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Dissimilar Metal Welding and its Allowance in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code

June 2024

Tate Patterson, Michael D McMurtrey

Changing the World's Energy Future



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Market-driven Optimization of the X-energy Next-generation Integrated Transportable High-temperature (XENITH) Microreactor, DOE-FOA-0001817

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ABSTRACT

Advanced reactors, such as the high temperature gas-cooled reactor, are being developed to solve current and future energy production needs. These advanced reactor designs may benefit by transitioning components via the use of two different alloys joined via arc welding processes. Historically, dissimilar metal welds have been used in industrial applications to change mechanical properties, corrosion resistance, and/or reduce cost. From a design perspective, transitions can be greatly beneficial, but the abrupt changes in material composition and mechanical properties can result in metallurgical issues and localized strain accumulation. Some of the metallurgical issues include solidification cracking, detrimental phase formation, and undesirable phase boundaries. Additionally, coefficient of thermal expansion, strength, and ductility mismatch result in localized stress and strain that will exacerbate cracking mechanisms and lead to premature failure. An example of this is reduction of creep resistance and premature creep cracking as compared to either alloy's properties. The American Society of Mechanical Engineers (AMSE) Boiler and Pressure Vessel Code (BPVC) Section III Division 5 instructs the high temperature reactor design rules, which does not provide significant guidance on dissimilar metal welds between two different alloys for elevated temperature service. The purpose of this document is to review the issues specific to dissimilar metal welding and how BPVC Section III Division 5 addresses reduced weld metal properties through stress reduction factors. Additionally, how other ASME BPVC sections address and permit dissimilar metal welds is discussed and recommendations are made regarding dissimilar metal welding.

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ACRONYMS

ASME	American Society of Mechanical Engineers
AWS	American Welding Society
BCC	Body-centered cubic
BPVC	Boiler and Pressure Vessel Code
CTE	Coefficient of thermal expansion
CSEF	Creep strength enhanced ferritic
DMW	Dissimilar metal weld
EDS	Energy dispersive spectroscopy
EPRI	Electric Power Research Institute
FCAW	Flux cored arc welding
FCC	Face-centered cubic
FN	Ferrite number
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
HIC	Hydrogen induced cracking
NRC	Nuclear Regulatory Commission
PAW	Plasma arc welding
PMZ	Partially melted zone
PQR	Procedure qualification records
PWHT	Post weld heat treatment
PWSCC	Primary water stress corrosion cracking
SAW	Submerged arc welding
SMAW	Shielded metal arc welding
SRF	Stress reduction factor
WPS	Welding procedure specification
WRC	Welding Research Council

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Dissimilar Metal Welding and its Allowance in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code

1. INTRODUCTION

The process of bonding metals consisting of two different alloys is referred to as dissimilar metal welding and has numerous advantages in industrial applications. Typically, the welds are performed to connect two components that are optimally designed with a specific material composition. These design criteria may include aspects such as strength, ductility, toughness, creep, fatigue, thermal conductivity, and/or corrosion resistance. Common industrial applications are joining low-alloy steels to austenitic stainless steels or nickel base alloys or cladding corrosion resistant alloys onto higher strength and/or lower cost materials. The historical use of dissimilar metal welds in nuclear reactors is not new, and many dissimilar metal welds were used in light water reactors to connect piping systems [1].

Although advantageous, there are major weldability challenges associated with dissimilar metal welds (DMWs). These challenges include variations in material properties that hinder the ability to produce a joint with the mechanical performance of either material. These issues include variations in:

- yield strength
- coefficient of thermal expansion (CTE)
- thermal conductivity
- melting temperature (solidus/liquidus temperatures)
- liquid viscosity
- phase transformation temperatures and microstructure formation

The mismatch between the materials to be joined, such as their respective yield strength and CTE, results in large variations in residual stress formation. Residual stress is the result of fusion welding processes creating a molten weld pool (fusion zone) and a thermal gradient within the adjacent solid materials. Expansion during solidification followed by contraction on cooling will cause thermally induced strains in the surrounding material. These thermally induced strains are capable of being as high as the yield strength.

In addition to macroscale material property issues, weld microstructures are influenced by mixing of each material and the filler metal(s). Because of differences in thermal conductivity, solidus/liquidus temperatures, and liquid viscosity, fusion welds are subjected to non-uniform mixing resulting in regions of the weld with non-conventional weld metal microstructures. These local areas may include unmixed zones, variations in solidification segregation, and/or depletion or enrichment from solid-state diffusion – all of which will result in varying mechanical and corrosion performance.

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) for nuclear reactor applications has minimally addressed the ability to perform such welding. The purpose of this document is to define what dissimilar metal welding is, what the major historical issues with DMWs are, and how ASME BPVC addressed DMWs. This document will also review how the welding procedure and performance qualification code addresses DMWs (Section IX “Welding, Brazing, and Fusing Qualifications” [2]) and how the non-nuclear pressure vessel codes address DMWs (Section VIII “Rules for Construction of Pressure Vessels” [3-5]).

2. DISSIMILAR METAL WELDING REVIEW

A DMW may pertain to any joint that is welded with a filler metal different from the base metal (heterogeneous weld), a cladding for altering surface properties, or a weld made between two different

base metals. However, these materials do not need to be drastically different. For instance, joining two austenitic stainless steels together, such as 304L to 304H or 304H to 316H, are DMWs. Additionally, many fusion and solid-state welding processes are used for DMWs. Solid-state processes are often used to mitigate the metallurgical challenges associated with joining drastically different alloys, such as steel to aluminum. However, this review will only focus on fusion welding processes, which refers to processes where material is heated to the melting point during the welding process. The specific fusion welding processes may include gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), flux cored arc welding (FCAW), plasma arc welding (PAW), submerged arc welding (SAW), or shielded metal arc welding (SMAW) – as these are processes permitted in ASME BPVC Section III, Division 5 for high temperature applications [6]. Of these processes, only GTAW and PAW can be performed autogenously, i.e., without filler metal. However, it is common to introduce a filler metal to fill a joint, especially for thick section components or alloys that crack without chemical composition modifications. GMAW, FCAW, SAW, and SMAW are consumable electrode processes.

These fusion welding processes develop a region of molten metal with additional regions characterized by microstructural changes or sharp transitions in chemical composition. The regions that can develop due to a heterogenous weld, where the fusion zone is a different composition than the base metal(s), are shown in Figure 1 [7, 8].

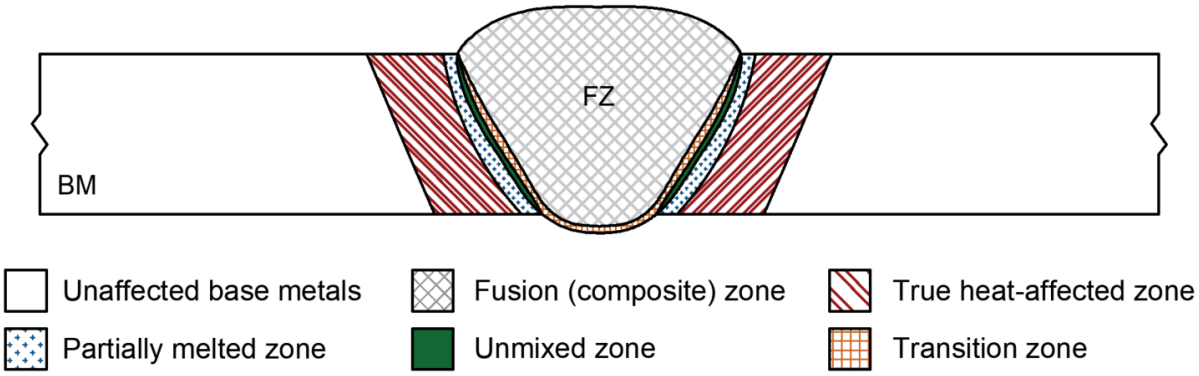


Figure 1. Schematic of the regions of a dissimilar metal weld.

The regions in Figure 1 have two major differentiating characteristics: 1) areas that undergo complete melting and 2) areas that do not fully melt or do not melt at all but undergo microstructural changes. The transition zone is a thin layer of material that is a mix between the filler metal and the base metal. The transition zone is only a characteristic of heterogenous or DMWs due to differences in composition. An example of a transition zone from a gas tungsten arc weld between F65 steel and Alloy 625 is shown in Figure 2 [9]. These complex regions are commonly referred to as weld metal swirls and are areas of significant interest due to the their high hardness and historical issues of hydrogen induced cracking (HIC) during service in sub sea oil and gas applications [9, 10].

Further towards the base metal may be an unmixed zone where 100% of base metal melting occurs, but the base metal does not mix with the filler metal. Moving further from the fusion zone results in a partially melted zone (PMZ), which is technically part of the heat affected zone (HAZ). PMZs are caused by preferential melting of grain boundaries, melting of segregated solute, and/or a phenomenon known as constitutional liquation. Select areas preferentially become liquid but the entire region does not melt. An example of liquation is shown in Figure 3, where liquid from the fusion zone penetrated the grain boundaries in the HAZ.

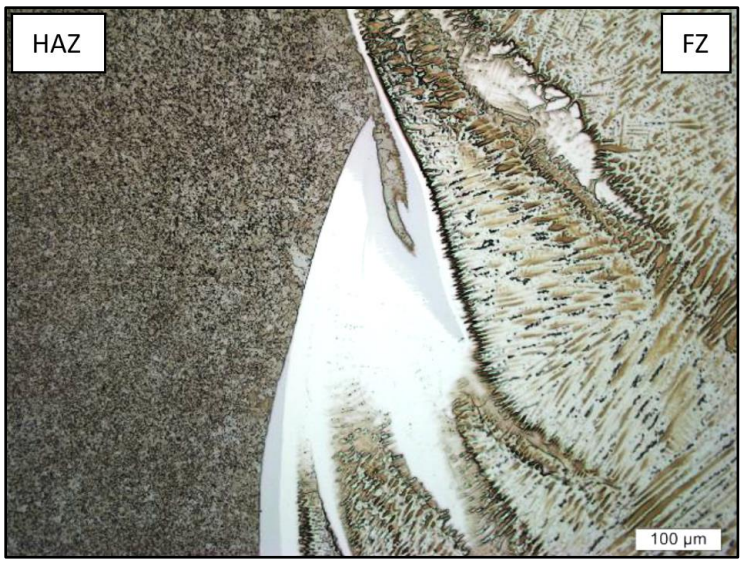


Figure 2. Transition region from a multi-pass gas tungsten arc weld on F65 steel (left side of micrograph) using Alloy 625 filler metal [9].

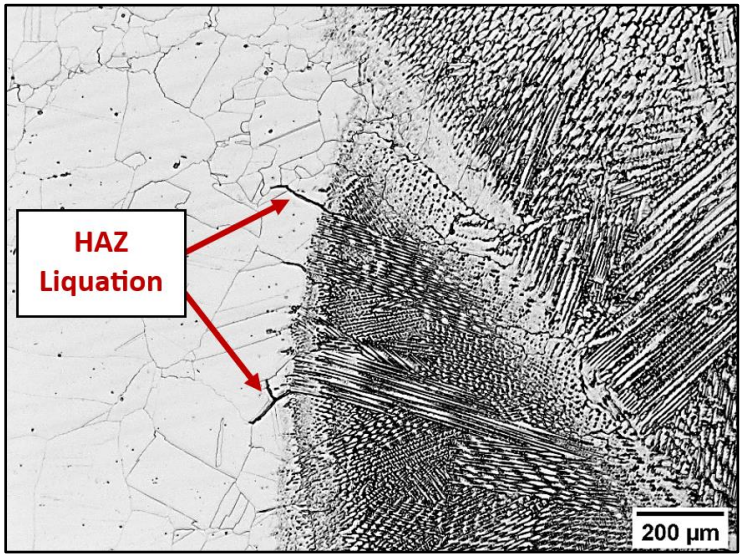


Figure 3. Example of liquid penetrating grain boundaries in the heat affected zone from the fusion zone (right side) [11].

For a single pass weld, the fusion zone will have a relatively homogenous composition at the macro scale – though micro segregation occurs as a result of solidification. Macro composition analysis is the first step in understanding the fusion zone composition to carefully control dissimilar metal weld properties. This is known as dilution and is defined as the amount the filler metal diluted by the base metal. Many factors influence dilution, which include the welding parameters, the joint geometry, and the thermal properties. Regardless, the resultant dilution can be measured based on the cross-sectional areas of the fusion zone and the known base plate area(s) consumed into the fusion zone. An equation and a schematic representation for the dilution for two different base metals is shown in Figure 4, (where each "A" refers to the relevant cross-sectional area).

