

Materials, Fabrication, and Repair Considerations for Hydrogen Reformer Furnace Outlet Pigtails and Manifolds

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Materials, Fabrication, and Repair Considerations for Hydrogen Reformer Furnace Outlet Pigtails and Manifolds

1 Scope

The American Petroleum Institute (API) Committee on Refinery Equipment, Subcommittee on Corrosion and Materials undertook a project to develop this technical report on materials, fabrication, and repair issues related to hydrogen and syngas reformer furnace outlet pigtails and manifolds. High reliability of outlet pigtails and manifold components, such as headers, tees, and fittings, is important to the successful long-term operation of hydrogen and syngas reformer furnaces. These components typically operate at high temperatures in the range of 750 °C to 950 °C (1382 °F to 1742 °F) where they are potentially subject to high-temperature creep, stress relaxation, hot corrosion, and thermal fatigue damage.

In recent years a number of reformer furnace operators have encountered problems of in-service degradation and cracking of outlet pigtails and manifold components, while others have had little or no problems of this type. Both direct experience in addressing specific cases of outlet pigtail and manifold cracking problems and indirect experience gained from surveying industry with regard to these problems were used in preparing this report.

The objective of the project was to develop an understanding, based on published literature and industry experience, of why some reformer furnaces have had problems with embrittlement and cracking of outlet pigtails and manifold components in service, while others have not had such problems.

2 Technical Approach

The project objective was achieved by reviewing relevant published literature and industry experience and then documenting the results of that review in this report. The published technical literature was reviewed using the following four databases:

- ScienceDirect (<http://www.sciencedirect.com/>),
- Engineering Village 2 (<http://www.engineeringvillage2.org/>),
- CSA Materials Research Database with METADEX (<http://www.csa.com/>),
- REFIN*COR 8.0 database (<http://www.nace.org/>).

The first two databases were available through a library service. The third database was available through The Welding Institute (TWI), while the fourth one was available through NACE International. The proceedings of AIChE Ammonia Plants & Related Facilities Symposia ^[1-4] were also searched because they were known to contain a number of relevant technical papers. These symposia proceedings are published as searchable CDs, which facilitated identification and review of relevant papers. In addition, literature was obtained through personal contacts with members of the API Subcommittee of Corrosion and Materials and records of roundtable presentations at past API meetings.

Industry was surveyed by sending a questionnaire to key contacts at companies who operate reformer furnaces or provide materials used in outlet pigtails and manifold components. A draft questionnaire was prepared and submitted to the API project committee for review and comment. Recommendations from that review then were incorporated into the final questionnaire. The survey was distributed in two ways. First, API sent it to select members deemed to have an interest in the topic. Second, it was sent to individuals in companies that operate reformer furnaces in other industries or in international refining companies not affiliated with API.

Section 6 of this report lists references to the published literature that is cited herein. The sources of industry comments have been kept anonymous; each respondent is simply identified by a code. The information and

data that were obtained from the literature and industry surveys are summarized in tabular and graphical formats, as appropriate, along with representative photographs, where available, and a discussion of the findings.

As requested by API, five major technical areas are addressed in this report: (1) materials selection, (2) welding consumable selection, (3) welding and repair practices, (4) mechanical design, and (5) case studies. Only equipment that is downstream of the reformer outlet and upstream of the hot-to-cold wall transition is included. This means that reformer tubes and ferritic materials are excluded from the report scope. In addition, methods of remaining life assessment, criteria for component retirement, and procedures for creep-life evaluation are excluded. Only inspection techniques that are recommended to ensure the integrity of fabrication or repair are included; inspection techniques that address condition assessment of in-service equipment are excluded.

3 Results of Literature Survey

3.1 General

This section of the report reviews the results of the literature survey. The following subsections correspond to the five major technical areas of interest, as indicated previously.

3.2 Materials Selection

3.2.1 General

Qualities required in construction material for high-temperature equipment include resistance to oxidation, carburization, and corrosion and adequate mechanical strength, thermal fatigue strength, and creep-rupture properties at the service temperatures^[5]. The primary in-service degradation mechanisms for high-temperature equipment are thermal degradation, such as creep and associated problems, metal dusting, and stress relaxation cracking.

3.2.2 Thermal Degradation

Thermal degradation, most notably creep, is the primary damage mechanism for high-temperature service. There are several historical examples throughout the 1960s and 1970s of thermal degradation and suggestions on proper materials selection to mitigate the phenomena, which illustrate the evolution of construction materials in the components. Francis and Glass^[6] studied a failure of outlet piping and described high-temperature stress-rupture failures in Type 304 stainless steel piping, which showed a brittle carburized layer. Harnby^[7] observed superior creep resistance of an Alloy 800 manifold compared with one made of the HU alloy because of the improved ductility of Alloy 800, which in turn was attributed to its lower carbon content. Blackburn^[8] remarked that the HK-40 and HT/HU cast alloys had moderate tensile ductility leading to manifold cracking, while wrought Alloy 800 proved to be a more suitable material due to its improved ductility over the HK. Kratsios and Long^[9] reported using centrifugally cast pipe made from HT modified alloy (20Cr-35Ni) material because of its high allowable creep and rupture stresses, despite its loss of ductility at lower temperatures. Also, HK alloy (25Cr-20Ni) cast pipe was found to have twice the rupture or creep strength of Type 310 wrought stainless steel. Blackburn^[8] also noted that the cast 20Cr-32Ni-Nb alloy was an improvement on Alloy 800, but could not compare it with Alloy 800H or Alloy 800HT because they were not available at the time of his work. HK, HT, and HU are standard heat-resistant alloy designations that were developed by the Alloy Casting Institute (ACI), which is now the Steel Founders' Society of America.

