 article [18], [19].

For CTE measurements, the weld deposit was prepared into 10 mm diameter cylinders at approximately 20 mm lengths for the UTP A 2133 Mn. The Alloy 800H was extracted in a 10 mm diameter cylinder and sanded to an approximately 10 mm length. Measurements were made using a NETZSCH DIL 402 SE dilatometer with a sample heating rate of 3°C/min and data recorded at each 1°C change. The reported test data is an average of three measurements for both materials. See section 3.1.3 and 3.1.4 for the results.

3. RESULTS

The welded qualification plate is shown on the left in Figure 3, and the mechanical test specimens machined from plate are shown on the right in Figure 3 The metallographic cross-section to indicate a weld without porosity, cracking, or lack of fusion defects is shown in Figure 4. From the metallographic transverse cross-section, the total percent of base metal dilution was measured at 11%. Based on this dilution, the weld metal deposit does not fall within an A-Number as defined in Section IX [14]. The high 4.8 wt% manganese concentration excludes it from an A-Number classification.

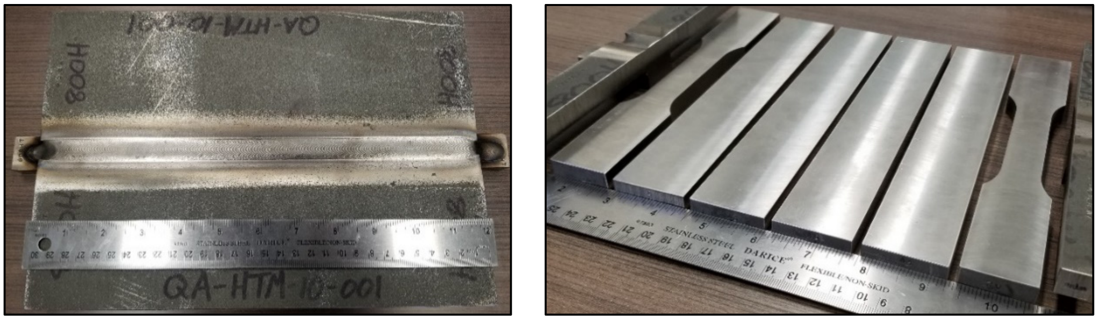


Figure 3. Alloy 800H welded with UTP A 2133 Mn filler metal using five passes (left), and ASME mechanical test specimens machined from the qualification plate (right).

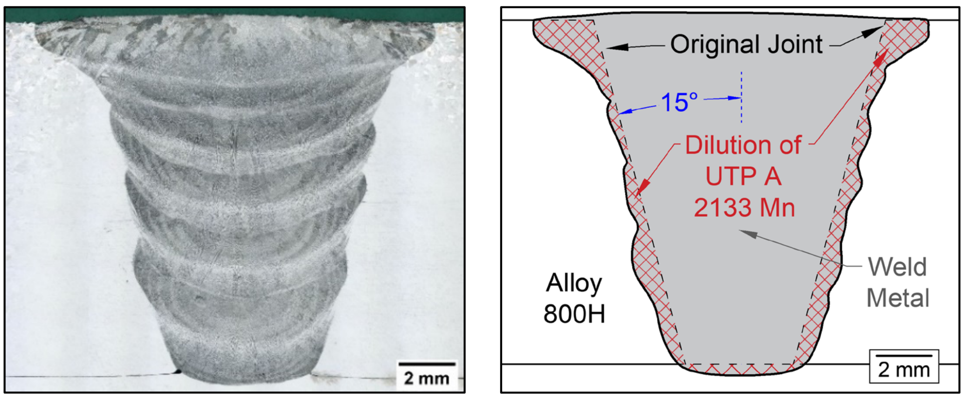


Figure 4. Alloy 800H welded with UTP A 2133 Mn filler transverse cross section (left) and estimated dilution of base metal in weld metal from the traced schematic (right).

3.1 Mechanical Testing

The following mechanical testing results include the bend and tensile tests required for ASME Section IX [14] weld qualification and additional material property measures to better understand the influence on creep-rupture strength.

3.1.1 Bend Testing

Figure 5 shows mechanical bend specimens after testing. The deformation throughout the weld can be seen, but the bend specimens did not contain defects, as defined in Section IX. Therefore, all bend specimens pass according to Section IX requirements [14].

