Understanding of Grade 91 DMW Failures

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Abstract

Welds between engineering alloys of differing composition and thermo-physical properties, commonly referred to as Dissimilar Metal Welds (DMWs), are an integral part of the equipment used in many advanced industrial processes, such as supercritical power plants and HRSGs. The great majority of DMWs are made to join components that operate at low or moderately elevated temperatures relative to the melting range of the alloys involved, and these welds routinely operate for long periods of time without incident. However, DMWs also are used in pressure part fabrication to join austenitic tubes or pipes to ferritic tubes or pipes or to join austenitic non-pressure part attachments to a ferritic tube or pipe. In these cases, the components of which the DMW is a part typically operate under conditions where creep damage coupled to the effects of frequent cycling is expected to influence the service life of the weld. Under these conditions, the performance of DMWs has been far less predictable. For example, the service history of DMWs made between low alloy ferritic tubing (e.g., Grade 22) and tubing fabricated from one of the 300-series austenitic steels (e.g., TP304H) and installed in superheaters (SH) or reheaters (RH) of large power boilers has been highly variable, depending critically on the choice of filler metal and, in certain cases, on the operating profile of the boiler. The reasons for the variability in performance now are understood to involve differences in the thermo-physical properties of the materials being joined as well as differences in local mechanical properties as these are altered by diffusion-driven compositional changes along the dissimilar metal interface. For the SH and RH DMWs, the response to the spate of early weld failures, where the weld was made using an austenitic stainless filler metal, was to switch to a nickel-base filler metal that minimized the incompatibility in the thermo-physical properties and reduced the local mismatch in mechanical properties by limiting the amount of carbon diffusion from the low alloy tubing into the more highly alloyed filler metal. The resulting two-to-threefold increase in the average service life of the DMWs underscored the basic soundness of the approach.

With this history in mind, when need arose to develop procedures for welding the creep strength enhanced steel Grade 91 to other alloys, and particularly to one of the austenitic stainless steels, the default choice of filler metal was, again, a nickel-base alloy. Since that decision was made, the frequency with which DMWs involving Grade 91 have failed after only relatively short periods of operation has drawn attention to the fact that the relative level of incompatibility between Grade 91 and other alloys clearly is even greater than was the case when low alloys such as Grade 22 constituted the ferritic component of the joint. Recent studies of failed DMW joints involving Grade 91 have confirmed that the failures are related not only to the fundamental welding metallurgy, but also to component manufacture, unit design, and the nature of the service. This paper reviews and summarizes what can be considered typical macroscopic and microscopic characteristics of the failures, including metallographic and fractographic features and compositional features, of the Grade 91 DMW failures and provides a hypothesis of the damage mechanism.

1. Introduction

Since 2008, numbers of Grade 91 DMW joints have failed prematurely in service, with service lives less than 16,000 hours being reported in some cases [1-7]. The failures have included Grade 91 DMW joints in main-steam piping, superheat outlet header leads, steam outlet piping, steamline flowmeters, superheat header lugs and superheat tube attachments. Figure 1 shows an example of a Grade 91 DMW failure in main steam piping.

Figure 1. Shown is a failed Grade 91-TP321H DMW in a section of main-steam piping, with water leaking from a through-wall crack at the dissimilar metal interface [1].

Although the metallurgical characteristics of many of the various failures have appeared to be similar based on the information that has been made available publicly, the failures have been attributed to different factors: stress concentrations and creep-fatigue [3], residual stresses [3], high system loads [5], insufficient weld buttering [2], and a creep-weak zone present in the Grade 91 DMW joints [1]. However, the

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manner in which the damage has developed and, consequently, the root cause of these failures remains poorly understood. This paper endeavors to summarize key characteristics of some of the failures as these have been established through optical metallography, SEM fractography and ESD compositional analysis of several Grade 91 DMW failures. It is hoped that in this way a better understanding of why these joints fail can be achieved and that the relative importance of the various influence factors can be assessed from the standpoint of fundamental welding metallurgy and the unique local creep behavior along the Grade 91 interface of the DMW joints.

Figure 2. Shown is a steam flowmeter that failed at a Grade 91-TP316H DMW [2].