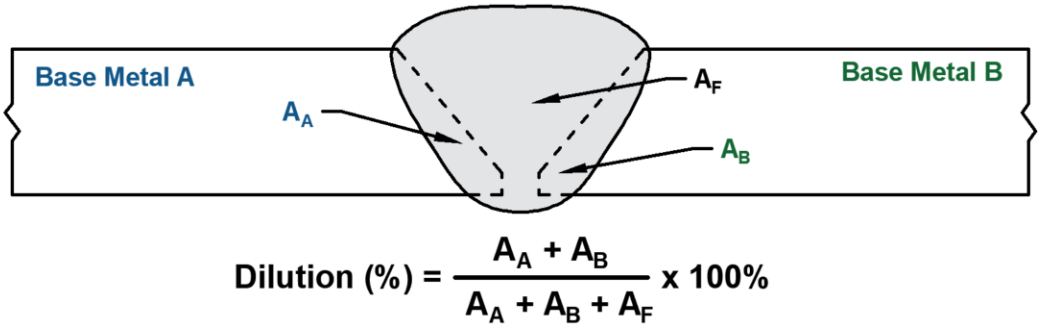


Figure 4. Schematic of base plate dilution from two different materials prepared as a V-groove butt joint.

As heat input (voltage, current, and travel speed), torch position, filler metal feed rate, and weld pass sequences change, the dilution (chemical composition) of each pass will change. Therefore, a composition gradient can exist between any range of the individual base materials and the filler metal(s). Fundamentally, a DMW is a functionally graded material. The schematic in Figure 4 is for a single pass weld. However, many applications rely on multi-pass welding to sufficiently join plates, pipes, forgings, or castings. Multiple passes will mix with each successive weld pass and/or the base metals, which will introduce successive reheating cycles into the previous HAZ and weld metal. This further complicates microstructure evolution, material properties, and predictability. All properties that were known from either base material are entirely eliminated as a result of dissimilar metal welding. The compositional space can lie anywhere between the individual alloys. Therefore, DMWs effectively create alloys that do not contain the historical property data to qualify an alloy for ASME BPVC Sec. III Div. 5.

Diagrams have been created to aid in predicting chemical compositions and resultant phases, called constitution diagrams. Two of the most common are the Schaeffler [12] diagram and the WRC-1992 diagram [13]. An example of using the Schaeffler diagram to predict the phases present between two steel alloys is shown in Figure 4. If it was assumed that Grade 91 (G91) steel was to be joined to a Type 316 stainless steel, microstructures will exist that are not representative of either alloy. The tie line shown in Figure 4 connecting the chromium and nickel equivalency values for G91 steel and Type 316 stainless steel indicate that 100% martensite, austenite and martensite, or austenite and ferrite phases can be present. The possibility or amount of each phase is entirely dependent on the dilution. Although useful for the stainless steel alloys or compositions that can fall within the empirical equations, these diagrams are limited in their usefulness to predict wide alloy ranges/compositions. However, these diagrams can be the first line of defense for proper selection of filler metals to mitigate cracking susceptibility [14]. For instance, ASME BPVC provides the WRC-1992 [13] diagram in Section III Division I – Subsection NB [15], as shown in Figure 6, to predict the amount of primary ferrite that will form during arc welding. The delta ferrite (ferrite formed upon solidification) is limited to a minimum ferrite number (FN) of 5 for specific weld metal compositions (Section IX A-Number 8 welds [2]). The 5 FN or greater requirement is due to ferrite fractions below 5 FN increasing the weld metal solidification cracking susceptibly. Conversely, delta-ferrite retention is deleterious for high temperature mechanical properties and should be eliminated for maximum creep life.

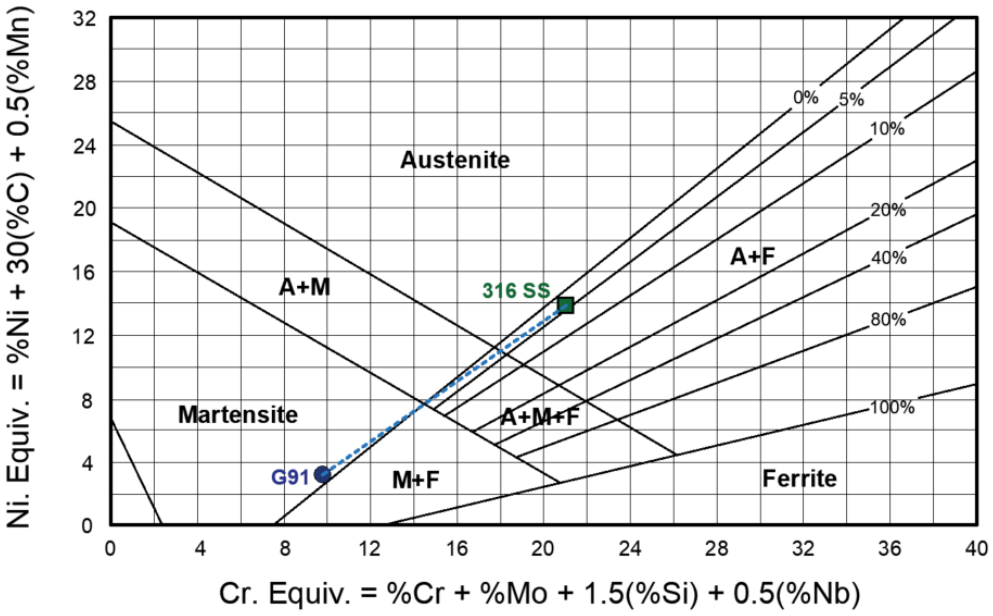


Figure 5. Example of a constitution diagram, the Schaeffler diagram [12], with overlaid material compositions for Grade 91 steel and Type 316 stainless steel joined via a tie line.

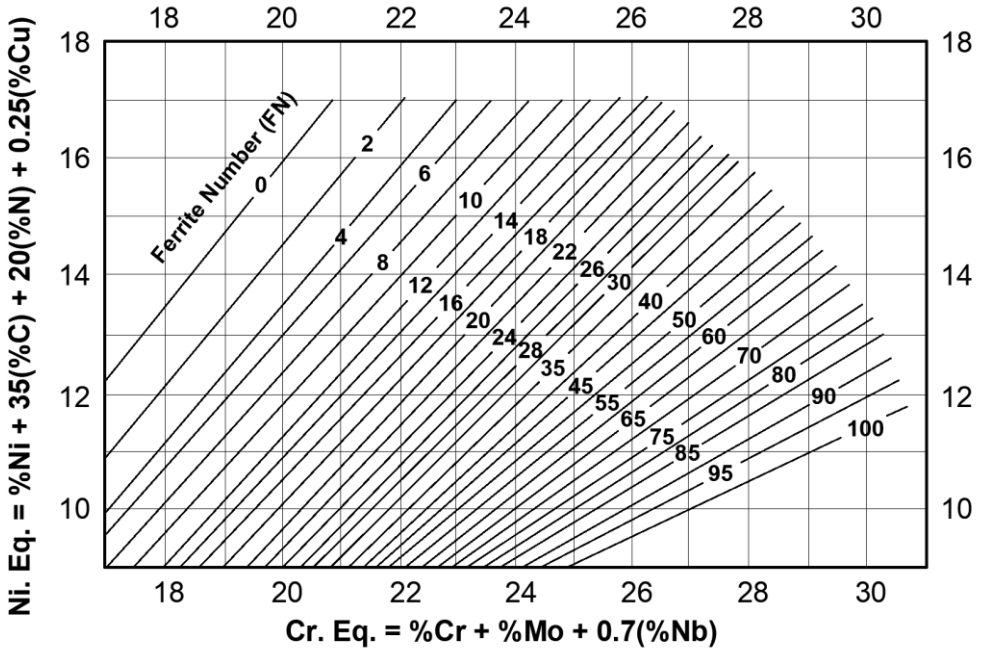


Figure 6. WRC-1992 developed by Kotecki and Siewert [13] and provided in subsections of BPVC Section III Division 1 [15-17].

2.1 Issues Associated with Dissimilar Metal Welding

Many failure mechanisms exist that result from welded dissimilar metal connections. These include, disbonding around “Type II” grain boundaries [18], creep failure [19, 20], carbide dissolution [21], and failure due to accelerated corrosion [9]. Other major weldability issues that are not directly related to dissimilar metal welding but are welding issues that must be accounted for include solidification cracking,

liquation cracking, ductility dip cracking (DDC), hydrogen induced cracking, intergranular corrosion (sensitization), stress corrosion cracking, reheat cracking (strain age and PWHT cracking), Type IV cracking, embrittling phase formation (σ-phase), and/or liquid metal embrittlement (LME) [7, 19]. Due to the major use of high carbon austenitic stainless steels for their creep resistance, welding induced sensitization will also be discussed. A lot of technological challenges must be overcome to successfully develop DMWs. The following subsections will expound on the issues specifically associated with joining two different materials. This will include material property mismatch, diffusion, and Type II boundaries.

2.1.1 Material Property Mismatch

Large variations in material strength, thermal conductivity, and CTE influence residual stresses that develop during welding and throughout service [22]. The higher the mismatch of CTE between the materials to be joined, the worse (higher) residual stress induced into the joint. If service conditions are such that the welded joint is exposed to thermal cycling, the thermal fatigue performance will be significantly reduced with greater CTE mismatch. From a fabrication perspective, residual stresses cause component deformation and difficulty maintaining part tolerances across welded joints.

A major design criterion applied by ASME Sec. III Div. 5, that other construction codes do not consider, is elevated temperature fatigue and creep-fatigue properties. It should be noted that this is not identical to thermally induced fatigue because test temperatures are constant. However, an example of CTE values for permissible Sec. III Div. 5 alloys (and filler metal) are shown in Figure 7. Grade 91 and Type 304 stainless steel have the greatest difference in CTE mismatch. Sharp changes in material properties are problematic and exacerbate crack formation and propagation. Therefore, the nickel base filler metals, such as Alloy 82 (ERNiCrFe-3 [23]) are advantageous to reduce the severity of the mismatch and allow for a graded transition [24, 25]. For further improvement, the Electric Power Research Institute (EPRI) developed a filler metal, known as P87, for improving joining of Grade 91 to austenitic stainless steels for fossil energy power plant DMWs [26]. The intent of this filler metal composition was to reduce the CTE mismatch and maintain similar C and Cr contents as Grade 91. Thus, reducing the internal stresses across the fusion boundary and reducing the concentration gradient to mitigate elemental diffusion. Other work was funded by the United States Department of Energy through a Nuclear Energy University Program to investigate these issues, but the research largely evaluated functionally grading materials and weld pool modeling for the laser powder bed fusion process [27]. Therefore, there was minimal progress on addressing DMW development and introduction into applicable ASME construction codes for use by industry.

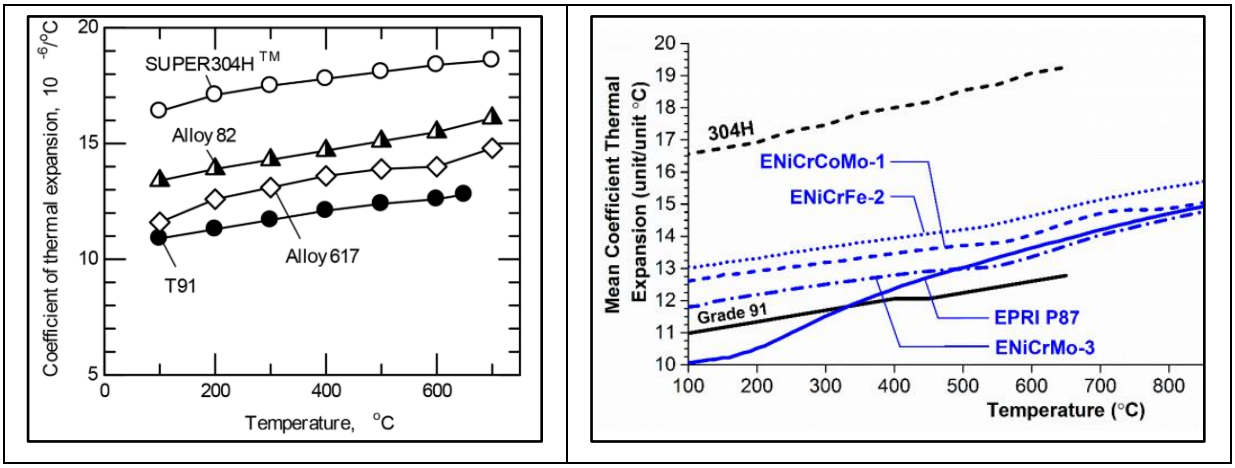


Figure 7. Variations in CTE between Grade 91, Alloy 617, Alloy 82, and Type 304 stainless steel [28] (left) and variations in CTE Grade 91 and filler metals used for DMWs (right) [29].

The electrode designations starting with “E” in Figure 7 indicate a shielded metal arc welding (SMAW) electrode as defined in American Welding Society (AWS) specifications A5.11 “Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding” [30]. The SMAW process is generally used in final fabrication where welder portability and a shelf-shielded process is needed to protect the weld pool from oxidation during field welding. The only filler metal permitted by BPVC Sec. III, Div. 5 [6] in the right plot of Figure 7 is ENiCrFe-2 (Alloy A). ENiCrFe-2 is a SMAW electrode approved to weld Alloy 800H materials, which is further discussed in Section 4.

