Continue Effort to Improve Alloy 800H Weldment

August 2022

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Date: August 9, 2022
To: Gerhard Strydom, National Technical Director, Gas-Cooled Reactors (GCR) Campaign
Tate Patterson, INL ART GCR Welding Engineer
Subject: Completion of Level 3 Milestone M3AT-22IN0604055, "Continue Effort to Improve Alloy 800H Weldment Creep Rupture Performance"

This memorandum formally documents the completion of the Level 3 milestone M3AT-22IN0604055 titled, “Continue effort to improve Alloy 800H weldment creep rupture performance,” by the transmittal of this deliverable document, entitled, “Issue memo ‘Preliminary assessment of UTP A 2133 Mn as a matching filler metal for Alloy 800H in Section III Division 5 applications.’” The deadline for this milestone is August 27, 2022. This milestone is part of the ART GCR work package AT-22IN060405, “Long-Term Very-High Temperature Reactor (VHTR) Material Qualification – INL.”

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) covers the construction rules for elevated-temperature nuclear components in Section III, Division 5 (ASME 2021a). In Division 5, the potential reduction in the creep rupture strength of weldments is addressed through provisions regarding the primary load, strain limits, and creep-fatigue at welds. An important parameter for the primary load and creep-fatigue provisions is the expected minimum stress-to-rupture of the weld. The expected minimum stress-to-rupture of the weld is a function of the stress-rupture factor (SRF) and the expected minimum stress-to-rupture of the base metal. In Division 5, the former is labeled R and the latter SR (Sham 2021). The SRF is defined as the ratio of the average rupture strength of the weld metal to the base metal (ASME 2021a; Sham 2021). It ranges from zero to one where one indicates the average rupture strength of the weld metal is better than or equivalent to the average rupture strength of the base metal. Historically, the average rupture strength of the weld metal was determined from specimens comprised exclusively of deposited weld metal. Data from cross welds and component welds were used to verify or revise the SRF values determined from the all-weld metal analysis. The contemporary approach for determining the average rupture strength of the weld metal is with cross-weld or a combination of cross-weld and exclusively weld-metal data (Sham 2021). Data collected from cross welds have the benefit of capturing the impact of the metallurgical discontinuity between the base and filler metal. Additional stresses induced by a mismatch in the coefficient of thermal expansion between the base and weld metal as well as a heat-affected zone may contribute to this metallurgical discontinuity (Corum 1990).
Currently, only six alloys are qualified in Division 5 for the construction of non-bolting, base material, Class A metallic coolant boundary components. Alloy 800H (33Ni-42Fe-21Cr) is one of these six alloys and is qualified for service temperatures up to 760°C with a maximum service life of 300,000 hours. Division 5 further stipulates the permissible weldment filler metals for each of the qualified base materials. For Alloy 800H, two nickel-based filler metals are permitted: ENiCrFe-2 (Alloy A) and ERNiCr-3 (Alloy 82) (ASME 2021a). Welding with the former filler metal shall be by shielded metal arc welding in accordance with ASME BPVC SFA-5.11, “Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding” (ASME 2021b). Welding with the latter shall be in accordance with ASME BPVC SFA-5.14, “Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods” (ASME 2021c). Technically, any welding process is permitted for which an ASME BPVC SFA-5.14 filler method is acceptable. However, gas metal arc, gas tungsten arc, plasma arc, and submerged arc are the intended welding processes. The SRF values for Alloy A and Alloy 82 range from 0.59 and 0.54, respectively, to 1.0. The lower range of these SRF values correspond to a 300,000-hour service life at 760°C (ASME 2021a). For Alloy 800H, the average rupture strength of the weld metal and hence the SRF values were established from a combination of cross-weld and exclusively weld-metal data (Shingledecker et al. 2017). The Alloy 800H design envelope for Division 5 applications may be restricted by these low SRF values. Consequently, it is sought to find an alternative filler metal with improved weldment creep-rupture strengths and improved SRF values for the qualified temperatures and service lives.