It should be noted that the failed Grade 91 DMW joints represent joints that were designed and manufactured by different OEMS and operated under widely varying conditions. Relevant background information for the Grade 91 DMW joints reviewed here is as follows:

- SH Outlet Lead: Supercritical Boiler, 348 mm OD x 60 mm wall, P91-to-TP321H joint made with Inco A filler metal, 540°C, 40,000 hours of operation
- Main Steam Lead: HRSG, 356 mm OD x 32 mm wall, P91-to-TP304H joint made with Inconel filler metal, 566°C, 125,000 hours of operation
- Steam outlet pipe A: OTC, 115 mm OD x 14 mm wall, P91-to-TP316H joint made with Inconel filler metal, 545°C, 70,000 hours of operation
- Steam outlet pipe B: OTC, 115 mm OD x 14 mm wall, P91-to-TP321H joint made with UTP 068 HH filler metal, 530°C, ~ 15,000 hours of operation
- Steam outlet pipe C: OTC, 115 mm OD x 14 mm wall, P91-to-TP321H joint made with UTP 068 HH filler metal, 545°C, ~ 15,000 hours of operation
- Steam outlet pipe D: OTC, 115 mm OD x 14 mm wall, P91-to-TP321H joint made with UTP 068 HH filler metal, 530°C, ~ 15,000 hours of operation
- Steam outlet pipe E: CT intercooler, 114 mm OD x 17 mm wall, P91-to-TP316H joint made with Alloy 625 filler metal, 538°C, 16,550 hours of operation
- Steam outlet pipe F: CT intercooler, 114 mm OD x 17 mm wall, P91-to-TP321H joint made with Alloy 625 filler metal, 538°C, ~ 75,000 hours of operation
- Flow Elements A: Petrochemical Plant, 406 mm OD x 27 mm wall, P91-to-TP316H joint made with Inco 182 filler metal, 507°C, ~ 60,000 hours of operation
- Flow Elements B: Petrochemical Plant, 327 mm OD x 27 mm wall, P91-to-F304 joint made with ENiCrFe-3, 514°C, ~ 14 years of operation
- SH Tube Attachment A: Subcritical boiler, 57 mm OD x 6 mm wall, Grade HH lugs welded to Grade 91 tubing using Inco A filler metal, 538°C; after 23,000 hours of operation more than 800 lugs had cracked or failed completely
- SH Tube Attachment B: Subcritical boiler, 57 mm OD x 6.6 mm wall, 321H lugs welded to Grade 91 tubing using Ni-base filler metal, 540°C; after 72,000 hours of operation over 1,000 lugs had cracked or failed completely

As indicated in Figure 2, the failure of Grade 91 DMW joints, especially the DMWs in thick-walled components, can cause significant damage to the power plant and, more importantly, can jeopardize the welfare of plant workers. It is for this reason that efforts to understand the damage mechanism or mechanisms involved and to identify the principal factors that reduce the lives of these joints are important in serving as the basis for improvements in the design, manufacture, maintenance and operation of these joints.

2. Examination Methodology and Characteristics of Grade 91 DMW Failures

An effective methodology for evaluating the condition of failed and damaged DMWs in which Grade 91 is one of the materials welded typically involves four key steps: 1) visual inspection with a low-power stereoscope, 2) microstructural examination by optical metallography, 3) examination by Scanning Electron Microscopy (SEM),

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including both fractography and high magnification examination of the intact portion of the interface, and 4) examination by Energy Dispersive Spectrometry (EDS) to assist in characterizing local compositional variations created during the welding and heat treatment processes.

2.1 Macroscopic Features of Grade 91 DMW Failures

The typical macrostructural features of a Grade 91 DMW failure involved a non-ductile cracking on Grade 91 side of the joint with no obvious branching, and the crack can be seen to closely follow the contour of the weld bead pattern as shown (Figure 1). In cases where the weld has not completely separated, the cracking typically is dominant on one side of the joint, with the damage concentrated within an arc of approximately 180°.

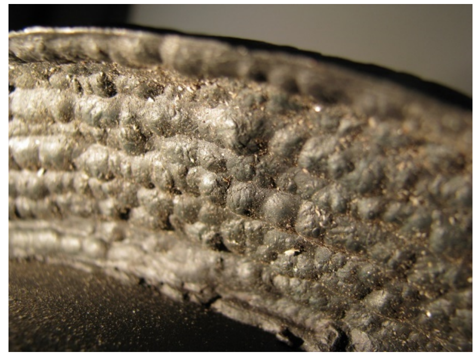

Figure 3. Shown is the typical appearance of the fracture surface on a failed DMWs in which the profile of the individual weld beads is evident [2].