These alloys, including Alloy 800 as it is currently specified, are mentioned here only from the historical viewpoint and are no longer used in outlet manifold systems. Prior to the introduction of Alloy 800H in 1973 and Alloy 800HT in 1989, the Alloy 800 material often satisfied the requirements for Alloy 800H, as it is currently specified. When enough background data are provided in the cited literature to show that the material referred to as Alloy 800 met the requirements for Alloy 800H, it is referred to as Alloy 800H in this report.

Currently, Alloy 800H/HT and its derivatives, including cast 20Cr-32Ni-Nb, are used extensively in high-temperature service, and their properties and performance are of considerable interest. The Special Metals Corporation^[10] states that Alloy 800H and Alloy 800HT variants have higher creep and rupture strength than Alloy 800. As summarized in Table 1, Alloy 800, 800H, and 800HT vary only with respect to carbon, aluminum, and titanium contents and minimum grain size. The range of allowable carbon decreases from Alloy 800 to Alloy 800H to Alloy 800HT. Alloy 800 and Alloy 800H have lower specified allowable aluminum and titanium contents than Alloy 800HT. In addition, the aluminum plus titanium content has limits for Alloy 800 HT. No grain size control is specified for Alloy 800, but the grain size must be ASTM 5 or greater for Alloy 800H or Alloy 800HT. Obviously, any lot of material satisfying the chemistry requirements of Alloy 800HT would also satisfy those of Alloy 800 and Alloy 800H, and any lot of material satisfying the chemistry requirements of Alloy 800H would also satisfy those of Alloy 800. Alloy 800 has higher mechanical properties than the others at room temperature, while Alloy 800H and Alloy 800HT have superior creep and rupture strength when operating at high temperature for extended periods of time.

Table 1—Chemical Composition and Grain Size Requirements for the Variants of Alloy 800

Parameter	UNS Designation/Alloy Name ^(a)		
	N08800/800	N08810/800H	N08811/800HT
Nickel	30.0-35.0	30.0-35.0	30.0-35.0
Chromium	19.0-23.0	19.0-23.0	19.0-23.0
Iron	39.5 min	39.5 min	39.5 min
Carbon	0.10 max	0.05-0.10	0.06-0.10
Aluminum	0.15-0.60	0.15-0.60	0.25-0.60
Titanium	0.15-0.60	0.15-0.60	0.25-0.60
Al+Ti			0.85-1.20
ASTM Grain Size		5 or coarser	5 or coarser

(a) Prior to 1973 and 1987, the Alloy 800H designation and Alloy 800HT designation, respectively, did not exist. Thus, historical references to Alloy 800 may in some cases be equivalent to Alloy 800H or Alloy 800HT as they are currently defined.

API 530^[11] has one set of average and minimum (design) stress-rupture curves that apply to both Alloy 800H and Alloy 800HT. These are based on analysis of stress-rupture data using the Larson-Miller parameter^[12]. The data and procedures used to develop these stress-rupture curves are reviewed in API 530^[13]. Annex F of API 579-1/ASME FFS-1^[14] has equations that define the minimum ultimate tensile strength and minimum tensile yield strength for Alloy 800 and both Alloy 800H and Alloy 800HT as a function of temperature. It also has equations for the high-temperature fatigue strength of Alloy 800H, Omega creep equations for Alloy 800, Alloy 800H, and Alloy 800HT, and equations for the combined Alloy 800H and Alloy 800HT stress-rupture curves in API 530. Thus, Alloy 800H and Alloy 800HT have similar stress-rupture behavior, which is represented by one set of curves in both API 530^[11] and API 579-1/ASME FFS-1^[14].

Examples of industry experience with stress-rupture performance of Alloy 800, Alloy 800H, and Alloy 800HT components are presented later in 4.10 in the review of the results of the industry survey that was performed as part of the current project.

All three Alloy 800 variants have similar corrosion resistance. Alloy 800H and Alloy 800HT are used for their high-temperature strength and are reported to have good oxidation and carburization resistance^[10].

Fisher^[15] carried out a study of materials to identify one with better creep properties than the wrought Alloy 800. He determined that centrifugally cast 20Cr-32Ni-Nb material (the cast “equivalent” of Alloy 800) should be used as it gave good weldability after prolonged high-temperature service. Producers’ data on the stress-rupture behavior of the 20Cr-32Ni-Nb alloy and industry experience with the stress-rupture performance of this alloy are presented and discussed later in 4.10. With regard to 20Cr-32Ni-Nb cast alloys, Shibasaki et al.^[16] found that Si, Nb, and C additions had a negative effect on ductility, while Mn had a positive effect on ductility.

Parks and Schillmoller^[17] found that Alloy 800H had a low tendency towards embrittlement but noted that the 20Cr-32Ni-Nb cast alloy has higher creep and rupture strength than Alloy 800H. A recent analysis by Thomas et al.^[18] pointed out a serious embrittlement issue with the 20Cr-32Ni-Nb cast material; they suggested that niobium-free grades should be developed in order to avoid such in-service problems.

Hoffman^[19] evaluated the aging of 20Cr-32Ni-Nb castings after 21 months of service at 852 °C (1565 °F) and found both $M_{23}C_6$ carbide and intermetallic Nb-Ni silicide precipitates. The silicides were mostly G phase with some η' phase and are expected to decrease creep resistance and promote liquation cracking during welding.

Hoffman and Gapinski^[20] evaluated samples of a 20Cr-32Ni-Nb cast outlet manifold that had developed fatigue cracks after it had been in service for approximately 192 months at an outlet gas temperature of 871 °C (1600 °F). In addition to carbide and silicide precipitation, they observed carbide coalescence. The observed aging significantly degraded the tensile strength, Charpy V-notch impact resistance, stress-rupture strength and weldability of the material. The carbides and silicides were solutionized by solution annealing at 1093 °C (2000 °F). However, complete solutionizing of secondary precipitates and spheroidization of the primary carbides required a minimum solution annealing temperature of 1149 °C (2100 °F). Better stress-rupture properties were achieved by solution annealing at 1204 °C (2200 °F) than by solution annealing at 1093 °C or 1149 °C (2000 °F or 2100 °F). The cracked region of the manifold was successfully repaired after in-situ solution annealing at 1149 °C (2100 °F) for 3 hours and operated successfully for four more years before the furnace was rebuilt. For new materials, the authors recommended keeping Si content as low as possible and maintaining a stoichiometric Nb/C ratio of 7.7.