ERNiCrCoMo-1 (Alloy 617) deposited by semiautomated multiple-pass gas tungsten arc welding was the first filler metal investigated. Alloy 617, like Alloy A and Alloy 82, is a nickel-based filler metal. It was selected for investigation because it has higher creep strength, or is overmatched, compared to the Alloy 800H base metal. Alloy 82 filler metal has lower creep strength, or is undermatched, compared to the Alloy 800H base metal at approximately 760°C and above (Marshall and Farrar 1999). In comparison to the Division 5 permissible filler metals for Alloy 800H, preliminary results of the cross-weld creep-rupture strength with Alloy 617 filler metal do not show significant improvement. Consequently, Alloy 617 filler metal is unlikely to offer significantly improved SRF values for Alloy 800H weldments. This was determined from 11 cross-weld creep-rupture tests that were tested in air in accordance with American Society for Testing and Materials (ASTM) standard E139, “Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials” (ASTM 2018). More information regarding this testing as well as the results from this work can be found in the following sources (Rupp 2021; Rupp and Sham 2022).

UTP A 2133 Mn filler metal (21Cr-33Ni-4.3Mn with several minor constituents and the remainder being iron) deposited by semiautomated multiple-pass gas tungsten arc welding is currently being investigated. UTP A 2133 Mn was selected as the next filler metal to investigate because of its similar chemistry to Alloy 800H as shown in Table 1. The UTP A 2133 Mn filler metal is comprised of higher amounts of Mn and Nb compared to the Alloy 800H base metal to
reduce the susceptibility to solidification cracking. A possible benefit of having a near matching composition is to achieve a similar tensile strength and coefficient of thermal expansion between the base and filler metal. A disparity in the tensile strength and coefficient of thermal expansion between the base and filler metal may result in the formation of additional stresses. This has compelled the European syngas industry since the late 1980’s to utilize filler metals with near matching chemistry for Alloy 800H (Grooten et al. 2019; van Zyl, Keltjens, and Al-Shawaf 2017). Literature on the creep-rupture properties of the filler metals with near matching chemistry for Alloy 800H weldments are promising, albeit limited (Orbons 1988; Swindeman et al. 2008).

Table 1. Chemical composition in weight percent of the Alloy 800H base metal and UTP A 2133 Mn filler metal being used in this investigation.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>Ti</th>
<th>Al</th>
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<tbody>
<tr>
<td>800H</td>
<td>46.2</td>
<td>30.6</td>
<td>19.7</td>
<td>-</td>
<td>-</td>
<td>0.54</td>
<td>0.56</td>
</tr>
<tr>
<td>UTP A 2133 Mn</td>
<td>Balance</td>
<td>32.1</td>
<td>21.6</td>
<td>&lt;0.1</td>
<td>1.23</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Co</th>
<th>Cu</th>
<th>Si</th>
<th>Mn</th>
<th>C</th>
<th>P</th>
<th>S</th>
</tr>
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<tbody>
<tr>
<td>800H</td>
<td>0.10</td>
<td>0.20</td>
<td>0.42</td>
<td>1.27</td>
<td>0.061</td>
<td>0.024</td>
<td>0.001</td>
</tr>
<tr>
<td>UTP A 2133 Mn</td>
<td>-</td>
<td>&lt;0.1</td>
<td>0.2</td>
<td>4.8</td>
<td>0.16</td>
<td>0.008</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Several semi-automatic gas tungsten arc welds with UTP A 2133 Mn filler metal were deposited on 12.5 mm (0.5 in.) thick Alloy 800H plate. The weld geometry was a 30° included groove angle and 4.8 mm (3/16 in.) root opening. This joint geometry matched the geometry of the previous welds with Alloy 617 and Alloy 82 filler metal. Originally, welds were made with reduced heat input (lower current). This was to reduce the amount of weld metal dilution (i.e., base material melted into the filler metal). Minimizing dilution is beneficial to maintain the higher Nb and Mn content intentionally added for mitigating solidification cracking. As shown in Figure 1, the low heat input (1.15 kJ/mm) resulted in lack of fusion defects, where the filler metal did not sufficiently adhere to the joint face. Increasing the heat input (1.31 kJ/mm) further eliminated the solidification cracks but showed potential for heat-affected zone (HAZ) liquation; see Figure 1. Despite the presence of a liquid film wetting the grain boundary, HAZ liquation cracks were not present. The arrows in the right-hand image of Figure 1 indicate the penetration of the filler metal into the HAZ grain boundaries and are not cracks.