In cases where the cracking is completely through-wall, the fracture surfaces frequently exhibit the characteristic "bead profile" appearance documented in Figure 3, which is a feature that was commonly observed in the failed SH/RH tubing DMW joints that occurred in such large numbers beginning in the late 1960s. This unique fracture appearance is characteristic of damage that occurs when cracking propagates preferentially through a relatively narrow zone of material that closely follows the dissimilar metal weld interface on the ferritic side of the joint.

2.2 Microscopic Metallographic Features of Grade 91 DMW Failures

In general, the damage in Grade 91 DMW joints initiates at or near the OD surface and progresses toward the ID surface of the joint. However, in some failures it has been found that the damage has initiated at or near the ID surface, at or near mid-wall of the joint, as documented in Figures 4, 5 and 6, or simultaneously at several locations through the thickness of the joint. In the majority of cases, creep cavities have been detected immediately ahead of the crack tip along Grade 91 interface.

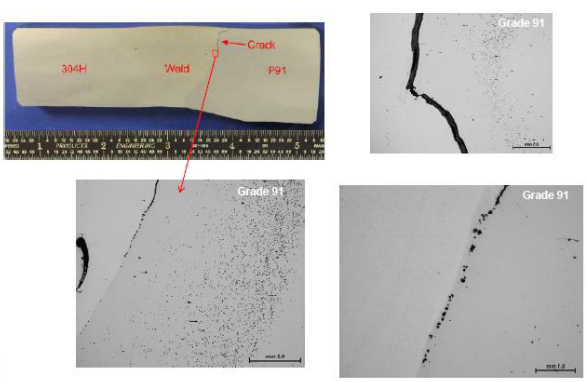

Figure 4. Shown are typical microstructural features of OD-initiated damage in a Grade 91 DMW, unetched [9].

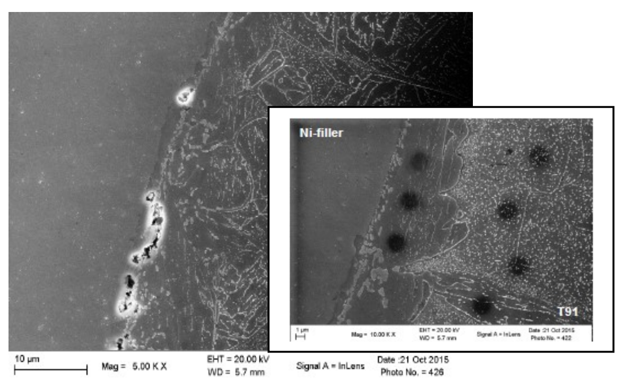

Figure 5. Shown is a typical view of the interface of a Grade 91 DMW as observed in the SEM, Vilellas [9].

In addition, in the majority of cases the damage is concentrated on one side of the joint. Often, on the side of the joint opposite the visible crack, no damage is found at all, as shown in Figure 7. This suggests that in many of these failures the influence of a bending moment is a significant factor in the damage process, with the bending moment occurring either due to thermal or mechanical effects that in many cases are related to the system design and the joint location.

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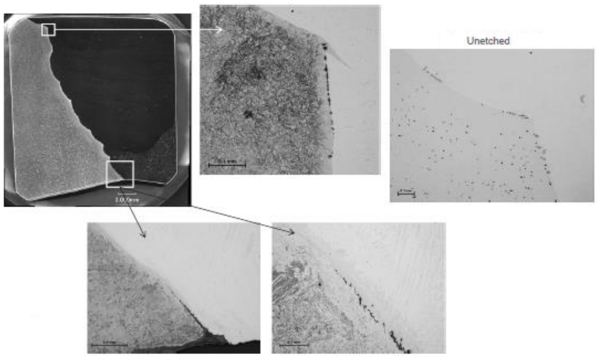

Figure 6. Shown are typical microstructural features of damage at the mid-wall and ID locations in a Grade 91 DMW, Vilellas [9].

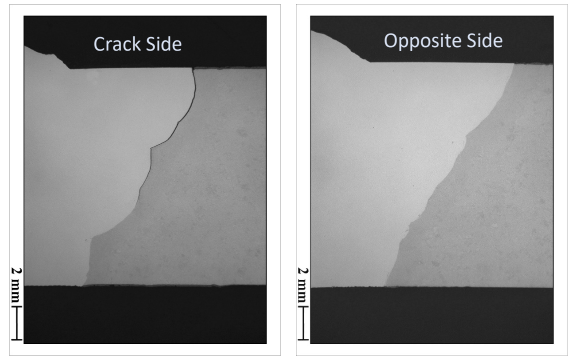

Figure 7. Shown is the typical damage distribution around Grade 91 DMW joint, Velillas [8].