An attempt was made to find time-temperature-transformation (TTT) diagrams for Alloy 800H, Alloy 800HT, and the 20Cr-32Ni-Nb alloy. Baker^[21] provided copies of two TTT diagrams that were presented at a conference in 1964, but not published. They show some limited data on the precipitation of $Cr_{23}C_6$ carbides for a 0.033 % C 21Cr-33Ni alloy and a 0.07 % C 21Cr-33Ni alloy. Because the data are limited and not well documented, they are not included in this report. No other TTT diagrams were found.

3.2.3 Metal Dusting

Metal dusting is a high-temperature corrosion mechanism that occurs in gaseous environments where the carbon activity exceeds one and the metal temperatures are in the range of 450 °C to 840 °C (842 °F to 1544 °F), with the worst risk being at temperatures between 650 °C and 730 °C (1202 °F and 1346 °F). The susceptible temperature range varies by alloy. Most hydrogen reformers do not operate in a susceptible temperature range, so metal dusting is not a major issue for the outlet manifolds and pigtails addressed in the current study, although some cases of metal dusting have occurred on waste heat boiler ferrules. Metal dusting is more commonly encountered in syngas plants and some waste heat boilers. Since metal dusting is not a significant concern for the scope of this review, it will only be discussed briefly here. The reader with an interest in this topic should consult the references that are given herein.

Shargay^[22] pointed out that the selection of material has a significant impact on the resistance of a component to metal dusting, but that no alloy is completely resistant to metal dusting. Chromium in ferritic stainless, austenitic stainless, and nickel-based alloys increases resistance to the phenomenon. As the amount of iron increases, the rate of metal dusting increases in both ferritic and austenitic stainless steel. Nickel increases resistance to metal dusting in nickel-based alloys, but decreases the resistance of austenitic stainless steels. The addition of silicon or aluminum improves the resistance to metal dusting in any family of alloys. Korkhaus^[23] suggested that higher Cr, Al, or Si alloyed Ni-base alloys be used in practice, based upon their resistance to metal dusting.

The Materials Technology Institute, Inc. (MTI) has been conducting a long-term research project on metal dusting. In the first phase of the MTI project, Jones^[24] completed an extensive survey of the literature and industry experience with metal dusting. Alloy 800, Alloy 800H, and the 20Cr-32Ni-Nb alloy were included in the review. In the second phase of the MTI project, Natesan and Zeng^[25] conducted a detailed research study of metal dusting behavior. Alloy 800 was one of the 32 commercial materials evaluated in the study; they did no work on the cast 20Cr-32Ni-Nb alloy. The composition of the Alloy 800 material that they evaluated satisfied the compositional requirements of Alloy 800H but not those of Alloy 800HT.

Dejaeger et al.^[26] remarked that Alloy 800 and its variants are prone to metal dusting and that high-nickel containing alloys, such as Alloy 600, were better choices for components that are commonly exposed to metal dusting conditions. Shibasaki et al.^[27] also came to the same conclusion, noting that Alloy 800, austenitic stainless steels, and Fe-based alloys experienced metal dusting, whereas high nickel-based alloys, such as Alloy 625, experienced no metal dusting under the conditions that they investigated. Stahl

and Thomsen^[28] recommended Alloy 601 to mitigate metal dusting because of its aluminum content. Baker et al.^[29] recommended the newly developed Alloy 693 above Alloy 601; it showed better resistance to metal dusting in laboratory tests because it has higher amounts of chromium and aluminum than Alloy 601.

3.2.4 Stress Relaxation Cracking

3.2.4.1 General

Shoemaker et al.^[30] and van Wortel^[31] point out that stress relaxation cracking is another significant threat to manifold and pigtail integrity when fabrication or operating temperatures are in the range of 500 °C to 750 °C (930 °F to 1380 °F). This general type of cracking can occur either during fabrication or during service. When the cracking occurs during fabrication, it is referred to as reheat cracking, stress relief cracking, or stress relaxation cracking. The term reheat cracking is used in this report to refer to cracking during fabrication. When the cracking occurs during service, it is referred to as stress relaxation cracking, creep embrittlement cracking, stress induced cracking, or stress assisted grain boundary oxidation cracking. The term stress relaxation cracking is used in this report to refer to cracking during service.

This cracking mechanism involves cracking of a metal because of stress relaxation that occurs during postweld heat treatment (PWHT) or during service at elevated temperature. It is most often observed in heavy wall sections. The affected materials include low alloy steels (Cr-Mo) as well as 300 series stainless steels and nickel-containing alloys such as Alloy 800H and Alloy 800HT. The critical factors affecting the occurrence of cracking include^[32]:

- type of material (chemical composition, impurity elements);
- grain size;
- residual stresses from fabrication and repair (cold working, welding);
- section thickness (which controls restraint and stress state);
- notches and stress concentrators;
- weld metal and base metal strength; and
- welding and heat treating conditions.

Reheat cracking occurs at elevated temperatures when creep ductility is insufficient to accommodate the strains required for the relief of applied or residual stresses. In many cases, cracks are confined to the heat affected zone or initiate at some type of stress concentration. Cracks are intergranular and show little or no evidence of deformation. They can be surface breaking or embedded depending on the state of stress and geometry. The cracking is most frequently observed in coarse-grained sections of a weld heat affected zone^[32].