Two filler metals that have been commonly used for dissimilar metal welding are Alloy 182 and Alloy 82. Alloy 182 (ENiCrFe-3) is a SMAW electrode, and Alloy 82 (ERNiCr-3), also known as Filler Metal 82, is a bare wire or electrode used for processes such as gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW). These welding processes require shielding gases and are generally restricted to controlled environments but are easily mechanized or automated.

Figure 8 shows how the choice in filler metal can influence the failure locations for long term creep testing. These failed creep specimens were Alloy 800H base plate welded with Alloy 82 filler metal (top) and Alloy 617 (ERNiCrCoMo-1 [23]) filler metal (bottom). The filler metal with higher strength (Alloy 617) largely resulted in creep cracking within the HAZ of the Alloy 800H, as opposed to the softer Alloy 82, which resulted in the creep failure through the fusion zone. Although microstructure is a major factor for the failure location, the non-uniform strain distribution imposed by different mechanical properties resulted in localization of stress and strain and contributed to the distinct failure locations.

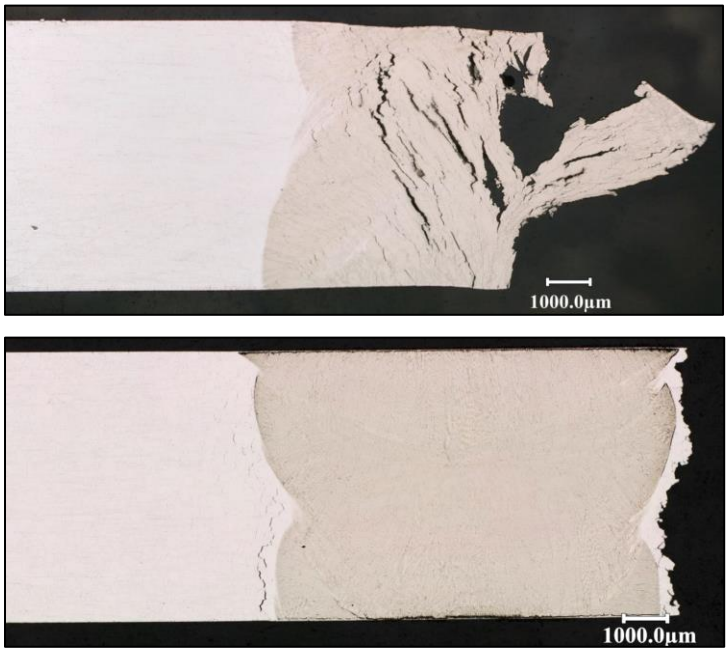


Figure 8. Variation in creep test failure locations for dissimilar metal welds on Alloy 800H using Filler Metal 82 (top) and Alloy 617 (bottom) [31, 32].

Arc welding will always influence the microstructure of the wrought alloy in the HAZ. In allotropic alloys that undergo two or more solid-state phase transformations, the HAZ is generally easy to visualize through metallographic preparation techniques. Polishing and chemical etching is effective when the material changes phase and/or alters its grain structure compared to the fusion zone and base metal microstructure. However, isotropic alloys that do not have phase transformations may not have apparent HAZs, such as the austenitic Fe-Ni-Cr alloy shown in Figure 8. HAZs are often regions of reduced

mechanical or corrosion performance as it cannot practically be returned to an identical state as the wrought material. Therefore, the HAZ should always be an area analyzed for its performance. Additionally, dissimilar metal welds will change the strain accumulation and may impart greater stress and strain locally across the HAZ. An example of failure through the Grade 91 HAZ of a dissimilar metal weld to Type 304 stainless steel is shown in Figure 9.

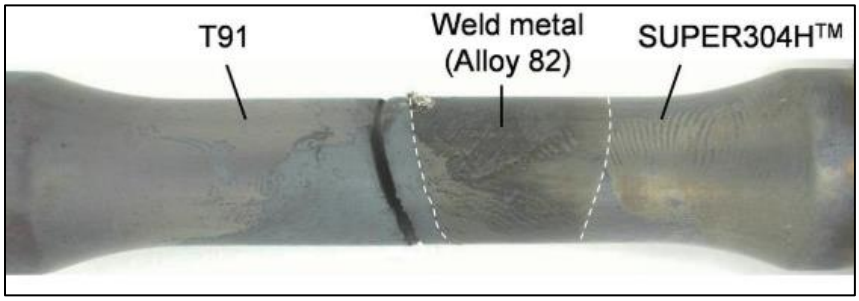


Figure 9. Example of a Grade 91 HAZ failure caused by a low cycle fatigue test of a DMW between Grade 91 and Type 304H stainless steel. Image extracted [28].

However, testing of DMWs poses an issue regarding stress and strain accumulation. For strain-controlled fatigue testing, as shown in Figure 9, strain accumulation will not be consistent across the specimen gauge length. Fundamentally, the test may be applying most of the strain to the material/region that deforms the most. Therefore, strain accumulation is not consistent as it would be for a single alloy with a homogenous structure and homogenous properties across the entire gauge length. Therefore, it is always difficult to make direct comparisons or relate the behavior to the individual alloys when attempting to perform standardized testing on cross-weld specimens.

2.1.2 Diffusion

When depositing alloys of different chemical composition, a large chemical potential may exist that drives elements towards regions with lower concentration (neglecting uphill diffusion). Interstitial alloying elements, such as carbon, have relatively high diffusivities compared to the matrix elements. Therefore, the high temperatures during welding allow rapid diffusion or migration from or into the HAZ adjacent to the weld pool [18, 33, 34]. These local regions may have drastically different properties over distances of 100 µm or less. Figure 10 shows examples of concentration profiles detected via energy dispersive spectroscopy (EDS) and the difference in hardness across the fusion boundary. This example is for F65 steel welded with Alloy 625, and the interlayer between both alloy compositions showed higher nano hardness of nearly 2 GPa or 250 HV [9] . The issues with the regions between dissimilar metal welds is that they result in compositions that are not characteristic of the base metal(s) nor the filler metals. Therefore, it is difficult to always predict the mechanical and corrosion properties. Transitions in chemical profiles will be exacerbated if post weld heat treatments (PWHTs) are needed or required by code. An example of the worsening influence of a PWHT is shown in Figure 11 [35]. Gittos and Gooch [35] reported that the as-welded condition resulted in martensite present along the interface and hardness values near 440 HV. After PWHT, they reported maximum hardness around 500 HV with further carbon migration and copious carbide formation.

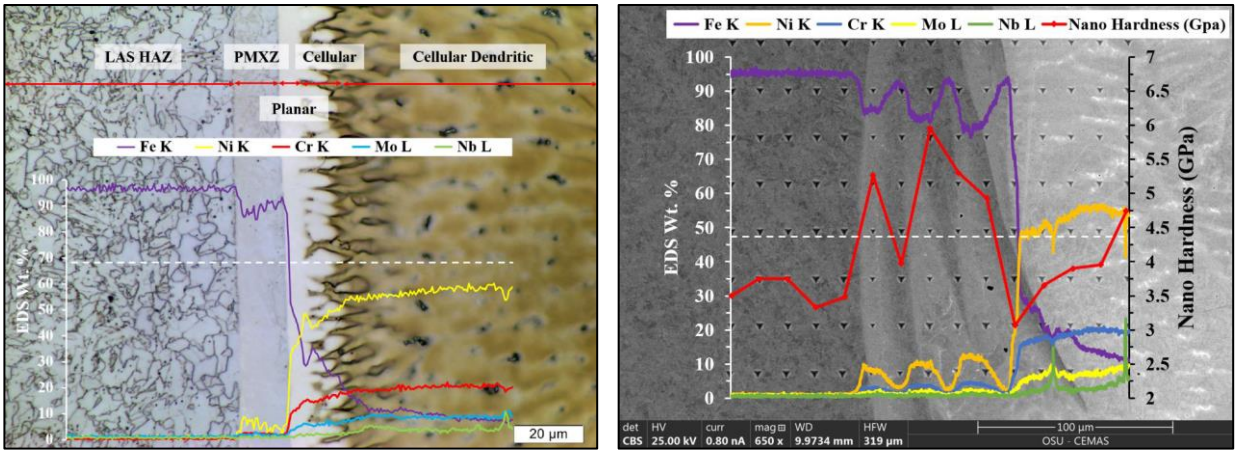


Figure 10. Elemental scans across a fusion boundary on a dissimilar metal weld on F65 steel (left side of images) to Alloy 625 (right side of images). The scanning electron micrograph (right) also shows the change in nano hardness across the boundary. [9]

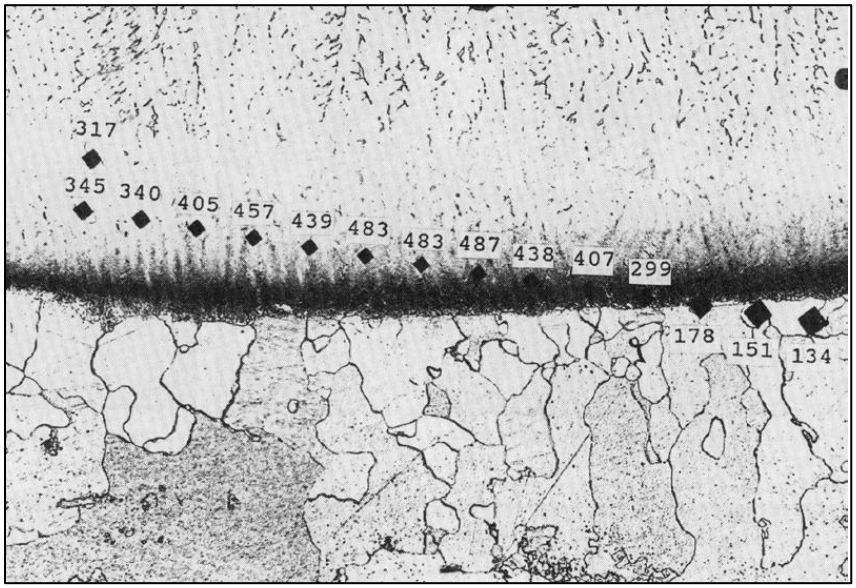


Figure 11. Interface of dissimilar metal weld of stainless steel (top) clad on Grade 22 steel (bottom) showing a high hardness martensitic band as a result of carbon diffusion during the PWHT at 720°C for 10 hours. [35]

2.1.3 Type II Boundaries

Type II boundaries are a metallurgical phenomenon that exists when an austenitic, face center cubic (fcc) structure solidifies on a solid ferritic, body center cubic (bcc) structure. For conventional nucleation, a solid grain or crystal nucleates from the solid material with the same crystal structure and grows in a preferential growth direction. The region separating each crystal is called a grain boundary. Under normal growth conditions, the grains nucleate from the HAZ and growth into the fusion zone, perpendicular to the fusion boundary. The grain boundaries normal to the fusion boundary interface are called Type I boundaries. The Type I nucleated grains are columnar and referred to as epitaxial (directional) nucleation.

However, the nucleation of materials that form different crystal structures disrupt the directional nucleation from the HAZ to the fusion zone. For steels cooling from liquid, the structures may change

from ferrite (bcc) to austenite (fcc) then back to ferrite (bcc) during cooling to room temperature. Therefore, grains must nucleate along the solid-liquid interface that have no relation to the grains in the HAZ. This is believed to occur due to an austenitic (fcc) structure nucleating on a delta ferrite (bcc) structure, such as a low-alloy steel. A schematic example of this is shown in Figure 12 [18, 33]. Once the boundary starts to cool, the delta ferrite transforms to austenite, and the original boundary migrates into the austenitic weld metal. This results in grains and grain boundaries aligned nearly parallel to the fusion boundary [33]. Figure 13 shows an example of a Type II boundary resulting from A508 steel clad with 309L stainless steel filler metal. It is believed that Type II boundaries are inherently weak interfaces that result in preferential crack sites. Due to carbon migration, Type II boundaries are also regions where high hardness martensitic microstructures may exist, exacerbating the likelihood for HIC.