2.3 Fractographic Features of Grade 91 DMW Failures

For fractographic examination of Grade 91 DMW using scanning electron microscope (SEM), specimens can be removed from a partial through-wall crack by opening the crack along the Grade 91 interface through the crack tip. The un-cracked portion of the specimens is notched using a jeweler's saw along the Grade 91 interface. Then, the specimen is fractured along the notch after cooling in liquid nitrogen. The method is known as "cryo-cracking" and is commonly used as part of a fractographic examination in cases where a fractured component has not completely separated. For the Grade 91 DMWs, use of this technique facilitates examination of damage zone ahead of the main fracture where the early-stages of creep cavitation often can be observed. Since most of the crack surface typically is linked to the weld surface and covered by a layer of high-temperature oxide, the examination focuses on the crack tip region.

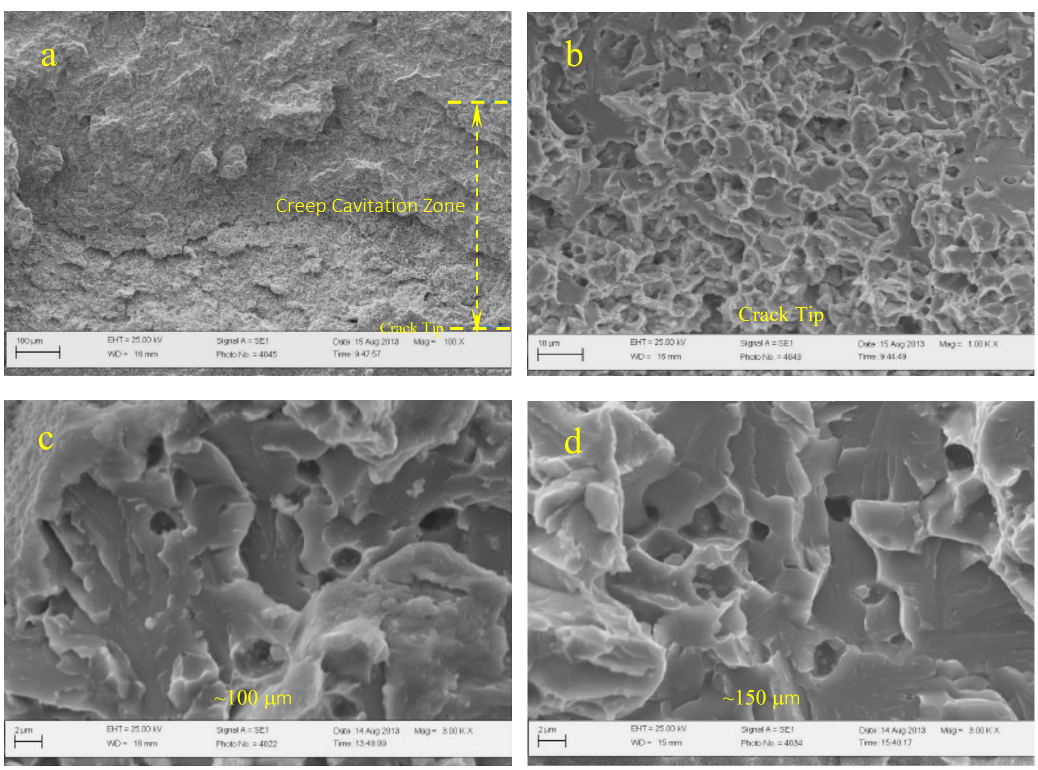

Figure 8. Shown are typical SEM fractographic features of creep cavity distribution ahead of crack tips in Grade 91 DMW joints; a) overall view of examined area, b) creep cavities at crack tip, c) creep cavities at ~100 μm ahead of crack tip and d) creep cavities at ~150 μm ahead of crack tip (6).

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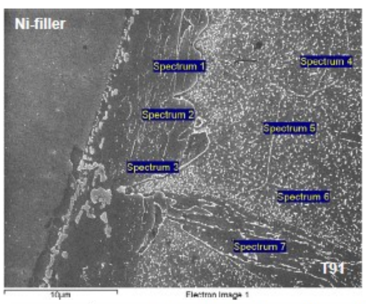
Figure 8 shows a typical example of creep cavitation in the damage zone ahead of a crack tip. Based on the current available data, the creep cavitation zone in front of the crack tip ranges in extent from approximately 20 – 100 μm for P91 butt weld-type DMWs and up to ~400 μm in T91 attachment DMWs. The creep damage in front of the crack tip governs subsequent crack propagation behavior. The size of the cavitation zone depends on the nature of the loading (axial tension, bending, tensile hold period, cyclic frequency and so on), which is significantly affected by the system design and unit operation. This is why the cavitation zone is often more extensive in the T91 attachments since a severe bending load can develop with a stress concentration through the root of the fillet DMW joints when the attachment couples are jammed or bound.