Fine intragranular precipitate particles make the grains stronger than the grain boundaries and force the creep deformation to occur at the grain boundaries. The grain size has an important influence on the high-temperature ductility and on the reheat cracking susceptibility. A large grain size results in less ductile heat affected zones, increasing the susceptibility of the material to reheat cracking^[32].

Van Wortel^[31] documented fifty stress relaxation cracking failures. A lack of high-temperature ductility was identified as the major cause of stress relaxation cracking, and it was observed that austenitic steels are especially susceptible between 500 °C (930 °F) and 750 °C (1380 °F). PWHT was identified as an effective method to avoid stress relaxation cracking. Another method to mitigate occurrences of stress relaxation cracking identified was using a stabilizing heat treatment before or after cold deformation. These methods were validated by field results.

Through published papers and presentations, including those from a Joint Industry Sponsored Research Program (JIP) that published parts of the results^[31, 33-37], various steps have been identified for reducing the risk of reheat cracking during fabrication and stress relaxation cracking during service for Alloy 800H. The primary recommendations are (1) limiting Al + Ti content to less than 0.7 %, (2) perform a stabilization heat treatment of base materials, (3) weld with a matching filler metal, and (4) perform a postweld heat treatment.

3.2.4.2 Limit Al + Ti Content to Less than 0.7 % in the Base Metal and Weld Metal

As shown in Table 1, the ranges of Al + Ti content overlap for Alloy 800H and Alloy 800HT. Because of this overlap, material is often “dual-certified” for both alloys. However, to get the lower susceptibility to reheat cracking and stress relaxation cracking in the range of 500 °C to 750 °C (932 °F to 1380 °F), the Al + Ti content should be controlled. The material then meets the requirements of Alloy 800H but not those of Alloy 800HT.

3.2.4.3 Require Stabilization Heat Treatment of Base Metal

A stabilization heat treatment at 982 °C (1800 °F) for 3 hours should be performed on 800H base materials after rolling, forming, or other manufacturing steps. This heat treatment is done after the ASTM-required solution annealing and is at a lower temperature. A stabilization heat treatment creates benefits by generating coarse carbide particles within the grains and on the grain boundaries. These carbides form by reacting with age hardening elements such as Ti, Al, and Nb. The result is that at operating temperature, less of these elements are available for the formation of fine carbides within the grains^[33].

Cold deformation can make the material susceptible to stress relaxation cracking, and the stabilizing heat treatment, after cold deformation, is effective at reversing this effect. In the stabilized condition, at least 15 % cold deformation is allowed without increasing the risk of stress relaxation cracking^[31]. However, Baker^[21] points out that a stabilizing anneal is recommended after up to 15 % cold work to Alloy 800H or Alloy 800HT and that solution annealing is recommended following high amounts of cold work. Solution annealing is typically performed at temperatures of 1150 °C to 1200 °C (2100 °F to 2200 °F) with the objective of producing a minimum grain size of ASTM Number 5^[10]. Increasing amounts of cold work will decrease the recrystallization temperature^[10], which must be kept in mind to avoid excessive grain growth during the annealing process.

3.2.4.4 Weld with Matching Filler Metal

For many product forms, such as longitudinally-welded pipes and fittings, and for many fabricated items, such as piping spools and vessels, current typical industry practice is to weld Alloy 800H or Alloy 800HT with an over-matching, Ni-based filler metal, such as ENiCrFe-3 (Inconel 182) or ENiCrCoMo-1 (Inconel 617); see Table 2. While these filler metals might be acceptable (or even preferred) for operating temperatures above 760 °C (1400 °F), in the temperature range of 538 °C to 704 °C (1000 °F to 1300 °F), these filler metals can increase susceptibility to stress relaxation cracking. There is also a risk of embrittlement of the Ni-based filler metals in this lower temperature range.

When Alloy 800H components are being fabricated for intended service at 538 °C to 704 °C (1000 °F to 1300 °F), it is recommended that the filler metal chemistry match the major elements of the base metal chemistry. These elements are primarily the nickel and chromium values, but the filler metals available will typically match the other elements as well. Chemistry for some typical electrodes and wires are shown in Table 2. Unfortunately, the American Welding Society (AWS) does not have a classification for a filler metal with Alloy 800H chemistry yet, so specific chemistries or brand name filler metals need to be specified.

Gas-tungsten arc welding (GTAW) and shielded-metal arc (SMA) welding are the welding processes with available matching filler metals and the most proven experience to date. Gas-metal arc welding (GMAW) also has been used. Submerged arc welding (SAW) is being evaluated in laboratory studies, but has not yet been applied in the field.

3.2.4.5 PWHT at a Minimum of 900 °C (1652 °F) for 1.5 Hours

PWHT of the Alloy 800 variants is considered the best prevention against in-service stress-relaxation cracking (although it creates the risk of reheat cracking). PWHT of Alloy 800, Alloy 800H, and Alloy 800HT is required for pressure vessels^[38] if the service temperature is above 538 °C (1000 °F). As of the 2007 ASME Code^[38], this requirement is in ASME Code Section VIII, Division I, UNF-56, Paragraph 56(e). The PWHT must consist of heating to a minimum temperature of 885 °C (1625 °F) for 1 1/2 hours for section thicknesses less than 25 mm (1 in.) and for 1 1/2 hours + 0.04 hour/mm (1 hour/in.) of thickness for section thicknesses exceeding 25 mm (1 in.). Cooling and heating rates are to be agreed upon by the purchaser and fabricator. Solution annealing in accordance with the material specification is an acceptable alternative. PWHT of tube-to-tubesheet and expansion bellows attachment welds is optional.

Industry practice is not to apply PWHT to welds on Alloy 800H or 800HT outlet pigtails because they operate at temperatures well above the range where stress-relaxation cracking occurs. The experience with this practice has been good. No serious problems that would lead to changing it have been encountered.

