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Changing the World's Energy Future

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AN INITIAL ASSESSMENT OF THE CREEP-RUPTURE STRENGTHS FOR WELDMENTS WITH ALLOY 800H BASE METAL AND ALLOY 617 FILLER METAL

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ABSTRACT

In Section III, Division 5 of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Alloy 800H is qualified for elevated-temperature nuclear construction for temperatures up to 760°C (1400°F) and a maximum service life of 300,000 hours. There are two permissible filler metals for Alloy 800H weldments specified in Division 5: ENiCrFe-2 (Alloy A) and ERNiCr-3 (Alloy 82). Low creep-rupture strengths of these weldments at the upper limits of the qualified temperatures and service lives may restrict the design envelope for elevated-temperature nuclear construction with Alloy 800H. As a result, an alternative filler metal is desired to improve the creep-rupture strengths of Alloy 800H weldments for the qualified temperatures and service lives.

This work investigates an overmatched filler metal. Specifically, a weldment with Alloy 800H base metal and Alloy 617 filler metal fabricated by semiautomated gas tungsten arc welding is investigated. A scoping creep-rupture test program was conducted of cross-weld specimens at temperatures ranging from 750 to 1000°C (1292 to 1832°F). Preliminary results on the creep-rupture strengths of the Alloy 800H weldment with an Alloy 617 filler metal do not show significant improvement compared to the filler metals currently qualified in Division 5 for Alloy 800H weldments. Consequently, work is in progress to investigate a matching filler metal.

Keywords: Weldments, Alloy 800H base metal, Alloy 617 filler metal, creep-rupture strength, elevated-temperature nuclear construction

1. INTRODUCTION

Section III, Division 5 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) issues design rules for the construction of components for elevated-temperature nuclear service. Currently, Division 5 permits only six alloys, including Alloy 800H, as non-bolting base materials for the construction of Class A metallic pressure boundary components. Division 5 permits service for components fabricated from Alloy 800H for temperatures and design lives up to 760°C and 300,000 hours, respectively. There are two permissible filler metals for Alloy 800H weldments specified in Division 5: ENiCrFe-2 (Alloy A) and ERNiCr-3 (Alloy 82) [1]. The former is permitted to be welded by shielded metal arc welding in accordance with the ASME BPVC SFA-5.11, "Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding" [2]. The latter is intended to be welded by gas metal arc, gas tungsten arc, plasma arc, and submerged arc welding processes. However, any welding process is permissible for which an ASME BPVC SFA-5.14, "Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods," filler metal is satisfactory [3].

In Division 5, the weldment creep-rupture strength is represented as the product of the stress-rupture factor (SRF) and the expected minimum stress-to-rupture of the base metal [1]. The SRF values are determined as the ratio of the average creep-rupture strength of the weldment to the base metal [4]. For the permissible temperatures and service lives, the SRF values range from 1.00 at low temperatures and short lifetimes to 0.59 and 0.54 at 760°C and a 300,000-hour life for Alloy 800H weldments comprised respectively of Alloy A and Alloy 82 filler metals [1]. Low creep-rupture strengths of these weldments at the upper portion of the qualified temperatures and service lives may restrict the design envelope for elevated-temperature nuclear construction with Alloy 800H.

As a result, an alternative filler metal is desired to improve the creep-rupture strengths of Alloy 800H weldments for the qualified temperatures and service lives. This work investigates an overmatched filler metal. An overmatched filler metal is defined as having a strength greater than the base metal. Specifically, this work studies a weldment of Alloy 800H base metal with Alloy 617 filler metal fabricated by semiautomated gas tungsten arc welding.

2. BACKGROUND

Weld factors were introduced into the ASME BPVC through Code Case N-47-26 in 1987. Prior to this code case, weldments were only minimally addressed. The purpose of the code case was to provide design rules for components comprised of weldments for elevated-temperature nuclear service [4, 5].

The SRF is treated as a knockdown factor to the time-dependent allowable stresses of the base metal to mitigate any potential negative effects of the weldment [1]. It is defined as R in Division 5. In Code Case N-47-26, the SRF values are calculated as the average rupture strength ratio of the deposited filler metal to the base metal [6]. Cross-weld and component-weld creep-rupture data were used to corroborate or revise the SRF values [4]. The cross-weld specimen configuration includes both the base and weld metal, which has the added benefit of capturing the impact of the metallurgical discontinuity. This discontinuity can be the result of a number of features including a heat-affected zone and non-uniform stresses and strains [5]. The modern-day practice is to use cross-weld or a mixture of cross-weld and deposited-filler-metal rupture data to calculate the SRF values [4]. A mixture of cross-weld and deposited-filler-metal rupture data was used to calculate the Alloy 800H SRF values [4, 6].