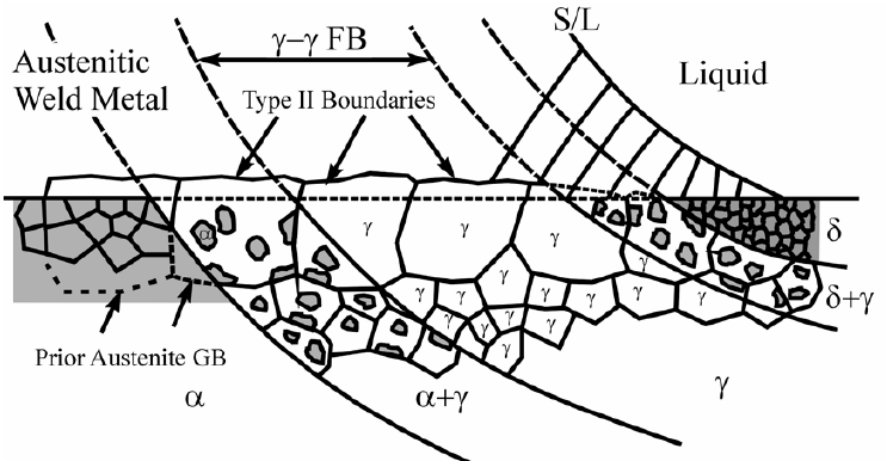


Figure 12. Schematic of the Type II boundaries occurring as a result of austenitic weld metal solidifying on top of a solid ferritic substrate. [18]

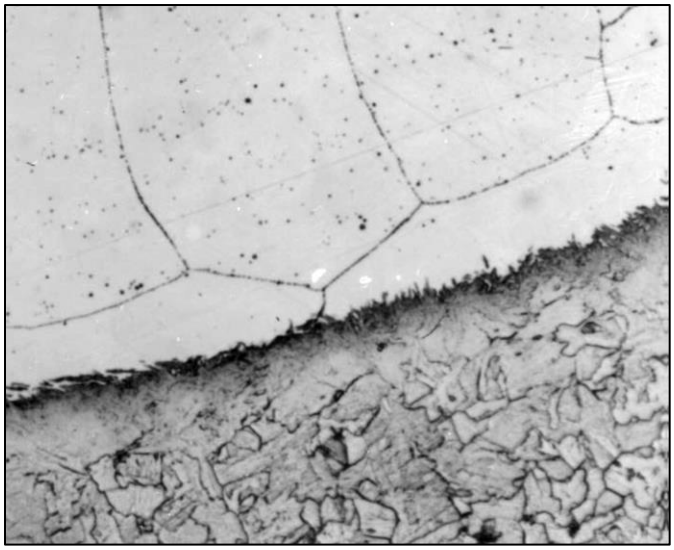


Figure 13. Example of a Type II boundary running nearly parallel to the fusion boundary (dark region) in A508 pressure vessel steel (bottom) clad with Type 309L stainless steel filler metal (top). [21]

2.2 Field Failures

This section will discuss some field failures of dissimilar metal welds reported in the open literature. Klueh and King [35] reported a creep failure that occurred in a Grade 22 steel welded to a Type 321 stainless steel using an Alloy 182 (ERNiCrFe-3) filler metal. The cross-section of one of these field failures is shown in Figure 14. This joint was part of a fossil fuel-fired steam plant that had been in operation for over 100,000 hrs. Their reports indicated that weld failure was a common problem, with failure generally occurring in the ferritic steel HAZ and located 5-15 μm from the fusion boundary. One of their theories for failure was due to a local area of chromium depletion, which lead to preferential oxidation.

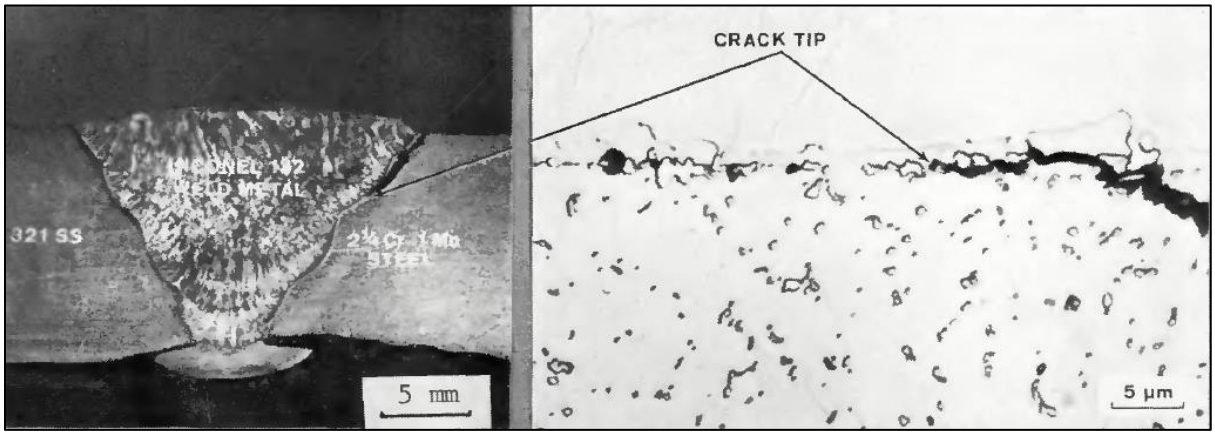


Figure 14. Creep failure through the HAZ of a Grade 22 steel welded to 321 stainless steel from Klueh and King [36]. Failure occurred after nearly 17 years of service operating near 560°C.

Non-uniform compositions and diffusion plague the potential utility of DMWs. As previously shown, carbon diffusion along the fusion boundary can result in high hardness and a martensitic microstructure that is highly susceptible to hydrogen uptake. Hydrogen uptake and HIC is an issue that has plagued the oil and gas industry. Figure 15 shows a field failure of a crack along 8630 steel welded with Alloy 625. The variation in electrical potential and cathodic protection is believed to have initiated hydrogen charging into the materials, which then coalesced in the high hardness martensitic regions. Cracking results once the thresholds for stress and hydrogen content are surpassed. Dodge et al. [10] reported that the cracks were subsurface, i.e., not surface breaking.

Another example of a hydrogen induced crack in what was reported to be a “reactor vessel wall” of a Grade 22 steel is shown in Figure 16 [37]. Gittos [35, 37] concluded that cracking resulted from HIC due to the martensite present from welding and PWHT. However, it was also reported that failure largely propagated through the 309L/347 stainless steel cladding. Therefore, it is possible that Type II boundary formation resulted in preferential crack nucleation sites along with the high hardness martensitic structures. A distinct Type II boundary failure is shown in Figure 17. These failure types are commonly referred to as disbonding based on their failure appearances, which cleanly propagate along the fusion boundary. To avoid these failures, careful consideration must be given to the base metal and filler metal compositions as well as heat treatment times and temperatures.

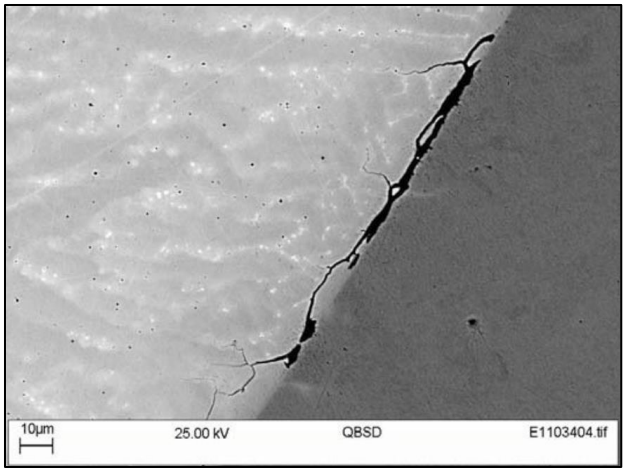


Figure 15. Hydrogen induced crack as a result of a high hardness martensitic region and galvanic couple due to a dissimilar metal weld between 8630 steel and Alloy 625. [10]

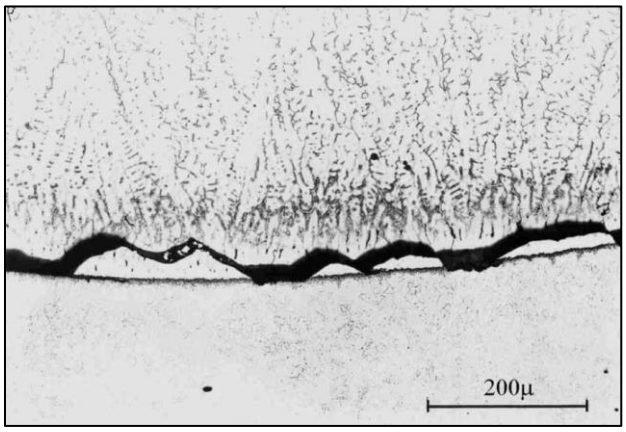


Figure 16. Disbonding of a Grade 22 steel clad with 309L/347 stainless steel filler metals and exposed to hydrogen. [37]

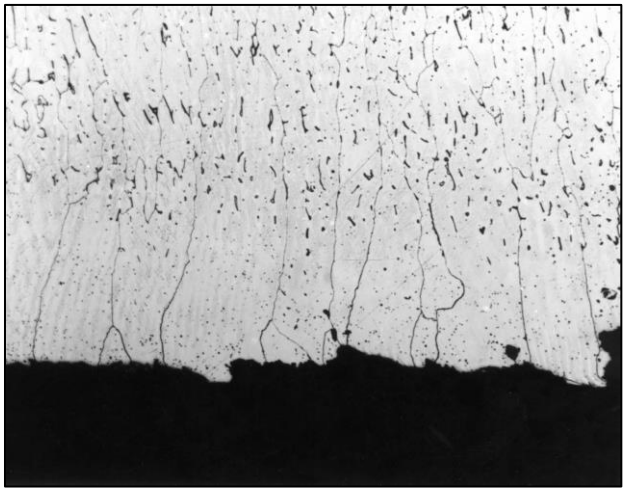


Figure 17. Failure along the Type II boundaries from a dissimilar metal weld of 309L deposited on A508 steel. [18, 33]

According to Dupont [38], alloyed steels welded with nickel base filler metals develop Type I carbides that result in creep void formation and premature failure along the interface, while stainless steel filler metals general result in cracking along prior austenite grain boundaries in the ferritic HAZ. Another issue that has been observed in field failures is caused by the presence of an "oxide notch". This is where an oxide forms at the weld toe and causes cracking along the fusion boundary. Much of the research regarding cracking of welds has stemmed from cracks found in energy production systems including fossil energy power plants and nuclear reactors. Table 1 contains a synopsis of actual DMW failures that have been reported.

Table 1. Reports of in-service dissimilar metal weld cracking.

Base Plate Combinations	Filler Metal(s)	Application	Reported Cracking Issue(s)	Reference
SA-508 Steel to 316 Stainless Steel	Alloy 82	Light Water Reactor	Primary Water Stress Corrosion Cracking	[20]
2¼ Cr - 1 Mo to Type 321 Stainless Steel	Type 309	Fossil Fuel Power Plant	"Oxide Notch" Corrosion in 2¼ Cr - 1 Mo HAZ near fusion boundary	[36, 39]
SA-508 Class 2 to Type 316 Stainless Steel	Alloy 82 Alloy 182	Pressurized Water Reactor (VC Summer and Ringhals 4)	Solidification Cracking and/or Primary Water Stress Corrosion Cracking	[40, 41]
Low Alloy Steel (similar to SA-508) Type 316 Stainless Steel	Alloy 132	Pressurized Water Reactor (Tsuruga Unit 2)	Primary Water Stress Corrosion Cracking	[42]
Grade 91 (P91) to Stainless Steel	Alloy 182	Fossil Fuel Power Plant	Creep Void Nucleation Along Fusion Boundary	[21]
Low Alloy Steel to Stainless Steel	Alloy 82 Alloy 182	Pressurized Water Reactor (Wolf Creek)	Primary Water Stress Corrosion Cracking	[43]
Grade 91 to Type 316 Stainless Steel	Alloy 182	Petrochemical Plant	HAZ Cracking	[44]

2.3 DMW Failure Mitigation Strategies

Besides careful alloy selection, optimizing weld metal dilution to maintain crack resistant compositions, and using welding techniques to minimize residual stress formation, two other strategies are used to improve the performance of DMWs. These are "buttering" and "safe-end" welds. The main purpose of these welds is to deposit materials that act as a gradual property transition, aid weld metal dilution to prevent cracking, or provide additional chemical resistance. Dupont et al. [45] evaluated functionally graded transition joints as an option to improve traditional techniques used in industry, but these full functional grading of joints have not been used, or at least reported, for industrial applications.

2.3.1 Buttering

Buttering is a process where a filler metal is deposited on one of the dissimilar metal joints to be welded. Generally, this process is performed on alloys that require a PWHT to improve the disrupted microstructure as a result of welding. An alloy that resists microstructural transformations, such as isotropic, austenitic metals, are deposited onto the heat sensitive alloy. A common example is dissimilar joints between ferritic steels and austenitic alloys as shown in Figure 18.

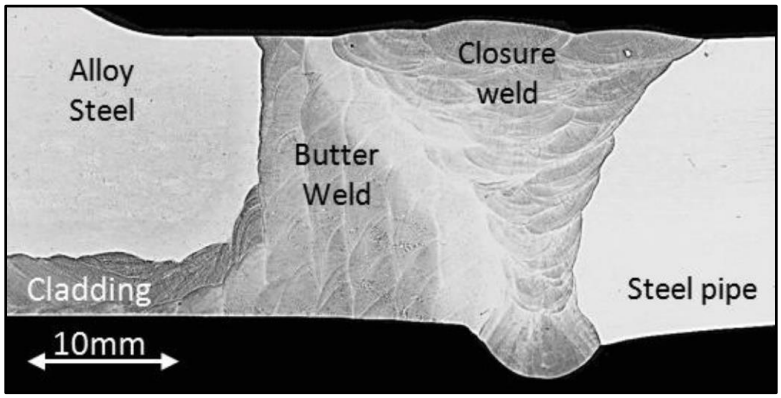


Figure 18. Example of applying a butter weld to the low-alloy steel for heat treatment prior to final fabrication using a "closure weld". Macrograph extracted from Dodge et al. [10].