3.3 Welding Consumable Selection

The primary criteria for choosing suitable weld metal are high-temperature strength, corrosion resistance, and weldability. Avery et al.^[5] noted that weld metals are inherently lower in thermal fatigue resistance than comparable wrought metals and that higher nickel content improves heat resistance of welds; they recommended weld metals of higher nickel content for high-temperature applications. Kiser^[39] recommended using a welding product comparable to the base metal in strength and corrosion resistance.

Table 2 lists the AWS specifications and names of common nickel-based weld metals that have been considered for fabrication and repair of hydrogen reformer outlet manifolds and pigtails made of the Alloy 800 variants or the cast 20Cr-32Ni-Nb alloy. Temperatures for application of these materials are indicated in Table 2 based on the recommendations of Shargay et al.^[40]. Inco-Weld A and Inconel 82 have adequate creep strength for use at temperatures below 760 °C (1400 °F), but are normally not used above that temperature because of low creep strength. Inconel 112 and Alloy 625 can be used at temperatures above 843 °C (1550 °F) when higher creep strength is needed, but should not be used where operating temperatures between 593 °C and 843 °C (1100 °F and 1550 °F) are anticipated because of long-term embrittlement issues. However, most reformer operators choose to use Alloy 617 for higher creep strength at temperatures above 843 °C (1550 °F). Inconel 117 and Alloy 617 are typically used at temperatures above 843 °C (1550 °F) when higher creep strength is needed; they reportedly do not embrittle in service.

The “matching” weld metals listed in Table 2 have compositions similar to those of the Alloy 800 variants and the cast 20Cr-32Ni-Nb alloy. Table 3 lists the compositions of these weld metals. Limiting composition values are available for the nickel-based materials, as indicated in the table. However, only nominal compositions are reported by the vendors of the proprietary “matching” materials. The vendor datasheets indicate that they are acceptable for use at temperatures up to 1050 °C (1922 °F) with no indication of potential embrittlement issues at lower temperatures. Böhler Welding Group provides a set of stress-rupture curves ranging from 750 °C to 1050 °C (1382 °F to 1922 °F) that are applicable to the 2133 Mn and 21/33 So materials.

Roach and VanEcho^[41, 42] found that the weldments they tested had lower stress-rupture strength than the comparable base metals. Inconel 182 weldments had the lowest stress-rupture strength when compared with Inconel 82, Inconel 112, and Inco-Weld A weldments. Several reformer operators^[43-45] have experienced accelerated creep damage, embrittlement, and failures with Inconel 182 weld metal. Failures have been attributed to a loss of rupture strength caused by embrittlement. Inconel 182 is now known to exhibit a loss of rupture strength and ductility at elevated temperatures.

Commonly used materials for joining Alloy 800 are the Inco-Weld A electrode and Inconel 82 filler metal. Avery et al.^[5] specifically recommended filler metal Inconel 82 for Alloy 800 welds. Roach and VanEcho^[41, 42] indicate that Inconel 82 weldments have higher stress-rupture strength than Inco-Weld A and Inconel 182 weldments but lower stress-rupture strength than Inconel 112 weldments. McMillan^[43] found success in using Inco-Weld A material in place of the aforementioned failing Inconel 182 filler metal.

Shibasaki et al.^[46] recommended the use of a high-nickel alloy metal (Inconel 82) for welding 20Cr-32Ni-Nb metals. Kobrin^[45] obtained superior results using Inconel 82, Alloy 625 filler metal, and Inconel 112 in place of Inconel 182. Orbons^[47] suggested using Inconel 112 in place of Inco-Weld A for applications at temperatures above 816 °C (1500 °F) because of its superior resistance to creep damage. Roach and VanEcho^[41, 42] also found that Inconel 112 had superior creep resistance compared with that of Inco-Weld A, Inconel 182, and Inconel 82 weldments. Van Wortel^[31] noted that all of the tested weldments of Alloy 800H and Alloy 800HT were susceptible to stress relaxation cracking in the as-welded condition and that Alloy 617 filler was the most susceptible. For applications that require the highest strength and corrosion resistance, Inconel 117 electrode and Alloy 617 filler metal are recommended^[70] for use at temperatures above 788 °C (1450 °F).

3.4 Welding and Repair Practices

Throughout industry certain welding practices lead to good long-term service performance. Avery et al.^[5] successfully welded pigtails using the gas tungsten arc method, consumable inserts or filler metals, and an internal gas purge to obtain the best root contours. They also cited an example where severe sulfidation and failure of an Alloy 800 furnace tube occurred because slag was not effectively removed during the construction welding process and the sulfur content of the furnace atmosphere was not properly controlled during the first month of operation. Grinding and abrasive blasting was suggested to avoid such failures. Pool^[48] suggested minimizing residual stresses in the construction welding process by use of preheating, cooling blankets, and controlled peening of hot welds.

Al-Jubeihi^[49] reported making successful repair welds from the process of grinding out cracks, depositing Inco-Weld A stringer beads, and grinding out defects one bead at a time while using dye penetrant tests and ultrasonic examinations to ensure quality repairs. Another successful repair method, as discussed by Thielsch and Cone^[50], involves grinding into through-wall cracks to remove 60 % of the cross-section and grinding back the surface area by 5 mm (³/₁₆ in.) to prevent re-cracking associated with embrittlement. The beveled area is then buttered using Inconel 182 electrodes, and the previously ground grooves are filled up by welding followed by a stringer bead technique. The method suggested for welding brittle materials involves buttering to minimize shrinkage, utilizing Inconel 182 filler metal that provides welds of high ductility, avoidance of weld grinding, minimizing starts and stops, using needle guns and wire brushes for slag removal, using a stringer bead technique, and uniformly preheating to temperatures in the range of 232 °C to 343 °C (450 °F to 650 °F). The shortcoming of this repair method is that Inconel 182 welds have poor high-temperature creep strength, as pointed out previously.