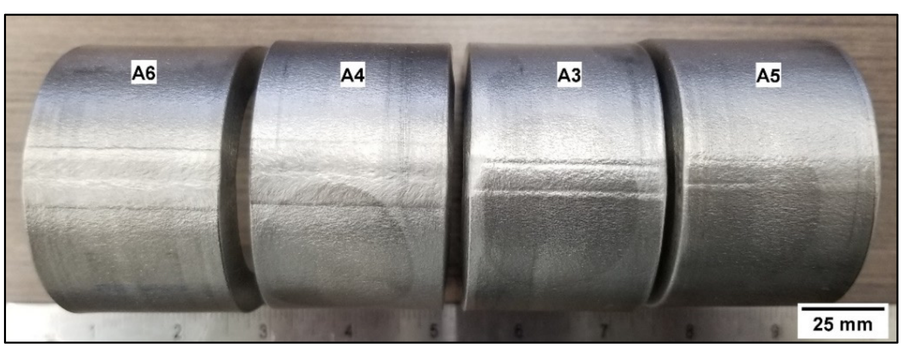


Figure 5. Two face bend tests (left) and two root bend tests (right) showing no indications of weld defects.

3.1.2 Tensile Testing

Both tensile specimens were pulled to failure as shown in Figure 6. These tensile tests were performed at ambient temperature. The failure location for both specimens was in the base metal with UTSs of 556 MPa and 552 MPa, which were higher than the minimum base metal tensile strength of 65 ksi (448 MPa) as specified in ASME Section IX [14]. The measured stress versus strain curves for both specimens are shown in Figure 7. By exceeding the minimum base metal tensile and having the failure location within the base metal, both tensile specimens passed Section IX requirements [14].

Figure 6. Cross-weld tensile samples showing the failure location in the Alloy 800H base metal for the Alloy 800H welded with UTP A 2133 Mn filler metal.

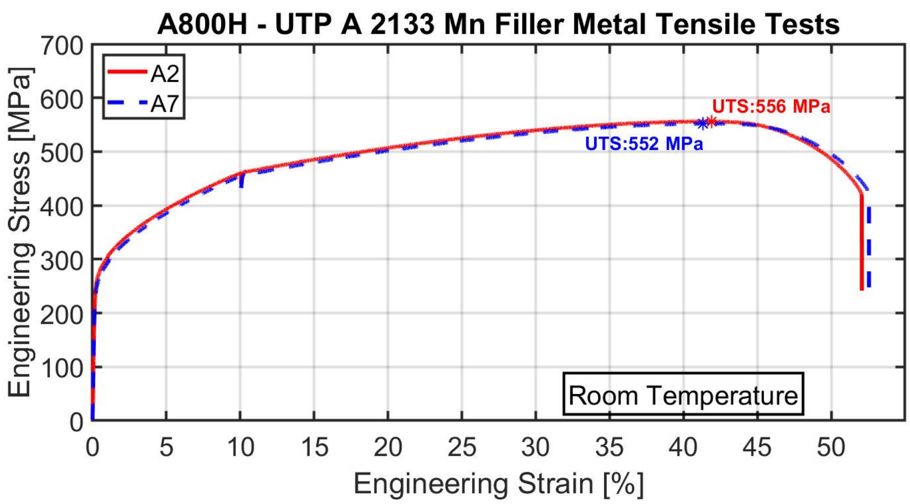


Figure 7. Cross-weld tension testing engineering stress versus strain plot for Alloy 800H welded with UTP A 2133 Mn filler metal.

3.1.3 Laser Ultrasound Measurements

For a better understanding of how local properties influence the cross-weld creep performance, a weld pad of UTP A 2133 Mn filler metal was deposited to evaluate the filler metal properties. Samples were machined out of the filler metal to perform laser ultrasound measurements using the same methods as reported by Reese et al. [19]. The results of temperature dependent Young's modulus and Poisson's ratio are shown in Figure 8. UTP A 2133 Mn filler metal showed a lower Young's modulus and Poisson's ratio compared to Alloy 800H.

Additionally, thermal expansion measurements showed that Alloy 800H and UTP A 2133 Mn filler metal has nearly the same change in length from ambient temperature to 1000°C and an approximate, average CTE of 16x10^{-6} mm/mm°C. The measured change in length results are shown in Figure 9. Based on the literature, the similar CTE may result in improved cross-weld creep-rupture lifetimes. [10], [11].