The average rupture strength of the weld (deposited filler metal, cross weld, component weld) can be better than, equivalent to, or worse than the average rupture strength of the base metal. The SRF is equal to one for the former two cases; otherwise, the SRF is between zero and one. The lower the average rupture strength of the weld is compared to the base metal, the closer the SRF value is to zero.

A formalized method for calculating the creep-rupture strengths in Division 5 has not been established [7]. The Larson-Miller parametric correlation is one approach for calculating creep-rupture strengths. This approach utilizes the Larson-Miller parameter (LMP), which combines time and temperature with the following correlation:

$$\mathrm{LMP} = \mathrm{T}\left(\log(\mathrm{t_r}) + \mathrm{C}\right) \quad (1)$$

where:

T = temperature, Kelvin

log = logarithm of base 10

t_r = time to rupture, hours

C = constant that is material dependent.

Furthermore, the LMP can be correlated with stress using the following equation:

$$\mathrm{LMP} = a_0 + a_1 \log(\mathrm{S}) + a_2 \left(\log(\mathrm{S})\right)^2 + \cdots \quad (2)$$

where:

S = stress, megapascals

log = logarithm of base 10

a_i = constants that vary with the number of polynomial terms fitted to the creep-rupture data [7].

3. EXPERIMENTAL METHODOLOGY

3.1 Material

An Alloy 800HT welded plate with Alloy 617 filler metal was fabricated using semiautomated multiple-pass gas tungsten arc welding (GTAW). The geometry of the joint was a 30° single V-groove with a 3-mm (0.12-in.) root opening. A tacked-on Alloy 800HT backing bar sealed the weld. In order to mitigate distortion, the plates were offset from parallel, approximately 6 mm (0.24 in.) on each side. The weld is compliant with Idaho National Laboratory (INL) Welding Procedure Specification I5.1 [8]. This welding procedure specification was developed in accordance with Section IX of the ASME BPVC (2007 version with 2009 Addendum) [9]. Additional information on the weld and welding process is available in the Engineering Calculations and Analysis Report number 1041 [10]. Section III, Division 1, Subsection NB, which Division 5 references, does not require a postweld heat treatment for nonferrous materials; hence, one was not performed [11]. From this point forward, this plate will be referred to as 800H/617. Alloy 800HT is a subset of Alloy 800H which will be elaborated on in the following paragraph.

The base-metal Alloy 800HT, UNS 08811, plate was acquired from Jessop Steel, heat 37458. The nominal thickness of the plate was 12 mm (0.47 in.). The chemistry of the plate as well as the Division 5 chemistry requirements for Alloy 800H are provided in Table 1 [1]. Heat 37458 is compliant with the chemistry and minimum room-temperature property requirements of Alloy 800H and will be referred to as Alloy 800H from this point forward.

Table 1: CHEMISTRY OF THE BASE-METAL ALLOY 800HT PLATE, HEAT 37458, AND ALLOY 800H CHEMISTRY REQUIREMENTS SPECIFIED IN DIVISION 5 IN WEIGHT PERCENT.

		Ni	Cr	Fe	Mn
Heat 37458		30.45	19.30	47.05	1.31
Division 5 requirements	minimum	30.0	19.0	39.5	-
	maximum	35.0	23.0	-	1.5

		C	Cu	Si	S
Heat 37458		0.063	0.21	0.37	0.001
Division 5 requirements	minimum	0.05	-	-	-
	maximum	0.10	0.75	1.0	0.015

		Al	Ti	Mo	Co
Heat 37458		0.43	0.45	0.21	0.11
Division 5 requirements	minimum	0.15*	0.15*	-	-
	maximum	0.60*	0.60*	-	-

* Al + Ti ≥ 0.50%

The Alloy 617, ERNiCrCoMo-1, filler metal was acquired from Oxford Alloys, heat XX3703UK. The diameter of the wire was nominally 1.14 mm (0.045 in.). The wire meets American Welding Society A5.14/A5.14M and ASME SFA-5.14/SFA-5.14M. The chemistry of the wire is provided in Table 2.