Kiser^[39] stresses the importance of surface area cleaning using grinding, machining, shot blasting, or pickling prior to repair welding. Wire brushing was considered insufficient for cleaning. A controlled-speed weave was recommended to spread the weld metal. Keeping the amperage within the recommended range was also suggested on the basis that excessive amperage can lead to micro-fissuring or a breakdown of the flux binder that causes the coating to spall and the electrode to go out of control. He also stressed that weld slag must be completely removed from the finished joint because residual slag can be damaging to equipment in high-temperature service.

Shi and Lippold^[51] performed hot ductility tests on the 20Cr-32Ni-Nb alloy using a Gleeble testing system to study its susceptibility to liquation cracking and ductility dip cracking. Thermal embrittlement of heat-resistant alloys leads to decrease or dip in ductility to a minimum value with increasing temperature. The ductility increases at temperatures above that of the minimum ductility. When the restraint at the weld joint exceeds the minimum ductility, cracking occurs. The results of the Gleeble simulations indicated that liquation cracking, and not ductility dip cracking, is responsible for cracking that occurs during repair welding of the 20Cr-32Ni-Nb alloy.

Kiso et al.^[52, 53] investigated the cause of cracking in the welds of heavy-section Alloy 800HT piping during fabrication. Alloy 617 filler metal and Alloy 117 electrodes were used to fabricate the welds. The cracking was observed at the outer surface of the weld where the Alloy 117 was used and was believed to reheat cracking that occurred during the stabilizing heat treatment at a minimum temperature of 900 °C (1652 °F). This stabilization heat treatment temperature was less than the recommended value of 982 °C (1800 °F) as previously discussed in 3.2.4. They indicated that the ductility dip in Alloy 617 and Alloy 117 is greater than that in Alloy 800HT, which increased their susceptibility to reheat cracking in the weld joints. Reduced heat

input, interpass temperatures less than 135 °C (275 °F), and liquid penetrant inspection before and after PWHT were used to avoid further cracking issues.

Hydrogen induced crack formation can lead to weld failures. Pattabathula et al. ^[54] noted this type of cracking can be mitigated by increasing the temperature above the dew point at the weld through addition of outside surface insulation and installation of windshields on the sides of the furnace. Another problem with welding operations, pointed out by Shibasaki et al. ^[27], involves differences between weld and base metal. The difference in thermal expansion coefficients can lead to elastic-plastic strain of the weld material. An approach suggested by Orbons ^[47] involves high-temperature preheating around the weld to prevent cracking of the base metal caused by weld shrinkage.

Lobley et al. ^[55] found that it was necessary to bore machine and solution anneal a 20Cr-32Ni-Nb cast header prior to repair welding because of its severe embrittlement in the aged condition. The bore machining was done to remove a brittle inner layer of material, but unfortunately the authors did not report the mechanism of embrittlement. The solution annealing was required to dissolve secondary carbide precipitates.

Anderson and Bruno ^[56] reviewed weldability issues that were encountered during the welding of a new cone piece to an existing tee (aged material) in a hydrogen reformer outlet manifold. Both pieces were 20Cr-32Ni-Nb castings from the same foundry. Metallurgical analysis of samples of the previously installed, aged cone piece on which an Electrode 117 weld bead had been deposited revealed both HAZ liquation cracking and reheat cracking, as shown in Figure 1 and Figure 2, respectively. The liquation cracking was believed to be caused by low melting point silicate precipitates that had formed during service, whereas the reheat cracking was believed to have been caused by a combination of mismatched mechanical properties and high inclusion content. They found that full solution annealing of the aged material was required to weld it successfully.

Penso and Mead ^[57] reviewed cracking that was found on existing 20Cr-32Ni-Nb statically cast tee pieces when new centrifugally cast 20Cr-32Ni-Nb reducer cones were welded to them. The location of this cracking is shown in Figure 3. It was found to be associated with intermetallic silicate precipitates in the existing (aged) material. Both tees were cut out and solution annealed at 1150 °C (2100 °F), and then all of the cracks were machined out. Welding was done using a GTAW process with Alloy 617 filler wire, a 50 °C (120 °F) preheat, and a maximum interpass temperature of 150 °C (300 °F). A buttering layer was first applied using low amperage. Dye penetrant (PT) inspection was performed after each circumferential bead of the first layer of buttering. If cracking was encountered, it was removed before welding again with a lower heat input. The joints were first tack welded, and then a root pass was applied. DP inspection was performed following every second fill pass and after blend grinding the cap pass.

Jack ^[58] reported cracking in a 21/33 weld between a tee and a subheader in a cast 20Cr-32Ni-Nb outlet manifold after 14 years of service at approximately 793 °C (1460 °F). This cracking is shown in Figure 4. Attempts to grind out and repair the cracking were not successful, so tapered sleeves of Alloy 800HT were designed and welded over the cracked weld and similar welds in the outlet manifold.

3.5 Mechanical Design

The details of mechanical design depend on operating pressure and temperature and affect the location of weld joints and the level of stress in pigtails and headers. Thus, these design details can influence the long-term service performance of the components. The operating pressure and temperature of a steam-methane reformer depends the type of reformer. Figure 5, from Kawai et al. ^[59], shows typical operating pressure and temperature ranges for three types of reformers: (1) ammonia (NH₃), (2) hydrogen (H₂), and (3) methanol (CH₃OH). The range of operating pressure decreases and the range of operating temperature increases as the reformer type changes from ammonia to hydrogen to methanol. These differences in operating conditions should be kept in mind when evaluating experience from reformer operation.