By using an austenitic material as a butter layer on the low-alloy steel substrate, a heat treatment can be performed that returns the low-alloy steel closer to its original properties and minimally influences the butter weld austenitic filler metal. Then, final welding can be performed between the Alloy 625 butter layer and the alloy being joined to the low-alloy steel. During this process, the entire HAZ of the final connecting welds will be contained within the Alloy 625 butter layer and not influence the low-alloy steel. If needed, a similar process or butter layer can be used for both alloys (sides of the joint) to be joined.

2.3.2 "Safe-End" Welds

Nuclear power applications have used attachments of stainless steel pressure piping to larger pressure vessels using what Dupont, Lippold, and Kiser [20] referred to as a "safe-end" welds. These welds turned into complex procedures to repair the original weld joint that used Filler Metal 82, which contains lower Cr (18-22 wt% [23]). It was believed that the lower Cr content was resulting in primary water stress corrosion cracking (PWSCC). PWSCC has resulted in numerous in-service weld cracking situations as previously shown in Table 1. A schematic of the final repair weld joining SA-508 steel to 316 stainless steel is shown in Figure 19 [20].

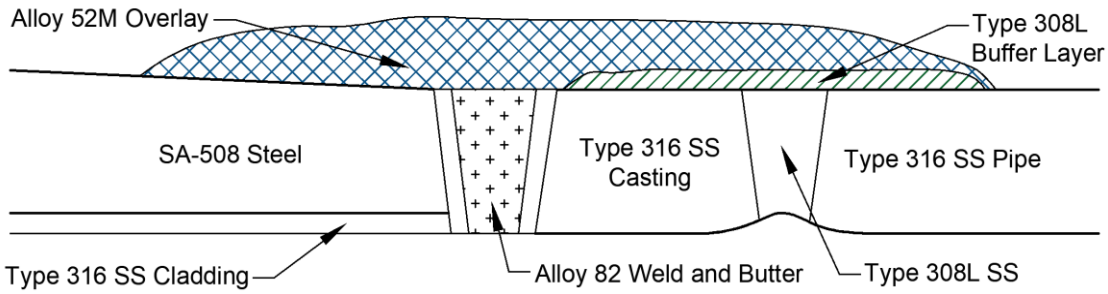


Figure 19. Schematic illustration of "safe-end" welds used in nuclear power application weld repairs. Figure recreated from Dupont, Lippold, and Kiser [20].

Because solidification cracking has resulted from direct overlays of Alloy 52M (ERNiCrFe-7A [25]) on austenitic stainless steel, an interlayer or buffer layer of Type 308L stainless steel filler metal was initially deposited. For the stress corrosion cracking resistance, the Alloy 52M was deposited across the entire weld joint from the SA-508 steel to the Type 316 stainless steel pipe. A cross-section showing a similar technique is shown in Figure 20. Type 309L was first deposited on the A508 steel that was joined with an Alloy 182 (ERNiCrFe-3). Finally, an overlay was deposited with Inconel 152 (ERNiCrFe-7) for improved corrosion resistance relative to ERNiCrFe-3.

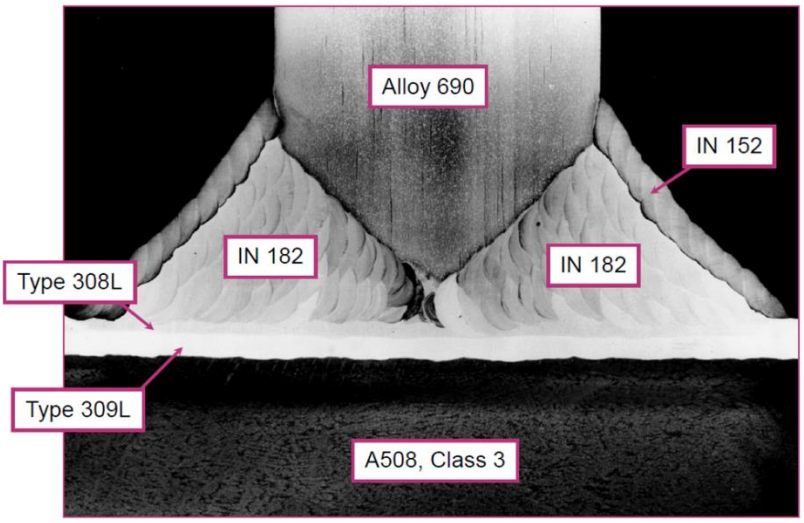


Figure 20. Schematic of the regions of a dissimilar metal weld between SA-508 and Alloy 690 welded with the SMAW process. [46]

2.3.3 Recommended Techniques

Many strategies are employed in industry to combat the issues associated with DMWs, and understanding if joints have been successfully used in the past can be key in preventing future issues regarding structural integrity. Process related strategies include development of welding parameters that utilize lower heat input, i.e., lower current/voltage for arc welding processes. With lower overall heat input, the thermally imposed stresses are reduced. Lower heat input can have numerous benefits, such as reducing solidification cracking susceptibility and/or reducing residual stresses and distortion. Another parameter that changes the heat input is travel speed. Increasing travel speed reduces the heat input, but care must be taken to avoid elongating the weld pool and increasing the solidification rate. Alloys, such as austenitic stainless steels, can be highly susceptible to changing the primary phase nucleating from the liquid, which can exacerbate solidification cracking susceptibility.

Filler metal selection and post-weld heat treatment procedures must be performed on a case-by-case basis. The base metals, fabrication restrictions, and service environment/conditions will all play a role in DMW performance. A general procedure for selecting DMW filler metals is as follows:

- As similar of chemical composition(s) as possible
- As low of a CTE mismatch as possible
- Select filler metals resistance to solidification cracking considering the influences of dilution (process, joint design, and material dependent)
- Select austenitic filler metals resistant to ductility dip cracking (filler metal composition and dilution dependent)

- Select filler metals resistance to reheat cracking or strain age cracking
- Grade the chemical composition from one material to another through two or more filler metals

It has been reported that the nickel-base alloy filler metals will outperform austenitic filler metals when Grade 91 or other CSEF steels to austenitic stainless steels or nickel alloys. Siefert and Parker reported that austenitic stainless steel filler metals, such as E309 or ER309, have shown a 2-3X reduction in creep life compared to nickel alloy filler metals [29]. Additionally, an ideal filler metal selection would include one that does not require a PWHT, and if a PWHT is used, it will not result in deleterious microstructural changes.

3. BOILER AND PRESSURE VESSEL CODE OVERVIEW

ASME has established rules for constructing steam boilers and other pressure vessels in the BPVC. These codes cover a wide range of pressure vessel types, including those used within residential buildings (e.g. water heaters), as well as nuclear power plants. The BPVC covers both mandatory requirements and nonmandatory guidance, which are distinguished in many cases by word choice. “Shall” denotes a requirement, “should” denotes a recommendation, and “may” is used to give permission and is neither a requirement nor a recommendation. Due to the wide range of applications, the BPVC has been divided into thirteen sections, as listed below:

- Section I – Rules for Construction of Power Boilers
- Section II – Materials
- Section III – Rules for Construction of Nuclear Facility Components
- Section IV – Rules for Construction of Heating Boilers
- Section V Nondestructive Examination
- Section VI Recommended Rules for the Care and Operation of Heating Boilers
- Section VII Recommended Guidelines for the Care of Power Boilers
- Section VIII Rules for Construction of Pressure Vessels
- Section IX Welding, Brazing, and Fusing Qualifications
- Section X Fiber-Reinforced Plastic Pressure Vessels
- Section XI Rules for Inspection of Nuclear Reactor Facility Components
- Section XII Rules for Construction and Continued Service of Transport Tanks
- Section XIII Rules for Overpressure Protection

A number of these sections are then further divided into divisions to cover specific areas within the broader section topics. Section III (relevant to nuclear facility construction) is divided into five divisions:

- Section III, Division 1 covers construction of light water reactor components.
- Section III, Division 2 contains the codes for concrete containments.
- Section III, Division 3 is the containment systems for transportation and storage of spent nuclear fuel and highly radioactive materials.
- Section III, Division 4 is the newest division, specific to fusion energy devices.
- Section III, Division 5 covers high temperature reactors.

Within this report, the most relevant sections are Section III, Division 5 (Sec. III, Div. 5) and Section IX. These will be discussed in more detail in later sections. A discussion of other sections of the BPVC will also be included as examples of how dissimilar metal welding is handled in some areas of the BPVC.

The BPVC is maintained and updated by committees and various subcommittee groups. The Committee on Construction of Nuclear Facility Components maintains Section III, and the Committee on Welding, Brazing, and Fusing maintains Section IX. These committees and subcommittee groups typically meet four times a year at the ASME BPVC Code Week meetings to discuss questions, concerns,

revisions or new rules, and to educate members on relevant topics. When there are questions regarding their intent, which may be submitted by external groups, the committees will provide interpretations for the rules, but will not, as a committee, act as consultants to answer general questions. The BPVC does not address all aspects of design and construction and states that aspects not specifically covered should be considered prohibited.

4. ASME BPVC SECTION III

ASME BPVC Section III is the construction code that pertains to nuclear reactor construction. For welding applications, different requirements apply to each division within Section III. These division requirements differ based on the perceived risks associated within each design category. As stated previously, this report will focus on Division 5 – High Temperature Reactors.

4.1 Introduction to Section III, Division 5

It is important to note that, while Div. 5 covers high temperature reactors, it provides rules for both high and low temperature components within the high temperature reactors. Div. 5 is divided into additional subsections and subparts. Subsections HA and HB are the most relevant to this work. Subsection HA provides the general requirements for metallic (Subpart A), graphite (Subpart B), and composite (Subpart C) materials. Subsection HB covers Class A metallic pressure boundary components for low temperature service (Subpart A) and elevated temperature service (Subpart B). Other subsections cover class B pressure boundary components, supports and support structures, as well as nonmetallic core components. Articles within these subsections are always designated by the Subsection/Subpart letters followed by a four-digit article number (e.g. HAA-1000 is the introduction of Subsection HA, Subpart A).

4.2 Section III, Division 5 Materials and Permitted Weldments

4.2.1 Similar Alloy Welds

There are currently six base alloys permitted for use as Class A components within ASME BPVC Sec. III, Div. 5 [6]. Five are included in the Code itself, which are 316H, 304H, 800H, Grade 91 (9Cr-1Mo-V), and Grade 22 (2.25Cr-1Mo). The sixth alloy, Alloy 617, is included through two code cases, N-872 and N-898, which represent the low and high temperature usage, respectively. Class A high temperature materials are described in Article HBB-2000 of Sec. III, Div. 5. This includes allowable base metals, as well as permitted welding procedures and classes of filler metals, which are shown here in Table 2, depicted in the BPVC in Table HBB-I-14.1(b). Although these are the base material combinations permitted by Sec. III, Div. 5, that does not indicate that more suitable options for filler metals are not commercially available. However, other commercial filler metals have not been evaluated based on Sec. III, Div. 5 testing criteria for incorporation of design criteria regarding stress, temperature, and service life.

Tables HBB-I-14.10A-1 through HBB-I-14.10F-1 give the Stress Rupture Factors (SRFs) for all of the accepted weld materials. SRFs are used to address the reduced weldment properties at certain conditions. For a given temperature and component lifetime, a SRF is given, either equal to 1.0 (no reduction in strength due to the weldment) or less (weldment reduces the expected life of the component). Stress rupture factors are the creep-rupture strength of the weld metal divided by the creep-rupture strength of the base material. They can go quite low, with 0.3 being used for certain 316H weldments operating at 1,300 °F, and a 300,000-hour lifetime. In some cases, SRFs are considered too limiting, and efforts are ongoing to expand the allowed weld filler metals to improve the SRFs. There is currently ongoing work for Alloy 800H to identify a filler metal with an improved SRF, which at some conditions is as low as 0.59 [11, 31, 32]. Alloy 617 was examined as an overmatched filler metal and was found to shift the failure outside of the weld and into the HAZ, but ultimately did not improve the SRF. UTP A 2133 Mn filler metal is now being considered as a new filler metal for Alloy 800H, and testing is currently ongoing to examine the SRFs of Alloy 800H welded with UTP A 2133 Mn. [47]

Table 2. Permissible welds within ASME BPVC Section III, Division 5.