Table 2: CHEMISTRY OF THE ALLOY 617 FILLER METAL, HEAT XX3703UK, IN WEIGHT PERCENT.

Ni	Cr	Co	Mo	Fe	Mn
53.91	22.41	11.49	8.98	1.37	0.11
Al	**C**	**Cu**	**Si**	**S**	**Ti**
1.10	0.089	0.04	0.04	0.001	0.34

The base metal grain size of the 800H/617 plate was an American Society for Testing and Materials (ASTM) grain size of 2. Grain size did not vary with distance from the weld. Grain size was measured in accordance with the comparison technique in ASTM E112-13, "Standard Test Methods for Determining Average Grain Size," using Plate II [12].

The average hardness of the weld and unaffected base metal was 196 and 131 HV, respectively. The hardness of the unaffected base metal was measured on the welded plate at the furthest point from the weld, approximately 101.6 mm (4 in.). Care was taken to ensure that the hardness measurements were not affected by the edge of the plate. These weld and unaffected base metal values are the average of six measurements. The hardness at the fusion line was 178 HV. Hardness decreased from the fusion line to the unaffected base metal at a rate of approximately 1.7 HV/mm (0.067 HV/in.). The hardness matched the unaffected base metal approximately 25.4 mm (1 in.) from the fusion line. This was determined from the average of a minimum of two but typically three measurements. Hardness was measured with a Leco LM-310AT Microindention Hardness Testing System. A force and dwell time of 300 gf and 13 seconds, respectively, was used.

3.2 Creep-rupture testing

Uniaxial creep tests were conducted in air with the load and temperature constant throughout the duration of the test. Testing was compliant with ASTM standard E139-18, "Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials," and INL PLN-3386, "Creep Testing" [13, 14]. Applied Test Systems creep frames were used with the load applied either directly or indirectly. Indirect loading utilized either a 3:1 or 20:1 lever arm. The load was applied to the specimen after the specimen reached and was soaked for three hours at the desired test temperature. Thermocouples positioned at the top and bottom of the specimen's reduced section monitored temperature. For tests conducted above 750°C, R-type thermocouples were generally employed; otherwise, K-type thermocouples were used. Dual-averaging linear variable differential transformers displacement transducers or HEIDENHAIN linear encoded photoelectric gauges were used to measure strain with a resolution greater than 0.01%. Round specimens with a 6.4-mm (0.25-in.) diameter and a 32-mm (1.3-in.) reduced parallel section were used. The adjusted length of the reduced section was used for calculating strain. An optical comparator was used to measure important specimen dimensions at room temperature at a magnification of 50× prior to testing. Calipers were used to measure the important specimen dimensions at room temperature after testing was completed.

A scoping creep-rupture test program was conducted at temperatures extending from 750°C up to 1000°C (1292 to 1832°F). Test temperatures were selected that were greater than those permitted in Division 5 for Alloy 800H in order to accelerate testing. The Alloy 800H SRF values of greatest concern occur at large LMP values which correspond to the highest permissible temperatures and longest design lives. Consequently, test conditions that result in large LMP values were necessary to evaluate Alloy 617's potential as a filler metal to offer improved SRF values for Alloy 800H weldments. The fastest approach for achieving test results with higher LMP values is by conducting tests at higher temperatures. For all of the tests conducted, the initial applied stress was smaller than Alloy 800H's yield stress at the test temperature [15]. The tests conducted in this scoping study had rupture lives ranging from 250 hours up to 11,000 hours.

Specimens were machined from the 800H/617 plate with the Alloy 617 filler metal transverse to the longitudinal direction of the specimen. The weld was centered with respect to the reduced parallel section. This is known as a cross-weld geometry with the reduced parallel section comprised of both base and weld metal.

3.3 Characterization

Specimens were characterized using a Keyence VHX-6000 light optical microscope. Standard grinding and polishing procedures along with electroetching were used to prepare the specimens. Acceptable electroetching results were achieved using a 10% oxalic acid solution with a voltage of 2.2 V for 20 to 30 seconds.