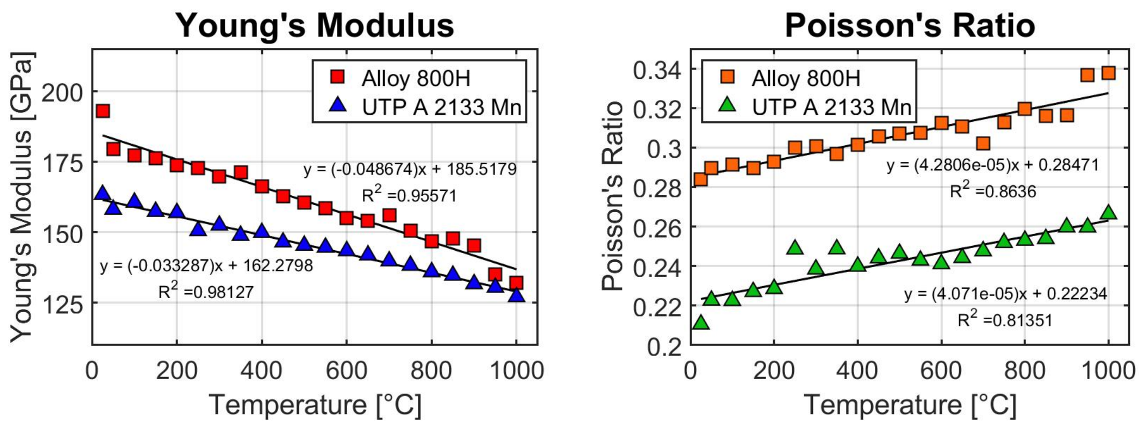


Figure 8. Laser ultrasound results showing Young's modulus (left) and Poisson's ratio (right).

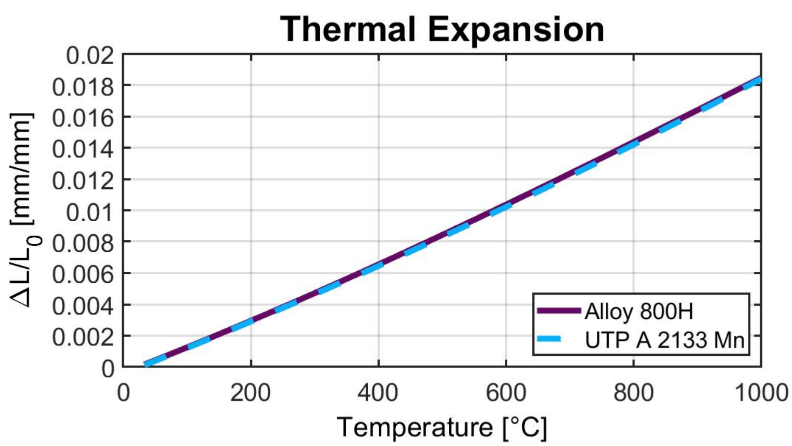


Figure 9. Change in length over original length versus temperature for Alloy 800H and UTP A 2133 Mn specimens.

3.1.4 Microstructure Analysis

Figure 10 shows optical micrographs for the as-welded fusion zone. The cellular-dendritic morphology is apparent at the higher magnification (right in Fig. 10) due to the interdendritic segregation. The relatively high manganese and niobium concentration in the UTP A 2133 Mn filler metal are intentional alloying elements to mitigate solidification cracking. Confirmation of the segregated constituents is shown via the EDS scans in Figure 11. These EDS maps were captured from the root pass, which would have received numerous reheating cycles from subsequent weld passes. However, the intercellular segregation remained and is mostly composed of manganese and niobium but depleted of iron. Nickel showed a homogenous concentration through the solidification structure (i.e., from dendrite cores to interdendritic regions). Chromium showed enrichment in the interdendritic regions, but to a lesser degree than niobium or manganese.

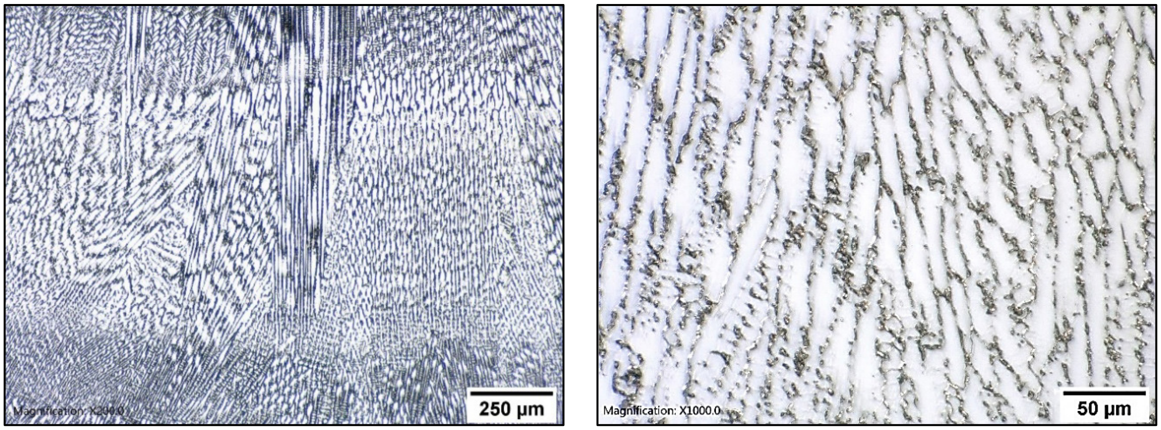


Figure 10. Optical microstructures showing the weld metal solidification structure.