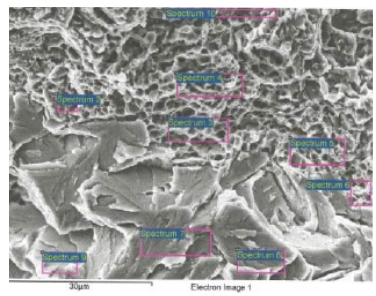
2.4 Chemical Characteristics of Grade 91 Failures

The chemical characteristics of Grade 91 failures can be examined using energy dispersive spectrometer (EDS) analysis on both metallographic and fractographic specimens with spot and line-scan modes. Figure 9 reveals an example of EDS analysis results obtained from a metallographic specimen and Figure 10 shows an example of EDS analysis results obtained from a fractographic specimen. As shown, the chemical features of the damage zone along Grade 91 interface consists of Grade 91 base metal with a "small" amount of nickel. In addition, an EDS line-scan across the Grade 91 interface is also presented in Figure 11, which reveals an identical pattern of Ni distribution. This suggests that the damage occurs in the unmixed zone (UNZ) of the DMW joint.



		Si	Cr	Fe	Ni	Mo
Spectrum 1	Yes		8.05	90.59	1.37	
Spectrum 2	Yes		8.72	90.05	1.23	
Spectrum 3	Yes	0.51	8.04	89.82	1.63	
Spectrum 4	Yes	0.62	8.12	90.06		1.19
Spectrum 5	Yes	0.43	8.57	91.01		
Spectrum 6	Yes		8.78	91.22		
Spectrum 7	Yes	0.71	8.41	90.88		

Figure 9. Shown is the EDS results on a metallographic specimen [9].



Spectrum	O	Cr	Fe	Ni
Spectrum 2		9.30	89.49	1.21
Spectrum 3		8.95	88.75	2.30
Spectrum 4	2.78	9.34	85.32	2.56
Spectrum 5		10.16	86.85	2.99
Spectrum 6		10.49	86.18	3.33
Spectrum 7		8.63	89.69	0.84
Spectrum 8		9.27	90.72	0.01
Spectrum 9		9.44	90.17	0.39
Spectrum 10	0.85	9.10	90.05	

Figure 10. Shown is the EDS results on a fractographic specimen [8].

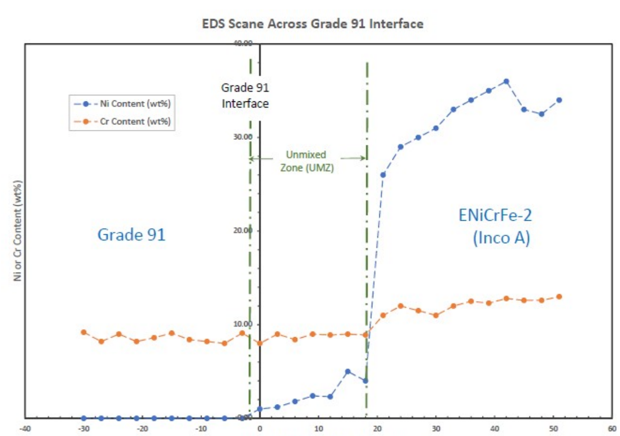


Figure 11. Shown is an EDS line scan across a Grade 91 DMW interface (6)

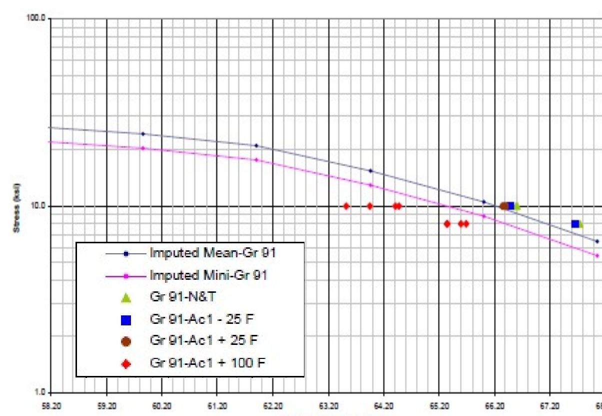


Figure 12. Shown are the effects of intercritical heating on the creep properties of Grade 91 (10)