4. RESULTS AND DISCUSSION

Preliminary results of the 800H/617 creep-rupture strength do not show significant improvement compared to the filler metals currently qualified in Division 5 for Alloy 800H weldments. This is most significant at large LMP values which corresponds to the SRF values of most concern for Alloy 800H weldments. This indicates that the Alloy 617 filler metal is unlikely to mitigate concerns of the SRF values restricting the design envelope for elevated-temperature nuclear construction with Alloy 800H weldments. This is illustrated by the 800H/617 data overlaid on the Alloy 800H creep-rupture Larson-Miller parametric curve with C equal to 15.12487; see Figure 1. The Alloy 800H Larson-Miller parametric curve and C came from "Verification of allowable stresses in ASME Section III Subsection NH for Alloy 800H" by Swindeman and colleagues [7]. Figure 1 also contains Alloy 800H, Alloy 82 deposited-filler-metal, and cross-weld data for specimens machined from welded plates comprised of Alloy 800H base metal and Alloy 82 filler metal. The latter will be referred to as 800H/82 from this point forward. The Alloy 800H creep-rupture data, Alloy 82

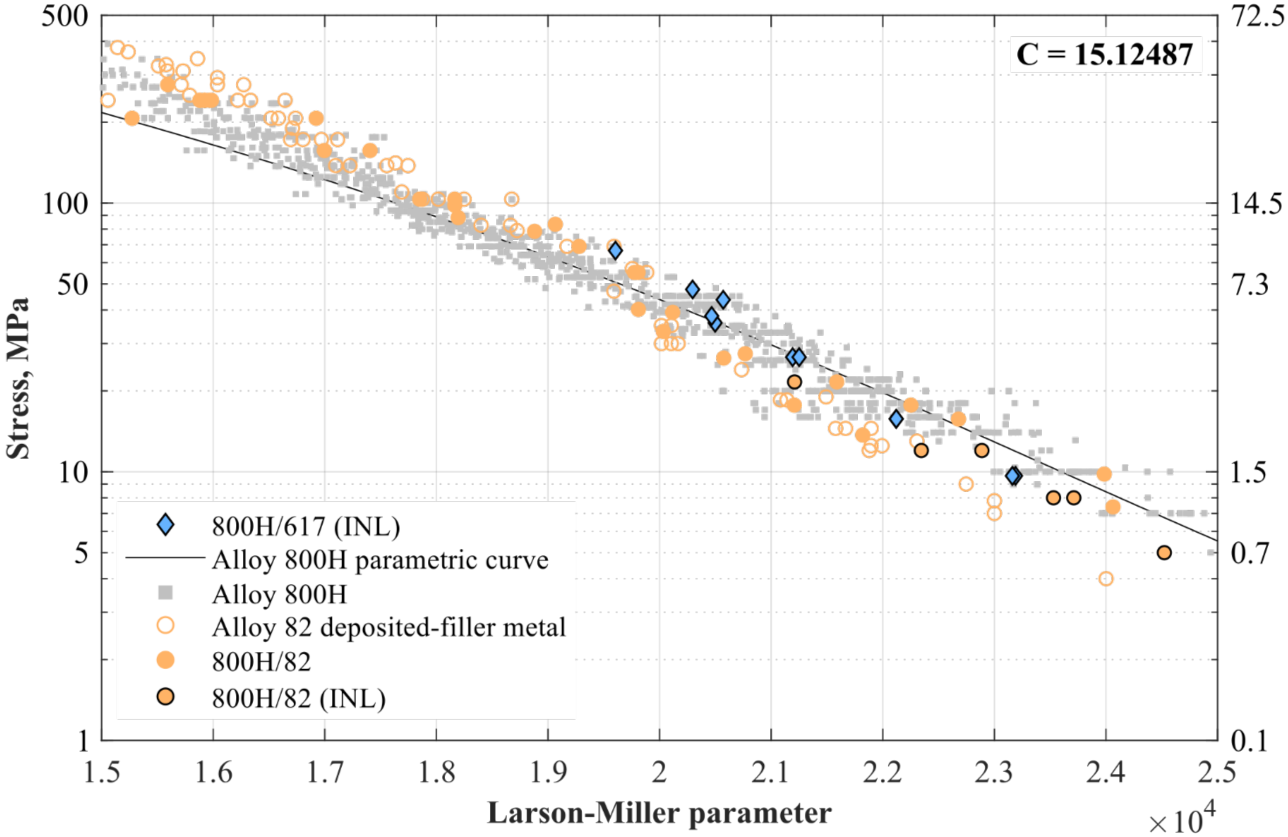


FIGURE 1: CREEP-RUPTURE LARSON-MILLER PLOT WITH C EQUAL TO 15.12487 INCLUDING THE FOLLOWING: 1) 800H/617 DATA, 2) ALLOY 800H PARAMETRIC CURVE, 3) ALLOY 800H DATA, 4) ALLOY 82 DEPOSITED-FILLER-METAL DATA, 5) 800H/82 DATA.