Table 2—Specifications of Typical Welding Consumables for Hydrogen Reformer Outlet Manifolds and Pigtails

Standard	Specification	Common Name	Applications ^(a)
<i>Welding Electrodes</i>			
A5.11, ENiCrFe-2 ^(b)	W86133 ^(c)	Inco-Weld A	Adequate creep strength for temperatures below 760 °C (1400 °F); acceptability above 760 °C (1400 °F) depends on stress levels.
A5.11, ENiCrFe-3 ^(b)	W86182 ^(c)	Inconel 182	Adequate creep strength for temperatures below 760 °C (1400 °F); acceptability above 760 °C (1400 °F) depends on stress levels.
A5.11, ENiCrMo-3 ^(b)	W86112 ^(c)	Inconel 112	Some operators have used it above 760 °C (1400 °F) when higher creep strength is needed. Should not be used for temperatures between 593 and 760 (1100 and 1400 °F) because of potential embrittlement with time. Most operators choose to use Inconel 117 for higher creep strength at temperatures above 760 °C (1400 °F).
A5.11, ENiCrCoMo-1 ^(b)	W86117 ^(c)	Inconel 117	Can be used above 760 °C (1400 °F) when higher creep strength is needed. Reportedly does not embrittle in service.
<i>Filler Metals</i>			
A5.14, ERNiCr-3 ^(b)	N06082 ^(c)	Inconel 82	Adequate creep strength for temperatures below 760 °C (1400 °F); acceptability above 760 °C (1400 °F) depends on stress levels.
A5.14, ERNiCrMo-3 ^(b)	N06625 ^(c)	Alloy 625	Some operators have used it above 760 °C (1400 °F) when higher creep strength is needed. Should not be used for temperatures between 593 and 760 °C (1100 and 1400 °F) because of potential embrittlement with time. Most operators choose to use Alloy 617 for higher creep strength at temperatures above 760 °C (1400 °F).
A5.14, ERNiCrCoMo-1 ^(b)	N06617 ^(c)	Alloy 617	Can be used above 760 °C (1400 °F) when higher creep strength is needed. Reportedly does not embrittle in service.
<i>"Matching" Weld Metals</i>			
BS EN 12072 ^(d)	1.4850 ^(e)	Thermanit 21/33	Acceptable for temperatures up to 1050 °C (1922 °F).
BS EN 12072 ^(d)	1.4850 ^(e)	Thermanit 21/33 So	Acceptable for temperatures up to 1050 °C (1922 °F).
BS EN 12072 ^(d)	1.4850 ^(e)	UTP A 2133 Mn	Acceptable for temperatures up to 1050 °C (1922 °F).
(a) As reviewed by Shargay, Laughlin, and Feather [39] for AWS welding electrodes and filler metals and as given in manufacturer's datasheet for "matching" filler metals			
(b) American Welding Society (AWS) standard			
(c) UNS specification			
(d) British Standard			
(e) DIN specification			

Table 3—Chemical Compositions of Weld Metals Used in Hydrogen Reformer Outlet Manifolds and Pigtails

Element	Weld Electrode or Metal							
	Inconel 182 ^(a)	IncoWeld A	Inconel 82	Inconel 112 ^(b)	Inconel 117	Thermanit 21/33	Thermanit 21/33 So	UTP 2133 Mn
Ni + Co	59.0 min	62.0 min	67.0 min	55.0 min	~61 ^(c)	33.0 ^(d)	33.0 ^(d)	33.0 ^(d)
C	0.1 max	0.1 max	0.1 max	0.1 max	0.05-0.15	0.20	0.12	0.14
Mn	5.0-9.5	1.0-3.5	2.5-3.5	1.0 max	0.30-2.5	2.3	4.8	4.50
Fe	10.0 max	12.0 max	3.0 max	7.0 max	5.0 max	~41	~39	~40
S	0.015 max	0.02 max	0.015 max	0.02 max	0.015 max	--	--	--
Si	1.0 max	0.75 max	0.50 max	0.75 max	0.75 max	0.20	0.20	0.30
Cu	0.50 max	0.50 max	0.50 max	0.50 max	0.50 max	--	--	--
Cr	13.0-17.0	13.0-17.0	18.0-22.0	20.0-23.0	21.0-26.0	22.0	22.0	21.0
Ti	1.0 max	--	0.75 max	--	--	--	--	--
Al	--	--	--	--	--	--	--	--
Nb + Ta	1.0-2.5	0.5-3.0	2.0-3.0	3.15-4.15	1.0 max	1.7 ^(e)	1.2 ^(e)	1.3 ^(e)
Mo	--	0.5-2.5	--	8.0-10.0	8.0-10.0	--	--	--
P	0.030 max	0.030 max	0.030 max	0.030 max	0.030 max	--	--	--
Others	0.50 max	0.50 max	0.50 max	0.50 max	0.50 max	--	--	--

(a) Inconel 182 is not typically recommended because of its poor creep strength.

(b) Inconel 112 is not typically recommended because of embrittlement concerns between 593 °C and 843 °C (1100 °F and 1550 °F).