The EDS results demonstrate that Ni content in the UMZ can be as high as 4 wt% and that the UMZ can be up to 20 μm in width. The significance of these compositional changes along the Grade 91 interface relative to the performance of the DMW is twofold: first, with increasing Ni content, the lower critical transformation temperature (A_{c1}) of the UMZ is significantly reduced and probably to levels below the PWHT temperature – i.e., 730 - 775°C (1350 - 1425°F). This means that the UMZ will undergo a partial phase transformation during PWHT, which will result in the creation of a severely “creep-weakened” zone of material along Grade 91 interface. This, in turn, will result in the development of a significant creep strength mismatch along the Grade 91 interface. Previous research (10) has demonstrated that intercritical overheating during PWHT of any Grade 91 material will significantly degrade the creep properties of Grade 91, as shown in Figure 12.

Second, due to dilution effects the thermal-physical properties of the material adjacent to the UMZ may be more akin to those of an Incoloy grade or a 300-series stainless grade than to an “undiluted” Inconel grade. Regarding the coefficient of thermal expansion, a significant thermal-mechanical mismatch between the Grade 91 interface and the surrounding material renders the Grade 91 DMW joints more vulnerable to interfacial damage during changes in operating temperature due to the inevitably large thermal-mechanical mismatch.

3. Summary of Characteristics of Grade 91 Failures

Based on the information reviewed above, the general patterns and characteristics of those Grade 91 DMW failures that occur where creep is a major influence on the damage process can be summarized as following:

- Failure occurs in a non-ductile manner with cracking developing at the dissimilar metal interface on the Grade 91 side of the DMW. Typically, the damage is concentrated on one side of the joint with the level of damage on the opposite side significantly lower or non-existent
- The damage at the weld interface concentrates in the unmixed zone (UMZ), where diffusion and solidification effects result in a highly-localized modification of the base metal composition
- Damage can initiate at the OD surface, at the ID surface or sub-surface depending on stress state; however, in the majority of the recorded failures cracking has initiated at or very near the OD surface
- Creep cavities initiate in the zone in front of the crack tip, driven by stress concentration effects, or they form in the areas where the metallurgical conditions (microstructure, temperature and stress) are suitable.
- The creep cavitation zone in the front of the crack tip is approximately 20 – 100 μm deep for P91 DMW joints and up to 400 μm deep for T91 attachments. The creep damage in front of the crack tip influences subsequent crack propagation behavior.
- The damage mode is consistent with a creep-dominated mechanism; the extent to which fatigue plays a role in the damage process, if at all, cannot be determined from the microstructural features of the damage
- In the areas where creep cavities are present, 1–4% Ni is detected in all cases. The Ni distribution across the UMZ is not uniform and increases toward the solidification terminals of the UMZ. The A_{c1} temperature of the UMZ may be lower than the specified PWHT temperature for Grade 91 welds. The area adjacent to the UMZ in the weld deposit (transition zone) may have a composition closer to an Incoloy grade or a 300-series stainless grade in which case the mismatch in thermo-mechanical properties between the weld and the Grade 91 base metal is exacerbated.

4. Hypothesis of Damage Mechanism for Grade 91 DMW Failures

A proposed mechanism for the development of creep-dominated damage in Grade 91 DMW joints involves three parts:

4.1 Formation of a creep-weak zone in the UMZ along the Grade 91 interface

As proposed by Savage et al (11), the fusion zone in a weld consists of two distinct regions, as indicated in Figure 13. The composite region represents the portion of the weld where base

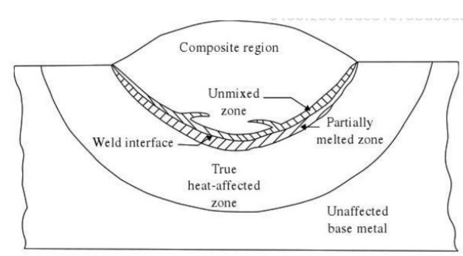


Figure 13. Regions of a fusion weld (11)

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metal and filler metal are thoroughly mixed to create a new and "composite" structure. Surrounding this region along the fusion boundary, there is a narrow region called the unmixed zone (UMZ). The UMZ consists of base metal that has melted and then re-solidified, but in which there has been no inter-mixing with the molten filler metal; as a result, any change in composition can only occur by liquid-phase diffusion.