deposited-filler-metal data, and a portion of the 800H/82 data was assembled by Swindeman and colleagues [7]. The remainder of the 800H/82 data came from testing conducted at INL. The SRF values offered by the Alloy 617 filler metal for Alloy 800H weldments do not show significant improvement which is exemplified by two points: 1) the 800H/617 creep-rupture data falls to the left of the Alloy 800H parametric curve and Alloy 800H creep-rupture data at large LMP values and 2) the creep-rupture strengths of 800H/617 are similar to the creep-rupture strengths of 800H/82 and the Alloy 82 deposited filler metal at large LMP values. It is worth mentioning that the 800H/617 data intersects and drops below the Alloy 800H parametric curve at larger LMP values compared to the 800H/82 and Alloy 82 deposited-filler-metal data. This suggests that the SRF values at these LMP values for the Alloy 617 filler metal would be improved compared to the SRF values for Alloy 82 filler metal. However, these SRF values are not as significant as those corresponding to the highest permissible service temperatures and longest design lives.

Despite similarities in the creep-rupture strengths, the accumulation of cavitation damage was markedly different for Alloy 800H weldments with Alloy 617 and Alloy 82 filler metal. Rupture in the 800H/617 specimens always occurred in the base metal with minimal damage observed in the filler metal. Representative light optical microscopy (LOM) images of the 800H/617 specimens are shown in Figure 2. The vast majority of the cavitation damage and consequently the rupture location occurred in the base metal and varied with the test conditions. For tests that resulted in lower LMP values, cavitation and consequently rupture was restricted to an area immediately adjacent to the fusion line. For tests that resulted in larger LMP values, cavitation damage was more widely distributed throughout the base metal. Unlike the cavitation damage at the lower LMP values, cavitation damage in the area adjacent to the fusion line was minimal. In contrast with the Alloy 617 filler metal, the rupture location in the 800H/82 specimens depended on the test conditions. Representative LOM images of the 800H/82 specimens are shown in Figure 3. However, significant cavitation damage was observed in the weld metal for all the specimens tested.

The difference in location of the cavitation damage and rupture between the two filler metals can likely be attributed to Alloy 617 being an overmatched filler metal to Alloy 800H. This is in comparison to Alloy 82 which is a slightly undermatched filler metal to Alloy 800H at approximately 760°C (1400°F) and

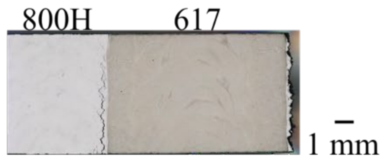
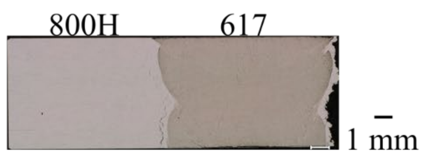
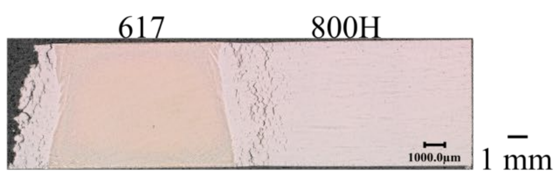
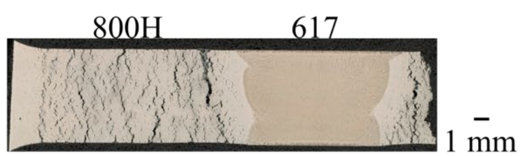
Test summary (Temperature,°C (°F)/ Stress, MPa (ksi)/ Rupture time, hours/ LMP)	LOM image of ruptured specimen	Location on Larson-Miller plot relative to Alloy 800H parametric curve
750 (1382)/ 66.6 (9.7)/ 10942/ 1.96 × 10^4		right
800 (1472)/ 47.7 (6.5)/ 6166/ 2.03 × 10^4		right
800 (1472)/ 35.8 (5.2)/ 9513/ 2.05 × 10^4		on
900 (1652)/ 43.7 (6.3)/ 258/ 2.06 × 10^4		right
900 (1652)/ 26.7 (3.9)/ 981/ 2.13 × 10^4		on
950 (1742)/ 15.7 (2.3)/ 915/ 2.21 × 10^4		left
1000 (1832)/ 9.7 (1.4)/ 1173/ 2.32 × 10^4		left