A heat treatment was performed on the 1.31 kJ/mm heat input weld at 875°C for three hours. The change in hardness between the as-welded and heat-treated condition was evaluated as a shown in Figure 2a. The fusion zone (FZ) hardness was slightly higher in the heat-treated condition, but the difference in the HAZ hardness between the two conditions was only minimal. The FZ
microstructures for the as-welded and heat treated conditions are shown in Figure 2b and Figure 2c, respectively. The apparent inter-dendritic segregation in the FZ of the heat-treated specimen is reduced, indicating solute diffusion during the heat treatment. This resulted in a change in the weld-metal properties as revealed by the higher hardness in the FZ of the heat-treated specimen. To enable a direct comparison with the creep results for the weldments with Alloy 617 and Alloy 82 filler metal, Alloy 800H welds with UTP A 2133 Mn filler metal were deposited using identical parameters with a heat input of 1.78 kJ/mm.

Figure 1. Macrographs showing half of the weld section for two different heat inputs (parameters) and the two weldability issues encountered.

A macrograph and Vickers hardness map using a 300 g load for an Alloy 800H weld with UTP A 2133 Mn filler metal which used a 1.78 kJ/mm heat input is shown in Figure 3. The successively reheated regions of weld metal resulted in the highest hardness with areas above 230 HV0.3. The lowest FZ hardness (approximately 150 HV0.3) was in the cap or final pass that did not receive a reheat. The HAZ showed less hardness variation with the highest hardness near 200 HV0.3 and the lowest hardness around 150 HV0.3. It is suspected that FZ hardness variation is largely attributed to the higher carbon and niobium contents in the filler metal, which allowed for niobium carbide (NbC) formation during reheating. An inspection of this weld did not reveal any weld related defects. Consequently, weld qualification in accordance with Section IX of the ASME BPVC is currently underway for the 1.78 kJ/mm weld (ASME 2021d).
Figure 2. (a) As-welded and heat-treated hardness results across the fusion boundary for an Alloy 800H weldment with UTP A 2133 Mn filler metal with a 1.31 kJ/mm heat input. Micrographs of the FZ from this weld in the (b) as-welded and (c) heat-treated conditions. The diamonds in (b) and (c) are hardness indentions.

Figure 3. Macrograph and Vickers hardness map using a 300 g load for an Alloy 800H weld with UTP A 2133 Mn filler metal fabricated with a 1.78 kJ/mm heat input.
Work is continuing to be performed to qualify the weld at INL in accordance with ASME BPVC Section IX. If the weld does not pass qualification, additional parameters will be investigated. Once weld qualification is passed, the same weld conditions will be qualified in the heat-treated condition. The post-weld heat treatment will be conducted at 875°C for three hours. Post-weld heat treatments are recommended for Alloy 800H to relieve residual stress and mitigate stress relation cracking. The heat treatment allows for coarsening of $M_2Cr_6$ carbides to prevent the formation of undesirable grain boundary carbide films during service (DuPont, Lipold, and Kiser 2009). Welds in both the as-welded and heat-treated conditions will be fabricated for cross-weld creep-rupture testing. Using the creep data, conclusions will be made regarding the potential for UTP A 2133 Mn filler metal to offer improved weldment creep-rupture strengths and consequently improved SRF values compared to the Division 5 permissible filler metals for Alloy 800H.

References