For the reasons discussed above, common industrial practice is to fabricate Grade 91 DMWs using Ni-based filler materials, such as Inco A, Inconel 625 or Alloy 182. With this combination, the liquid UMZ of a Grade 91 DMW will tend to consist of melted Grade 91 with a small amount of Ni that has entered by liquid-phase diffusion. It is estimated that the Ni content in the liquid UMZ is approximately 1 wt% prior to solidification. During solidification of the weld pool, the Ni content increases across the UMZ due to partitioning effects associated with planar growth and reaches its maximum level (~4 wt%) at the planar terminals. Since the partitioning coefficient (k) of Ni in Fe is less than 1 (k<1) with a relatively shallow liquidus and solidus slope and an extremely narrow solidification gap, the enrichment of Ni across the UMZ is moderate, as illustrated in Figure 14.

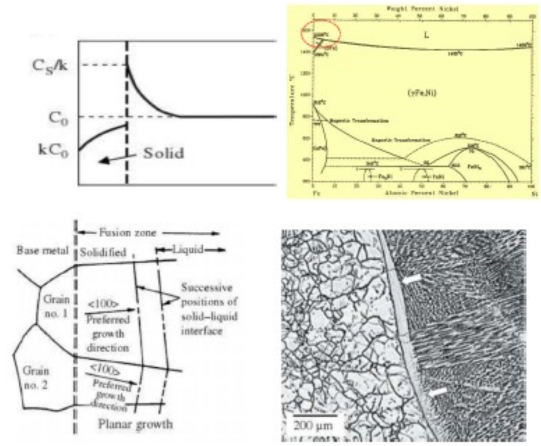

Figure 14. Solute redistribution during a planar growth (11)

Due to the increase in Ni content, the A_{c1} of the UMZ decreases substantially, in some cases to levels significantly lower than the minimum temperature of the specified PWHT temperature range. As such, partial phase transformation may occur in the UMZ during PWHT, which results in a significant reduction in the creep strength of the material within the UMZ (a creep weak zone).

4.2 Unique mismatch behavior along Grade 91 interface

Along the Grade 91 interface, there are two distinct zones of material that have an important influence on joint behavior: 1) the UMZ and 2) the transition zone adjacent to the UMZ on the weld side of the joint, where due to dilution effect the original Inconel-type composition may be more similar to that of Incoloy grade or an austenitic stainless steel grade. The presence of these two zones leads to two types of mismatch along the Grade 91 interface. The first is a mismatch in creep strength between the UMZ and the adjoining regions due to the reduction in creep strength of the UMZ. The influence of a mismatch in creep strength on the performance of welds has been a topic of discussion since the mid-1980s when failures in longitudinal seam welds in high energy piping led to extensive research into the effects of localized differences in mechanical properties on the creep behavior of composite structures. Wells' (12) study showed that the stress state in the cusp region of a double-Vee type longitudinal seam weld would become increasingly triaxial (constrained) as the mismatch in the creep rates between the base and weld metals increased. Similarly, a stress concentration effect with some degrees of triaxiality could be induced along a dissimilar metal interface at changes in direction (see Figures 6 and 7) due to a creep strength mismatch.

The second type of mismatch is a mismatch in the thermal-mechanical behavior between the transition zone and the adjoining regions due to a differential in the thermal expansion coefficient. The influence of thermal-mechanical mismatch is particularly pernicious during cyclic operations. The significance of a mismatch in thermo-physical properties on the behavior of DMWs was recognized as early as the 1950s when the initial failures in SH and RH DMWs made with austenitic stainless steel filler metals began to occur. Because of the disruptive effects of the SH and RH DMW failures in the Power industry, there were numerous investigations into the cause of DMW failures by such organizations as ASME, ASTM, EPRI, MPC and others in the 1970s and 1980s [13-24]. As the result of the research, the industry began to specify nickel-based welding filler metals largely because of their improved compatibility in the coefficient of thermal expansion (~4%) with the low alloy ferritic steels relative to austenitic stainless steel fillers (~17%). Subsequent experience demonstrated that the service life of DMW joints made with nickel-based filler metals was approximately 3-5 times longer than for those made with austenitic stainless steel fillers [19]. Unfortunately, in Grade 91 DMWs, because of the greater thermal conductivity of Grade 91 relative to Grade 22 and due to the potential presence of a transition zone with a composition more closely resembling an Incoloy or austenitic grade than a purely nickel-based grade, the influence of a mismatch in coefficient of thermal expansion may be worse than that which existed in the original low alloy DMWs made with austenitic filler metals.