FIGURE 2: REPRESENTATIVE LOM IMAGES OF RUPTURED 800H/617 SPECIMENS TESTED AT INL. C WAS EQUAL TO 15.12487 FOR THE 800H/617 LMP AND ALLOY 800H PARAMETRIC CURVE.

above [16]. An overmatched weld has strength greater than the base metal, while an undermatched weld has strength less than the base metal. The reason(s) for the significantly unimproved creep-rupture strengths for the Alloy 617 filler metal at larger LMP values is unknown. It has been determined that the creep resistance of Alloy 800H at 1000°C (1832°F) is inadequate. Significant oxidation is observed in the base metal of the 800H/82 specimen tested at 1000°C (1832°F). Additionally, significant cavitation damage was observed in the base metal of the 800H/617 specimen tested at 1000°C (1832°F). This is in stark contrast with the weld metal and area in the base metal immediately adjacent to the fusion line in the 800H/617

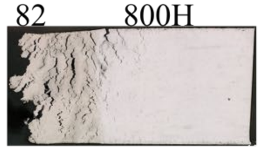
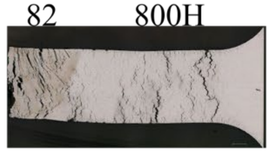
Test summary (Temperature,°C (°F)/ Stress, MPa (ksi)/ Rupture time, hours/ LMP)	LOM image of ruptured specimen	Location on Larson-Miller plot relative to Alloy 800H parametric curve
900 (1652)/ 21.6 (3.1)/ 905/ 2.12×10^4	 800H 82; 1 mm	left
925 (1697)/ 12 (1.7)/ 3369/ 2.23×10^4	 82 800H; 1 mm	left
900 (1652)/ 12 (1.7)/ 24405/ 2.29×10^4	 82 800H; 1mm	left
975 (1787)/ 8 (1.2)/ 5362/ 2.35×10^4	 800H 82 800H; 1 mm	left
950 (1742)/ 8 (1.2)/ 18329/ 2.37×10^4	 82 800H; 1 mm	left
1000 (1832)/ 5 (0.7)/ 13774/ 2.45×10^4	 82 800H; 1 mm	left

FIGURE 3: REPRESENTATIVE LOM IMAGES OF RUPTURED 800H/82 SPECIMENS TESTED AT INL. C WAS EQUAL TO 15.12487 FOR THE 800H/82 LMP AND ALLOY 800H PARAMETRIC CURVE.

specimen. Test temperatures above those permissible by Division 5 are not believed to be the lone contributor to the unimproved creep-rupture strengths of the 800H/617 specimens. The syngas industry utilizes Alloy 800HT for service conditions up to 954°C (1749°F) [17]. The creep-rupture strengths of 800H/617 specimens conducted at 950°C (1742°F) fell to the left of the Alloy 800H parametric curve.

5. ONGOING WORK

An alternative filler metal for Alloy 800H weldments with improved creep-rupture strengths compared to the Division 5 permissible filler metals continues to be pursued. UTP A 2133 Mn, a matching filler metal, welded using GTAW is currently being investigated. The European syngas industry has been utilizing matching filler metals for Alloy 800H for over 30 years, which they prefer over the Ni-based filler metals. This is because of the mismatch in the coefficient of thermal expansion between the Ni-based filler metals and Alloy 800H resulting in additional stresses. Although limited, the creep-rupture data available in the literature on these matching consumables is encouraging [7, 18].

6. CONCLUSION

This work characterized the creep-rupture behavior of a weldment with Alloy 800H base metal and Alloy 617 filler metal fabricated by semiautomated GTAW. Preliminary creep-rupture data of the Alloy 800H weldment with Alloy 617 filler metal do not show significant improvement compared to the filler metals currently permitted in Division 5 for Alloy 800H weldments.

This indicates that the Alloy 617 filler metal is unlikely to offer significantly improved SRF values for Alloy 800H weldments.

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