(c) Ni is remainder and Co is 9.0-15.0

(d) Ni only

(e) Nb only

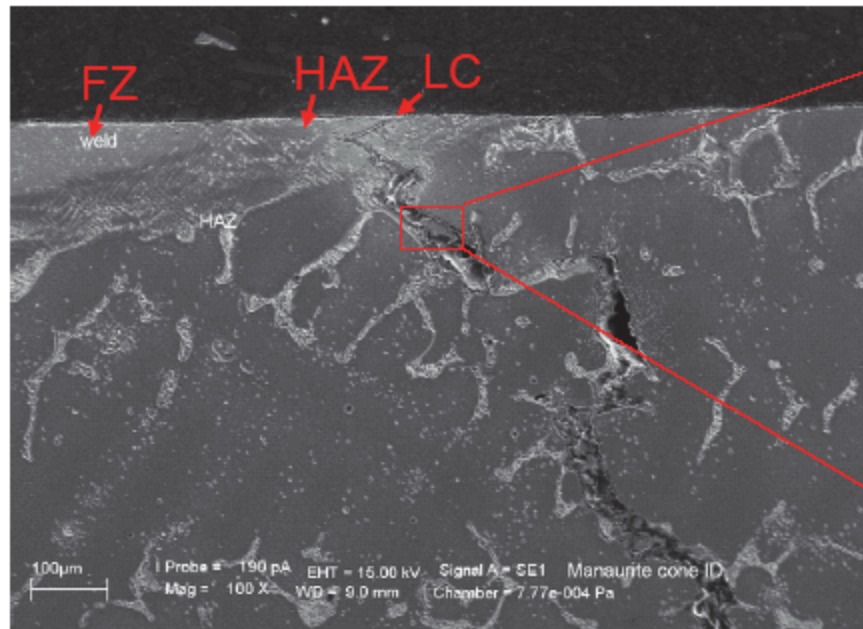


Figure 1—Example of HAZ Liquation Cracking in Aged 20Cr-32Ni-Nb Casting, from Anderson and Bruno ^[56]

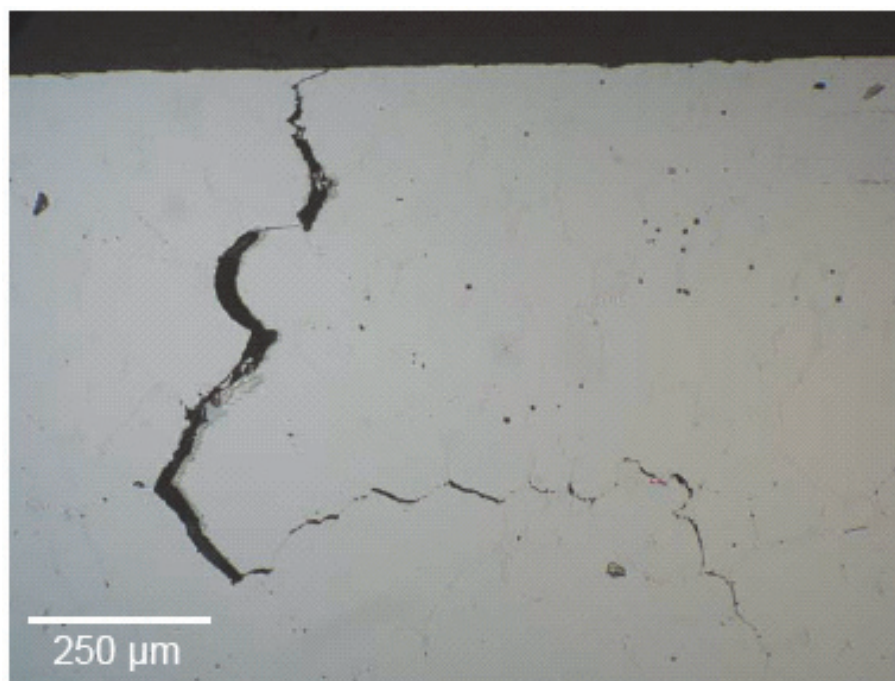


Figure 2—Example of Reheat Cracking in Aged 20Cr-32Ni-Nb Casting, from Anderson and Bruno ^[56]

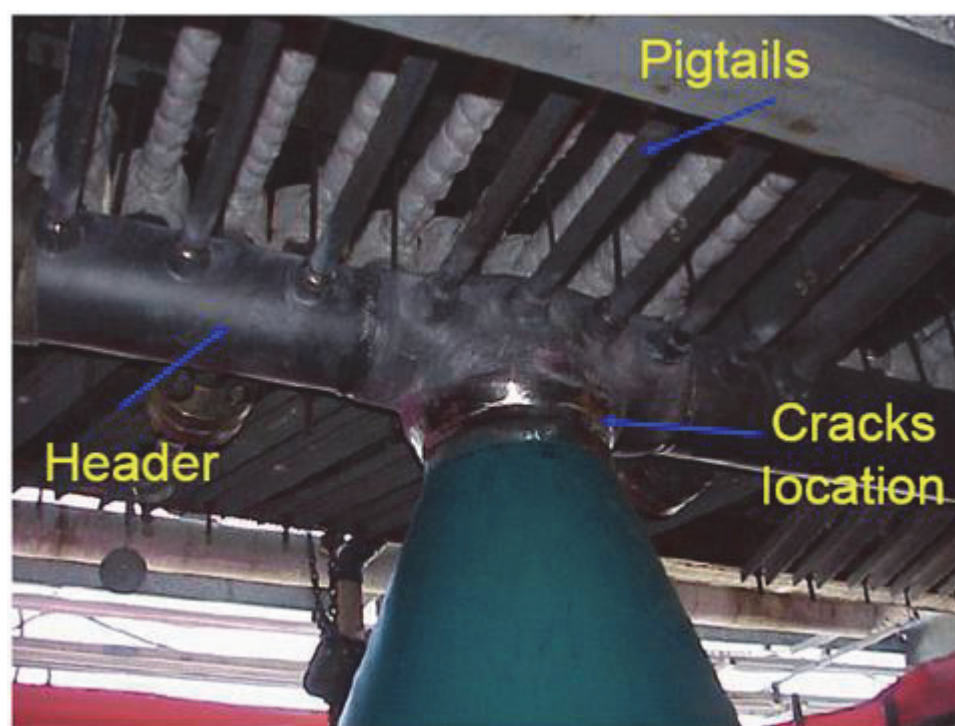


Figure 3—Location of Cracking in Aged 20Cr-32Ni-Nb Cast Tee Piece after Welding a New Cone Piece to it, from Penso and Mead ^[57]