Base Material	Spec. No.	Class
Types 304 and 316 Stainless Steels	SFA-5.4 SFA-5.9 SFA-5.22	E308, E308L, E316L, E16-8-2 ER308, ER308L, ER316, ER316L, ER16-8-2 E308, E308T, E308LT, E316T, E316LT-1, EXXXT-G (16-8-2 chemistry)
Alloy 800H (Ni-Fe-Cr)	SFA-5.11 SFA-5.14	ENiCrFe-2 ERNiCr-3
2.25Cr-1Mo	SFA-5.5 SFA-5.23 SFA-5.28 SFA-5.29	E90XX-B3 (>0.05% C) EB3, ECB3 E90C-B3, (>0,05% C), ER90S-B3 E90T-B3 (>0.05% C)
9Cr-1Mo-V	SFA-5.5 SFA-5.23 SFA-5.28	E90XX-B9 EB9 ER90S-B9
Alloy 617	SFA-5.14 (GTAW Only)	ERNiCrCoMo-1

4.2.2 Dissimilar Metal Welds

For DMWs, very little is stated in Sec. III, Div. 5. In HBB-3123.1, the BPVC states that caution should be exercised in designs and construction involving dissimilar metals having different coefficients of thermal expansion in order to avoid difficulties in service [6]. No other guidance is given for DSM in Sec. III, Div. 5. The Alloy 617 Code Case does not expand on this, and simply states in HBB-T-1345.4 that the requirements for DMWs are in the course of preparation. To the authors' knowledge, however, no work is being conducted to include DSMs for Alloy 617, or other Sec. III, Div. 5 materials.

5. ASME BPVC SECTION IX

ASME BPVC Section IX is the "Qualification Standard for Welding, Brazing, and Fusing Procedures; Welders; Brazers; and Welding, Brazing, and Fusing Operations" [2]. This section of Code is for qualifying welding parameters and operators for various welding processes, positions, and joint configurations. Sec. IX is a standard (requirements, specifications, and guidelines to ensure fit for purpose) that can be adopted into law through contracts and legal documents. However, the purpose of Sec. IX is to confirm sound welding process parameters for fabricators performing component construction. These sound welding practices are executed through procedure qualification records (PQRs) and welding procedure specifications (WPSs). The PQR contains information on the process parameters, joint configuration(s), and required mechanical tests to "qualify" a welding process, joint type, and weld orientation for a given group of materials. The WPS is the document that instructs the qualified welder or welding operator the parameters they can use to weld a particular joint. In essence, the WPS is like a welding cookbook.

Because it is not feasible to evaluate all materials, processes, and possible welding parameters, Sec. IX has groups of materials categorized as P-Numbers and subcategorized with Group numbers. Welding filler metals are categorized as F-Numbers, and some weld metal deposits are categorized with A-numbers. These grouping schemes allow for similar alloys to be qualified by welding similar or lower P-

No. classifications of alloys. Specifically, F-Numbers were group based on what was considered to be their “usability characteristics” and the “ability of welders to make satisfactory welds with a given filler metal”. The caveat to this is that filler metals cannot be “indiscriminately substituted” without considering the welding process, metallurgical phenomena, service conditions, and mechanical/corrosion performance.

Sec. IX categorizes three types of variables for each welding process. These variables are known as “essential”, “supplementary essential”, and “nonessential”. Essential variables are process parameters that are considered to be crucial to weldment mechanical performance regardless of the application (excluding toughness). If parameters are changed outside of the allowable bounds, a new or different procedure qualification must be performed or worked under, respectively. Supplementary essential variables are required, and become essential, only if toughness testing is mandated by the Construction Code, such as Sec. III or Sec. VIII. The supplementary variables are considered to only influence toughness properties in the weld metal, HAZ, or base metal. Non-essential variables can be recorded and/or specified on the WPS, but changing these variables does not require reperforming a weld qualification and creating a new PQR. The variables for each process are found in tables provided in Sec. IX BPVC in section QW-200 [2].

These essential, and potentially supplementary essential, variables must be recorded in the PQR with the test results. The recordings in the PQR are confirmation that the welding contractor successfully passed the test criteria defined in Sec. IX. The information on the PQR can then be passed to the WPS. The Sec. IX weld qualification tests include tension, guided-bend, fillet-weld, toughness, and stud-weld tests. These tests merely act as a go/no go gauge to confirm that ultimate tensile strength (UTS) and weld metal ductility are comparable to or greater than the base metal. An example of a welded test coupon for 0.5-inch thick plate is shown in Figure 21.

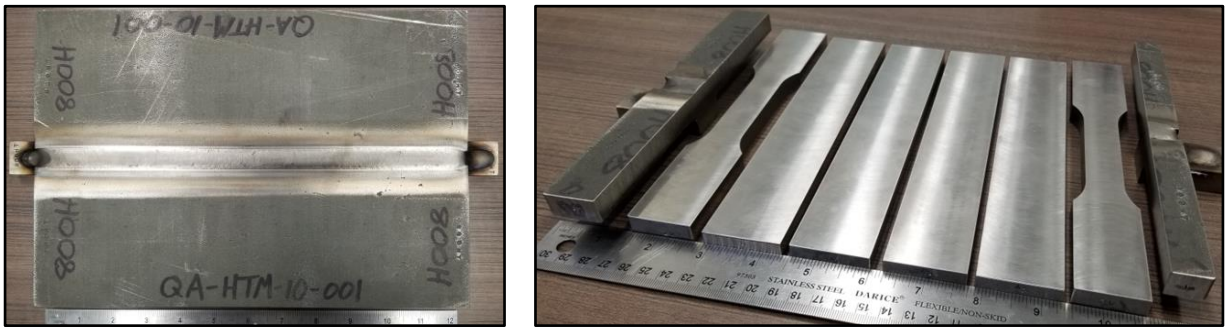


Figure 21. Example of a welded test coupon used for an ASME Sec. IX qualification (left) and two tensile specimens and four bend tests extracted from that plate for testing (right).

Successful testing of the 0.5-inch welded plate shown in Figure 21 would allow for welding plate thicknesses ranging from 3/16 inch to 1 inch (2T) in thickness (Sec. IX Table QW-451.1 or QW452.2[2]). A passing dissimilar metal cross-weld tensile test is shown in Figure 22, where failure was entirely in the base metal and above the minimum specified base metal ultimate tensile strength. For a DMW cross-weld tensile test to pass Sec. IX criteria, it must meet QW-153.1(b) and surpass “the minimum specified tensile strength of the weaker of the two, if base metals of different minimum tensile strengths are used.” [2]

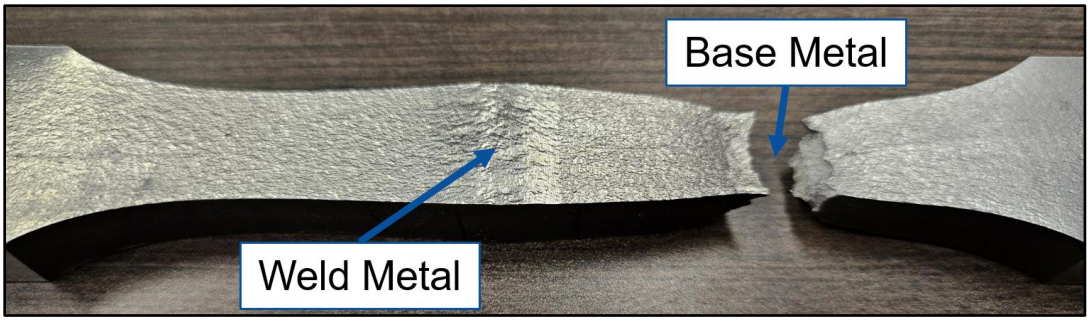


Figure 22. Example of a weld coupon used for an ASME Sec. IX qualification. The plate shown was 0.5 inch thick plate with a 0.5 inch weld thickness.

The coupon shown in Figure 21 was prepared such that four transverse bend tests (two root and two face) and two full thickness tensile specimens were extractable. For base metals that have drastically different bending properties, Section IX allows for performing longitudinal bend tests – both root and face bends. An example of a successful transverse bend test is shown in Figure 23. Although no discontinuities are visible on the face side of the bend test, Section IX allows for open discontinuities up to 1/8" regardless of the direction of measure. Any opening greater than this must be rejected as a defect, and those weld procedures cannot be used unless requalification efforts were successfully passed based on Sec. IX requalification criteria.



Figure 23. Example of a successful transverse bend test showing no indications of cracking, lack of fusion, or surface breaking porosity.

Depending on the alloy, it may be required to identify the chemical composition for conformance to Sec. IX. The A-Numbers for the weld deposits are provided in Table QW-442, which lists the maximum or range of elements permissible in the weld metal. If dilutions were to change such that the weld metal chemical composition fell outside of an A-Number range qualified, requalification would be required using parameters that fall within a permissible A-number.

To summarize, mechanical tests satisfying Sec. IX criteria are not an exhaustive test of weld properties and are not performed on the exact joint geometries. Section IX is merely used to demonstrate capable procedures, welders, and welding operators. Specific criteria that involve toughness testing, corrosion resistance, creep rupture lives, fatigue lifetimes, etc. are either defined through the construction codes or must be defined via additional engineering restrictions.

6. HOW OTHER ASME CODES ADDRESS DISSIMILAR METAL WELDS

This section will highlight the recommendations or requirements for DMWs imposed by other ASME construction codes. These codes include ASME BPVC Sec. 1 [48], ASME BPVC Sec. III Div. I [15-17], ASME BPVC Sec. VIII[3-5], and ASME B31 [49, 50].

6.1 Section I – Rules for Construction of Power Boilers

ASME BPVC Section 1 is the "Rules for Construction of Power Boilers" [40]. Within Sec. I, reference to DMWs is included within a nonmandatory appendix [48]. Specifically, the guidelines are for creep strength enhanced ferritic steels welded to austenitic stainless steels for "transport or collection of steam". The creep strength enhanced ferritic steel referenced is Grade 91, and the differences in service temperatures are defined as low temperature service (≤550°C) or high temperature service (>550°C). This appendix states recommendations for design, loading, filler metals, transition pieces, geometries, and welding techniques. The following contains some of the main recommendations for DMWs within BPVC Sec. 1:

- Locate dissimilar metal welds in areas with enough space to accommodate nondestructive examination and repair welding.
- Dissimilar metal welds should not be placed in high restraint conditions.
- Aoid terminal locations and allow for sufficient component flexibility.
- Place welds away from locations of thermal cycling.
- Filler metals ERNiCrMo-3, ENiCrMo-3, ERNiCrCoMo-1, and ENiCrCoMo-1 filler metals should be avoided due to potential for "embrittling" phases at the weld fusion line.

These recommendations minimize intrinsic stress through component design or avoid filler metals that are known to result in detrimental phases. The filler metals specified are Alloy 625 (E/ER NiCrMo-3) and Alloy 617 (E/ER NiCrCoMo-1). The E is for shielded metal arc welding electrodes [30] , and ER is for bare metal welding rods and electrodes [23]. Additionally, Sec. I contains a mandatory table, Table PW-39.2, regarding the PWHT temperatures for dissimilar welds between the P-number materials listed. For instance, G91 steel (P-No. 15E Group 1) welded to 316 stainless steel (P-No. 8) is required to have a PWHT between 705°C and 785°C. However, a note on the P-No. 8 materials explains that certain 300 series alloys can result in sensitization when exposed to temperatures between approximately 540°C and 845°C. The general remedies for sensitization are also recommended, which include the following:

- Use of a low carbon, "L", grade
- Use of a stabilized grade of stainless steel, e.g., Type 321 or Type 347
- Buttering the carbon steel with a Ni-base alloy, performing the PWHT, and then, completing the dissimilar weld without a final PWHT

Although useful and possible mitigation techniques for Sec. I applications, these options are not all possible for Sec. III, Div. 5 due to its restriction on permissible materials. The lower carbon grades have reduced high temperature creep strength and are less desirable for high temperature applications.

6.2 Section III Division I Rules for Construction of Pressure Vessels

Within Sec. III Div. I, there is a substantial amount of overlap and verbatim phrases used to define the welding and dissimilar metal welding requirements within each subsection. These subsections include Subsection NB – Class 1 Components [15], Subsection NC – Class 2 Components [16], Subsection NCD – Class 2 and Class 3 Components [17], Subsection NF – Supports [51], and Subsection NG – Core Support Structures [52]. These subsections allow for DMWs assuming that the welds can meet the design criteria and mandated weld tests. Additional weld test requirements depend on the materials used and may

include drop weight tear testing, Charpy V-notch testing, and delta ferrite measurements. Otherwise, Subsection NB and NG specifically state that “caution should be exercised in design and construction involving dissimilar metals having different coefficients of thermal expansion in order to avoid difficulties in service" [15, 52]. Likewise, Subsection NC Class 2 Components [16] allows for joining any combination of materials permitted in its “Article NC-2000” as long as the requirements with Subsection NC are met and the welds can meet the requirements imposed by Sec. IX [2]. Therefore, DMWs are permissible for all subsections within Division I as long as they meet all property criteria and can be designed for according to all Div. I Subsection design rules.