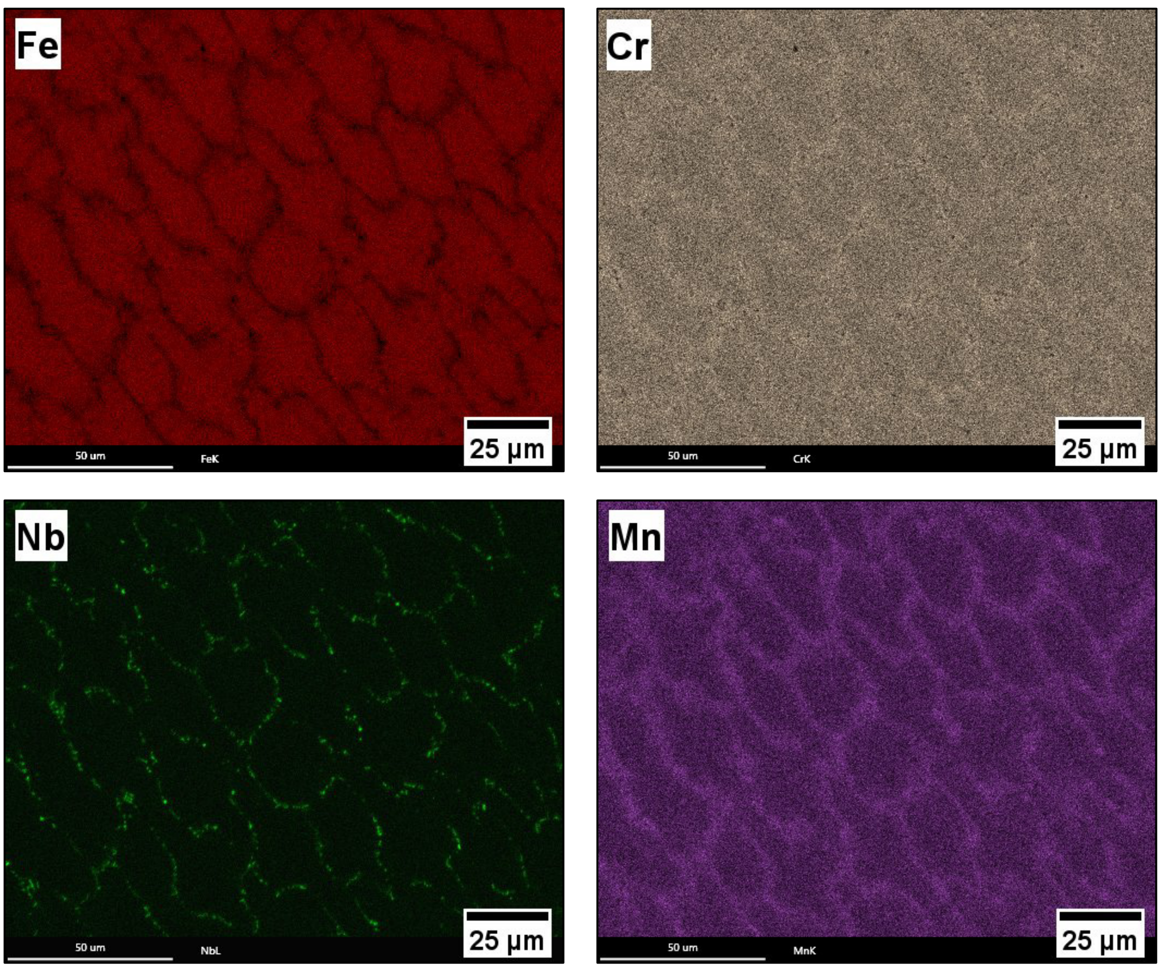


Figure 11. EDS scans in the root pass weld metal showing depletion of iron but enrichment of chromium, manganese, and niobium in the interdendritic regions.

4. SUMMARY

The UTP A 2133 Mn filler metal showed the ability to pass an ASME Section IX weld qualification using multi-pass pulsed GTAW deposited on a 0.5-in. thick Alloy 800H plate. Additional property measurements showed that the UTP A 2133 Mn alloy has a lower Young's modulus and Poisson's ratio than the Alloy 800H. However, the coefficient of thermal expansion measurements showed a similar change in length (CTE) between ambient temperature and 1000°C, which suggests the material is a good candidate for increasing the SRFs. Future testing will assess the creep-rupture lifetime and compare it with the previous results for Alloy 82 and Alloy 617 filler metals.

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