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These two mismatches can result in the creation of a substantial shear stress along the Grade 91 interface during unit operation, especially when units are operated in a cyclic mode, which today is the common mode of operation for a large number of fossil and combined-cycle power plants.

4.3 Necessary stress state

As reviewed above, the damage in Grade 91 DMWs is normally concentrated on one side of the joint, with the damage level on the opposite side typically being significantly lower. Identical damage patterns were observed in the T22/T11 SH and RH DMW joints made with nickel-based filler metals. The laboratory simulation tests by Combustion Engineering (CE) and EPRI (16-18, 25) showed that the service-type failure mode could not be duplicated when only a uniaxial load was applied and that the application of a bending load was necessary to accurately duplicate the failures in the field.

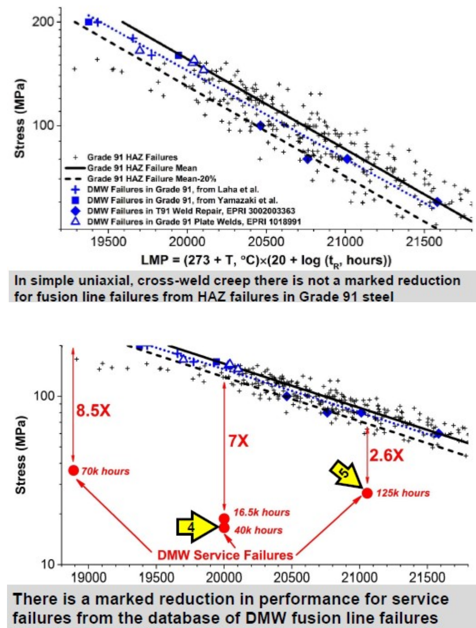

Figure 15. Uniaxial creep testing of Grade 91 DMW in comparison with actual service failure (25)

Figure 15 shows a review of uniaxial creep test results for Grade 91 DMWs carried out by EPRI (25). As can be seen, damage and failures have occurred only in the Type IV region of the joint, which does not mirror the interface damage observed in the in-service failures. The service failures that have occurred so far suggest that a stress level 2.6 to 8X higher than the calculated axial stress from steam pressure alone is necessary for creep-dominated interfacial damage to occur. There is sufficient evidence suggesting that bending load in a cyclic mode is a necessary stress condition for development of Grade 91 DMW interface damage mode.

5. Remarks

Many of the Grade 91 DMW failures have been the direct result of creep-dominated damage that has initiated in and propagated through the unmixed zone along the Grade 91 interface. During the manufacture of a Grade 91 DMW, the interfacial region along the Grade 91 side of the joint may develop in a way that promotes the formation of a severely creep-weakened zone that exhibits a mismatch in both creep strength and thermal expansion behavior. Because this vulnerable interface is so narrow in extent (<100 μm) when it is loaded in a direction normal to the plane of the interface, the stronger material on either side of the interface minimizes the amount of strain that can accumulate. It is likely that this is the reason that some type of applied bending is required for the development of premature damage along the Grade 91 interface (i.e., the so-called "peel" effect). In addition, there is no clear evidence whether decarburization occurs in the UMZ. However, if it does occur, the creep-weak zone due to partial phase transformation in the UMZ still dominate the damage behavior along the Grade 91 interface.

In the US, a significant effort has been made by OEMs, metallurgical research labs and universities to understand and improve the condition of the interface region in Grade 91 DMW joints. Initiatives are under the way between ATC-combustion Engineering Solutions (ATC-CES) and Chinses Special Equipment Inspection and Research Institute (CSEI) to: 1) improve the understanding of the strain behavior along the Grade 91 interface under various loading conditions; 2) comparatively evaluate the creep behavior of the UMZ and Type IV zone relative to "normal" Grade 91 base metal; 3) investigate modifications in the weld geometry that would "shield" the dissimilar metal interface from the effects of bending loads during operation; 4) explore the feasibility of alternating weld deposit compositions in order to improve the metallurgical condition of the Grade 91 interface; and 5) conduct long-term creep testing to validate possible improvements in DMW design.

Also, a substantial work has been done in comprehending and modeling the stress state responsible for Grade 91 DMW failures. From the design standpoint, considerable amount of work has been made to locate Grade 91 DMW joints in a low stress and no bending condition where Grade 91 DMW joints can be easily inspected and replaced.

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