6.3 Section VIII Rules for Construction of Pressure Vessels

BPVC Section VIII is the “Rules for Construction of Pressure Vessels” and is separated into three subsections labelled as Division 1 [3], Division 2 [4], and Division 3 [5]. Sec. VIII Div. 1 is the “Rules for Construction of Pressure Vessels”, and Div. 2 and Div. 3 are alternative design rules and methods for construction of pressure vessels. Specifically, Sec. VIII Div. 1 states in UG-18 that: “a vessel may be designed and constructed of any combination of materials permitted in Subsection C, provided the applicable rules are followed and the requirements in Sec. IX for welding dissimilar metals are met” [3]. However, the base metals, weld metals, and HAZs must meet the criteria imposed throughout Div. 1. Other warnings are made in Sec. VIII Div. 1., such as for PWHT. There are also notes regarding galvanic corrosion considerations and other requirements are imposed, such as “titanium or zirconium and their alloys shall not be welded to other materials” [3].

Sec. VIII Div. 1 also has a nonmandatory appendix where DMWs are addressed in paragraph UHA-A-2. In this paragraph, it is stated that the coefficients of thermal expansion of the base material and the weld metal should “receive careful consideration” for ferritic stainless steels welded with “austenitic electrodes” for service applications under “severe temperature conditions, particularly those of a cyclic nature” [3]. Although this paragraph highlights the importance of reducing the CTE mismatch, it only refers to joints made on “ferritic stainless steels” using an “austenitic electrode”. The term electrode technically only applies to SMAW or GMAW processes, where the filler metal conducts the welding current.

6.4 ASME B31 Code for Pressure Piping

ASME B31 Code for Pressure Piping contains numerous subsections that pertain to the design, materials, fabrication, construction, and operation of pipelines and piping systems. Two of these subsections that are applicable include ASME B31.1 Power Piping [49], and ASME B31.3 Process Piping [50].

ASME B31.1 Power Piping code applies to applications including pressures greater than 15 psi of gauge pressure for "steam, water, oil, and gas” [49]. B31.1 permits the use of DMWs but states that the weld metal shall be similar to either base metal or an intermediate composition. However, for austenitic steels joined to ferritic steels, it is mandated that the weld metal have an austenitic structure. It also mandates that the filler metal for nonferrous metals shall be based on a recommendation of the manufacturer. Exceptions to this are based on fabricator and designer agreements for situations such as highly corrosive environments, where greater electrochemical resistant weld metals are needed. Cathodic protection and electrical isolation are also recommended to be used on dissimilar metal joints.

ASME B31.3 Process Piping is the code for pressure piping to provide the “engineering requirements deemed necessary for safe design and construction of piping installations” [50]. Some of the conditions that B31.3 states for DMWs are similar to B31.1 and includes the following [50]:

- Consideration should be given to the possibility of “adverse electrolytic effects” for dissimilar metal combinations.

- Heat treatments between ferritic and austenitic components or filler metals shall be performed according to the ferritic material “unless otherwise specified in the engineering design”.
- Weldments allowed to cool prior to heat treatment shall have the cooling rate controlled or use “other means to prevent detrimental effects in the piping”.

Other than providing caution regarding some of the issues relating to DMWs, ASME B31.3 does not provide extensive guidance or rules governing DMWs.

7. DEMONSTRATION WELD TESTING AT INL

INL performed a DMW between two Sec. III Div. 5 alloys, Grade 91 and Alloy 800H, using a mechanized cold-wire GTAW process. For this demonstration, a defect-free weld was produced to show the weld metal microstructure and limited mechanical performance without procedural nor performance optimization. A photo of INL’s research welding system used to complete the weld joint is shown in Figure 24. The Grade 91 plate was 0.75-inches thick, and the Alloy 800H was 0.5-inches thick. A V-groove was prepared with a 30° included angle, a 0.25-inch root opening, and a backing plate of Alloy 800H. Alloy 82 was used as the filler metal, and a total of 10 passes were required to fill the joint. The first root pass was deposited on the Grade 91 and backing bar. The second root pass was deposited on the Alloy 800H side and fused to the first pass. Passes were continually alternated between each plate following this sequence and ending on the G91. The final two passes can be seen in the photograph of the completed joint in Figure 25. Figure 25 also shows a section of the liquid penetrant test, which was applied the following day, with no indications of cracking.



Figure 24. INL’s experimental weld system.

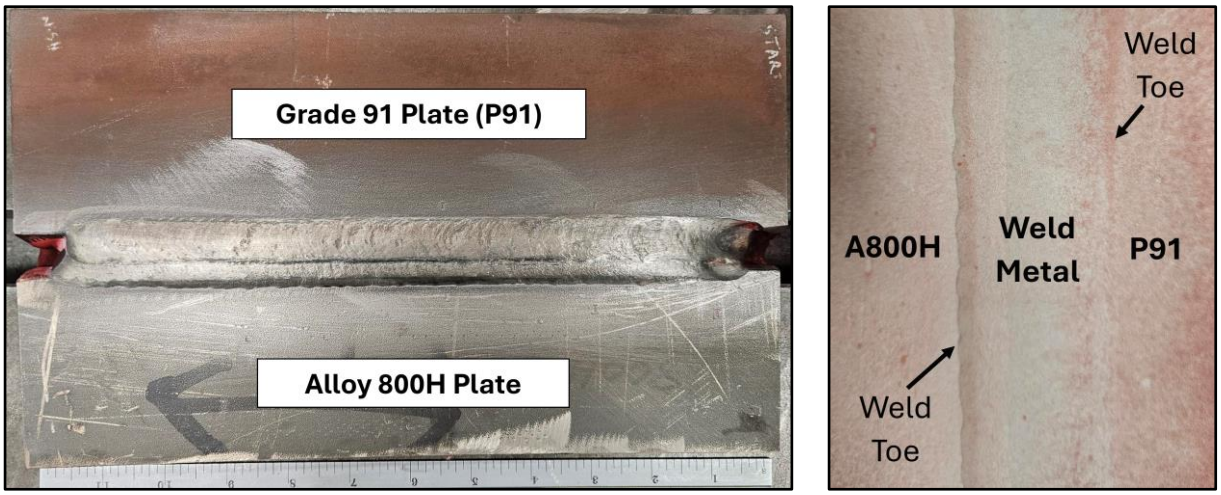


Figure 25. Completed weld coupon between Grade 91 steel and Alloy 800H (left) and photo of the developer from liquid penetrant testing performed 24 hours after welding. No indications of surface breaking cracks were apparent (right).

A metallographic cross-section of the welded joint is shown in Figure 26, and higher magnifications of the microstructures at different regions of the weld are shown in Figures 27 and 28. The varying shades of light and dark within the weld metal are caused by the amount of dilution from either Grade 91 or Alloy 800H within each weld pass and the reheating cycles from each successive weld pass.

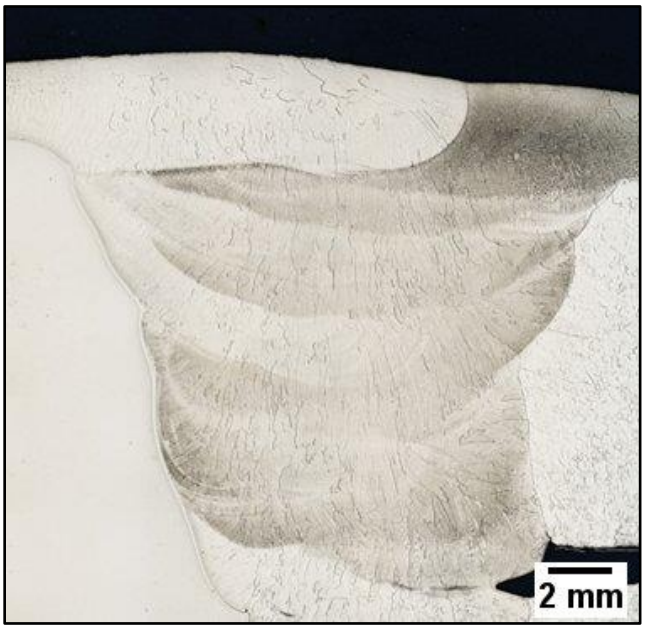


Figure 26. Cross-section macrograph of the completed weld with Grade 91 steel on the left and the Alloy 800H on the right.

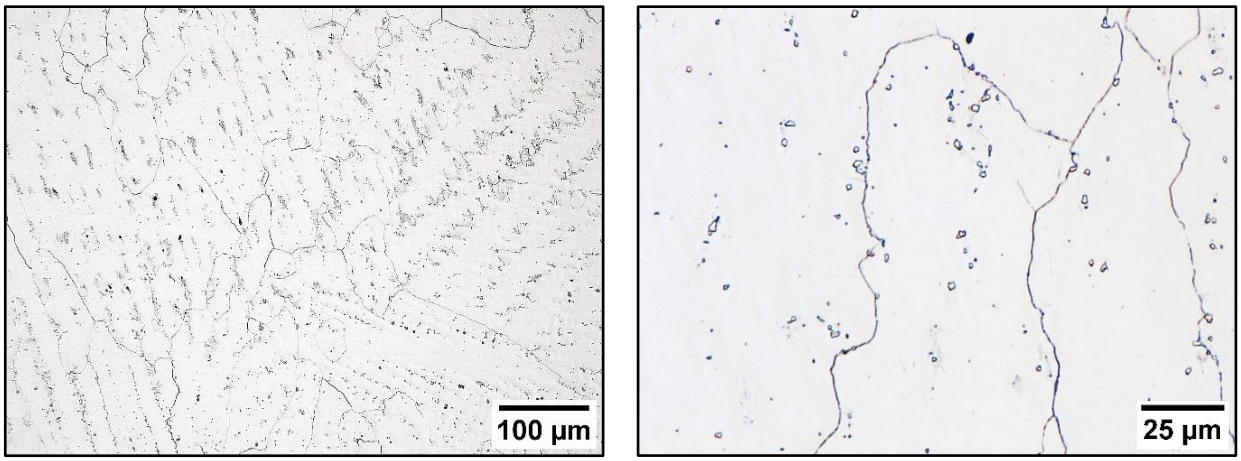


Figure 27. Micrographs of the weld fusion zone showing precipitates and solidification segregation of the FM82 filler metal.

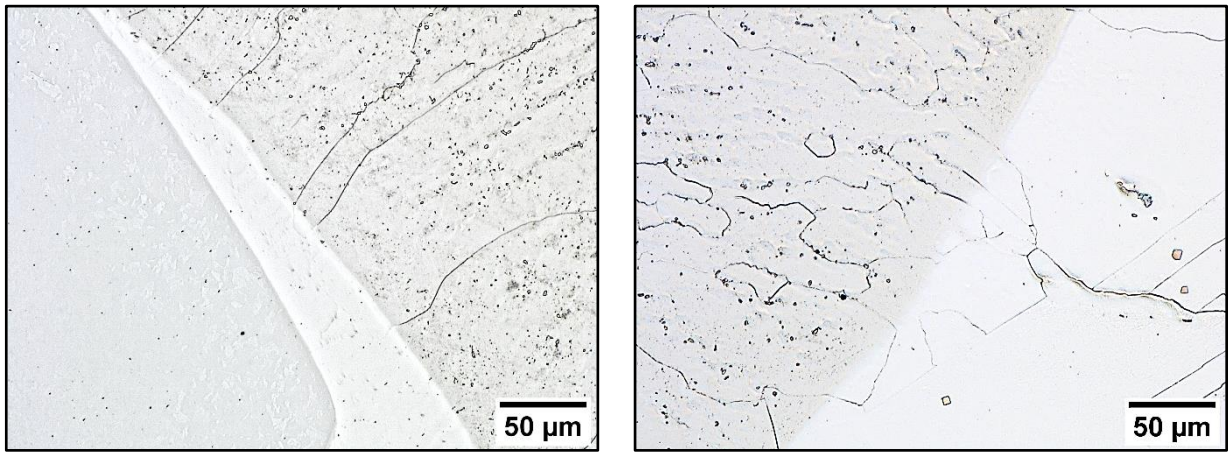


Figure 28. Micrographs captured at the fusion boundary of Grade 91 (left) and Alloy 800H (right).

In Figure 27, the weld metal microstructure showed solidification segregation via the precipitates that reflect light differently than the bulk of the material. The greatest concern for these welds is the fusion boundary and HAZ in Grade 91, as shown on the left in Figure 28. There is a distinct featureless region along the fusion zone that transitions into an entirely martensitic HAZ. Figure 29 shows the variation in hardness between the HAZ of Grade 91 and the fusion zone. The hardness ranged between 313 and 397 $HV_{0.01}$. The hardness indent with a value of 346 $HV_{0.01}$ was placed in the HAZ adjacent to the fusion boundary. Moving into the weld metal (right) approximately 50 µm resulted in a hardness drop to 171 $HV_{0.01}$ (nearly half of the HAZ hardness). The abrupt interfaces and changes in material properties are highly likely to result in reduced cross-weld structural performance in relation to either of the alloy's wrought properties. However, butter layers and heat treatment procedures can mitigate such drastic changes. The tensile testing results passed Sec. IX requirements with a tensile strength of 590 MPa, which is above the minimum requirement for the weaker of the two metals, i.e., Alloy 800H (450 MPa). Failure was entirely in the Alloy 800H base metal, and the stress-strain curves are shown in Figure 30.

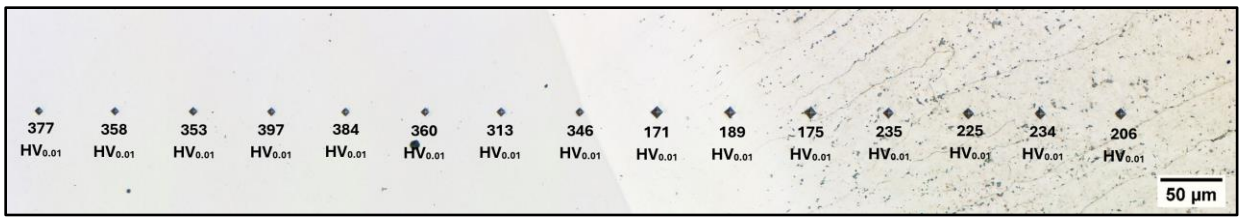
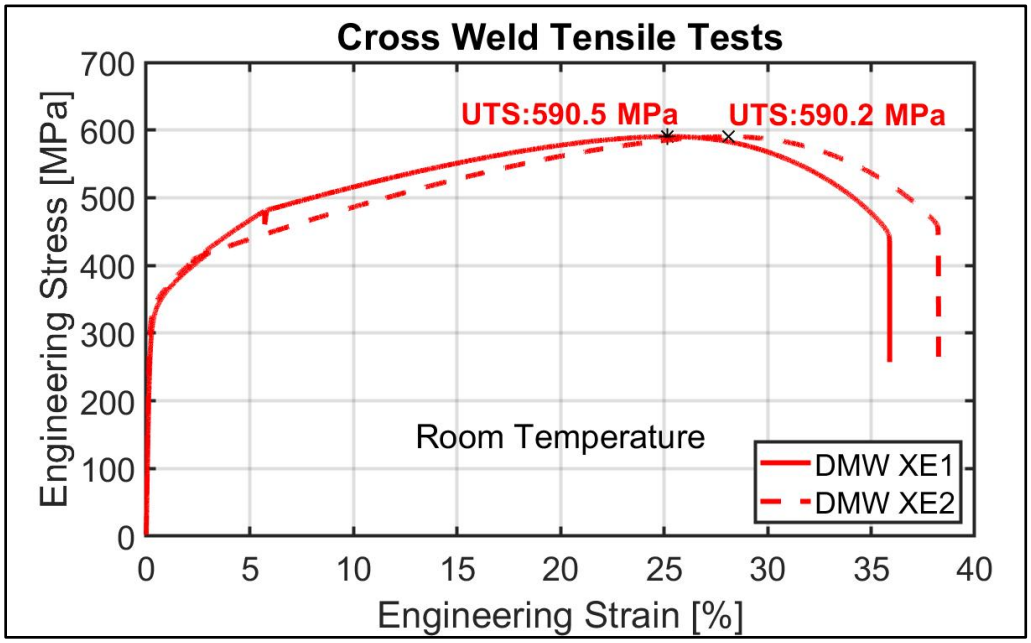


Figure 29. Micro Vickers Hardness traverse from the Grade 91 HAZ (left) into the FM82 weld metal (right) using a 10-gram load.



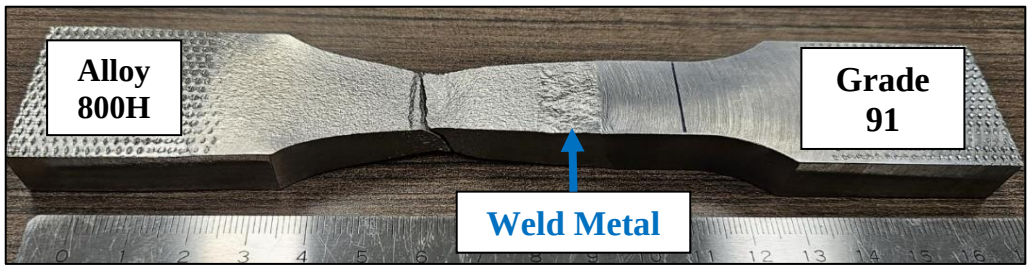


Figure 30. Cross-weld tensile test stress-strain data from the Sec. IX qualification weld coupon (top) and a fractured tensile specimen showing failure within the Alloy 800H base metal.



Figure 31. Transverse (cross-weld) side bend tests based on Sec. IX dimensions. Code rejectable defects were shown along the fusion boundary between the FM 82 and Grade 91 in two of the four bends.

8. SUMMARY AND RECOMMENDATIONS

The following list contains the main takeaways regarding dissimilar metal welding and its allowance in ASME BPVC.

- Little guidance is given on DMWs between two different alloys in the high temperature reactor design rules according to Sec. III, Div. 5 of the BPVC.

- Sec. IX defines how to qualify a welding process and material combination but is merely a means of demonstrating sound welding procedures. It does not provide an exhaustive analysis of weldment properties. These properties are determined/mandated by the ASME construction codes.

- The nonnuclear pressure vessel codes, such as Sec. I and VIII, allow for DMWs, but the requirements are vague, and caution must be used for each application of a DMW.

- Major challenges exist for welding dissimilar metals together due to mismatches in strength, CTE, corrosion properties, and microstructural transformations.

For successful DMWs, it is recommended that each joint and material combination be evaluated on a case-by-case basis. Ideally, component designs should be such that the DMW can be kept out of areas of high loads, mechanical cycling, thermal cycling, or corrosive environments unless tests have been performed to show sound behavior of the specific joint. The possibilities of dissimilar metal welds based on approved Sec. III, Div. 5 alloys are shown in Table 3 and designated with a relative weldability difficulty of low, medium, and high. Filler metal selections for any of these alloy combinations would also be on a case-by-case basis. The welding process or processes to be used will influence the available filler metal selections. For example, Alloy 82 filler metal has been shown to be susceptible to PWSCC, and precautions must be taken to avoid high pressure and high temperature steam exposure, or if the welded section is within the reactor core or in regions of high neutron flux, Alloy 617 filler metal should not be used due to cobalt activation. Grade 91 or other CSEF steels welded to austenitic alloys present a significant challenge and have resulted in premature failure in multiple service applications [53]. It is recommended to design components such that connections between CSEF steels and stainless steels or nickel alloys do not exist.

Table 3. Relative difficulty of DMW combinations for alloys allowable in ASME BPVC Sec. III, Div. 5.

	Type 304	**Type 316**	**Alloy 800H**	**Alloy 617**	**Grade 91**
Type 304					
Type 316	Low				
Alloy 800H	Medium	Medium			
Alloy 617	Medium	Medium	Medium		
Grade 91	High	High	High	High	
Grade 22	High	High	High	High	Low

For designing DMWs from a mechanical loading perspective, the following criteria should be followed:

- Only place DMWs in regions of low restraint
- Avoid thermal cycling of DMW connections
- Use shallow groove angles for greater distribution of stress across the interfaces
- Minimize weld reinforcement and/or grind the weld face and root flush with the base metal to eliminate stress concentrations along the weld toes

Another challenge with DMWs includes post weld heat treatment procedures. The construction codes, such as ASME BPVC Sec. III, Div. 1 and Div. 5 may mandate specific heat treatment procedures (times and temperatures) for each alloy. If two drastically different alloys are joined, e.g., Grade 91 and 316H stainless steel, performing a post weld heat treatment according to either alloy contradicts the mandated heat treatment for the other alloy. This challenge will either need to be overcome by foregoing a PWHT or developing a weld buttering strategy to PWHT prior to the final closure weld. For either method, it will likely require testing and generation of sufficient data showing satisfactory results and data to satisfy the Code and/or the Regulatory committees.

Initial development of welds for construction must start with the requirements listed in Sec. III, Div. 5 Clause HBB-Y-2300 “Requirements for Welded Construction” [6]. This includes identification of the joint types, welding processes, filler metals and compositions, post weld heat treatments, delta ferrite determination (if applicable), and weld qualification procedures. After successfully developing the welding parameters and adhering to the requirements imposed by Sec. IX [2], data must be produced for time-independent data and time-dependent data for cross-weld test specimens. The time-independent data must be generated according to the requirements of the wrought material as listed in HBB-Y-2100 [6].

Potential test conditions are shown in Tables 4, 5, and 6. Table 4 contains a range of elevated temperature tensile testing conditions that must be completed from room temperature to 50°C above the maximum use temperature in 50°C increments. Table 5 shows a proposed creep testing matrix, and Table 6 shows the proposed low cycle fatigue and creep-fatigue testing matrix to indicate the performance of a DMW. Note that Tables 5 and 6 are not a mandate and that no guidance is provided by Sec. III Div. 5 on how to properly evaluate the low cycle fatigue and creep-fatigue time-dependent properties of a weldment. The actual conditions used, particularly for creep testing, may vary significantly, depending on the testing temperature, creep strength of the material, and desired length of test. In general, parameters for the creep test are based on expected rupture life. Short, intermediate, and long-term creep testing, on the orders of one thousand, ten thousand, and several tens of thousands of hours respectively, are all useful when examining the properties of the DMW.

Table 4. Possible matrix of elevated temperature tensile test conditions for a DMW to determine yield strength, ultimate tensile strength, elastic modulus, elongation, and reduction of area from room temperature to 50°C above the maximum use temperature.

Test Type	Temperatures (C)
Elevated Temperature Tensile Test	20, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900 (or 50°C above max use temperature)

Table 5. Possible matrix of creep test conditions for a DMW. Temperatures and stresses should be applied only as appropriate.

Test Type	Temperatures (C)	Stress Conditions (MPa)
Creep	550, 650, 750, 850	10, 20, 30, 50

Table 6. Possible matrix of low cycle fatigue and creep-fatigue test conditions for DMW testing.

Test Type	Temperature (°C)	Total Strain (%)	Strain Rate (s^{-1})	Hold Time (min.)
Low Cycle Fatigue	550, 650, 750, 850	0.5, 1.0	0.001, 0.002	NA
Creep-fatigue	550, 650, 750, 850	0.5, 1.0	0.001, 0.002	30, 60

Note: These testing matrices are not a requirement imposed by any Standard, Code, or Committee, but contain enough data to show relative time-dependent behavior of the dissimilar metal weldment compared to data available for either of the base materials or welded metal base materials. The behavior of the joint may require less or additional testing. Ultimately, the decisions on sufficient data will fall upon the respective ASME code committee(s) and/or the Nuclear Regulatory Commission (NRC).

The goal of acquiring this time independent and time-dependent data is to generate a table or tables of appropriate weld stress rupture factors (SRFs) such as those provided in BPVC Sec. III, Div. 5 Tables HBB-I-14.10A-1 through HBB-I-14.10E-1 [6]. For proper designs to be made involving welded connections, the influence of that welded connection on the mechanical properties and structural integrity of the component must be known. Sec. III, Div. 5 evaluates the mechanical performance of materials at varying temperatures, but environmental degradation of components is not evaluated. These considerations must be made based on sound engineering judgement, and ideally, backed with experimental test data. Therefore, great care must be taken in selecting which alloys to join and the filler metals that will be used. Ultimately, these decisions must be on a case-by-case basis for mitigating potential issues and generating the best performing weldment.

Because dissimilar metal welds between two different metals are not included in the design models and tables in Sec. III, Div. 5 for elevated temperature use according to Sec. III, Div. 5 design rules, it is highly likely that their use would only be permitted by the United States Nuclear Regulatory Commission (NRC) if high temperature data was generated to show acceptable weldment properties. Data likely required by the NRC would include creep, low cycle fatigue, and creep-fatigue throughout the intended operating temperatures. Without the NRC's approval to deviate from ASME BPVC for high temperature nuclear reactors, the designs must be made such that any structural DMWs fall outside of the elevated

temperature regime. Therefore, Sec. III, Div. 5 welding requirements would allow for other alloys and construction based on Sec. III, Div. 1 design criteria. It is recommended that this lack of guidance in Sec. III, Div. 5 on dissimilar metal welding should be brought before the ASME BPVC committees, likely starting with the Allowable Stress Criteria Working Group, and a request for further guidance and recommendations to be included in the Sec. III, Div. 5 code, similar to other sections of the code. In addition to the ASME BPVC committees, it is recommended that this issue also be brought to the Department of Energy Office of Nuclear Energy Programs, namely the Advanced Reactor Technologies Program and the Advanced Manufacturing and Materials Technologies Program to request support in addressing this shortcoming in the ASME BPVC.

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