Advances in Materials Technology for Fossil Power Plants
Proceedings from the Seventh International Conference
October 22–25, 2013, Waikoloa, Hawaii, USA
https://doi.org/10.31399/asm.cp.am-epri-2013p0513

D. Gandy, J. Shingledecker, editors

MATERIAL BEHAVIOR OF T23 AND T24

John A. Siefert, Electric Power Research Institute
1300 West W. T. Harris Blvd., Charlotte, NC, 28262

John N. DuPont, Ph.D., Department of Materials Science, Lehigh University
5 East Packer Ave., Bethlehem, PA, 18015

ABSTRACT

The use of the bainitic class of creep strength enhanced ferritic steels T/P23 and T24 has increased over the last decade in a wide range of applications including replacement headers, superheater and reheater tubing and in waterwall tubing. Many issues have been reported in one or both of these materials including hydrogen induced cracking, reheat cracking and stress corrosion cracking. To appropriately address these issues, work has been initiated that includes a literature review, development of a database of phase transformation temperatures, investigation of tempering behavior, and an analysis of the effect of phase transformation on residual stresses. Such information will be provided in the context of understanding why these two materials appear highly susceptible to these cracking mechanisms.

INTRODUCTION

The progression of alloy development for higher strength materials including a new generation of high strength bainitic and martensitic materials, termed creep strength enhanced ferritic (CSEF) steels, has occurred in recent years to improve the efficiency and economy of fossil fuel generation. Fundamentally, these materials are divided into martensitic grades (such as Grades 91, 92, 911 and VM12-SHC) and bainitic grades (such as Grades 23 and 24). The composition ranges for the two advanced bainitic materials of interest in this paper, T23, P23, T24 and P24, (generally referred to collectively here as Grades 23 and 24), are given in Table 1. Although it is convention to compare Grades 23 and 24 to mainstay CrMo alloys like Grades 11, 12 or 22, it should be mentioned that these two bainitic CSEF steels share more in common with respect to chemical composition, weldability and mechanical behavior with CrMoV materials. It appears this fact was not recognized or at least acknowledged earlier in the development of Grades 23 and 24. Thus, the CrMoV legacy would have enlightened industry on the fact that these materials share similar issues that are now facing industry in specific applications of Grades 23 and 24.

These new bainitic CSEF steels, possessing relatively large increases in strength, have been widely utilized in recent years to reduce section thicknesses in boiler and HRSG headers, tubing, waterwall panels and other components. This increase is shown as a function of allowable stress for CSEF steels T23, T24 and T91, as compared to T22 in Figure 1. A reduced section thickness for a given component provides an advantage in thermal fatigue behavior, reduced complexity during erection and field installation in the form of lower lifting capacities, structural steel requirements and welding considerations, and decreased inspection time. Unfortunately, this perceived reduction in complexity has not fully come to fruition in many cases as issues have been identified and will be detailed in this paper.

Table 1: Chemical Composition of Bainitic Materials T/P22, T/P23 and T/P24 [1,2]

Element	**T/P22**	**T/P23**	**T/P24**
Carbon, C	0.15	0.04-0.10	0.05-0.10
Manganese, Mn	0.30-0.60	0.10-0.60	0.30-0.70
Silicon, Si	0.25-1.00	0.50	0.15-0.45
Sulfur, S		0.010	0.010
Phosphorous, P		0.030	0.020
Chromium, Cr	1.9-2.6	1.9-2.6	2.2-2.6
Nickel, Ni		0.40	
Molybdenum, Mo	0.87-1.13	0.05-0.30	0.90-1.10
Tungsten, W		1.45-1.75	
Vanadium, V		0.20-0.30	0.20-0.30
Niobium, Nb		0.02-0.08	
Nitrogen, N		0.015	0.012
Boron, B		0.0010-0.0060	0.0015-0.0070
Aluminum, Al		0.030	0.020
Titanium, Ti		0.005-0.060	0.06-0.10
Ti/N		≥3.5[1]	

[1] Alternatively, in lieu of this ratio minimum, the material shall have a minimum hardness of 275HV in the hardened condition, defined as after austenitizing and cooling to room temperature but prior to tempering.

Despite the expected base material behavior, welding these materials in both fabrication and field environments has posed issues with respect to several unique cracking mechanisms. Service experience as well as research and development continue to demonstrate the need to treat all CSEF steels individually as each steel grade lumped into this material class exhibits its own unique set of challenges and behavior. For example, since its introduction to the ASME Code in 1995 Grade 23 has seen six code revisions [1]. In addition to this, there are at least four US patents, which contain various amounts of information pertinent to the development of Grade 23 [4-7]. Multiple code revisions and patents underline the crucial observation that the new class of bainitic materials require more closely controlled chemistry and fabrication requirements to ensure successful implementation.

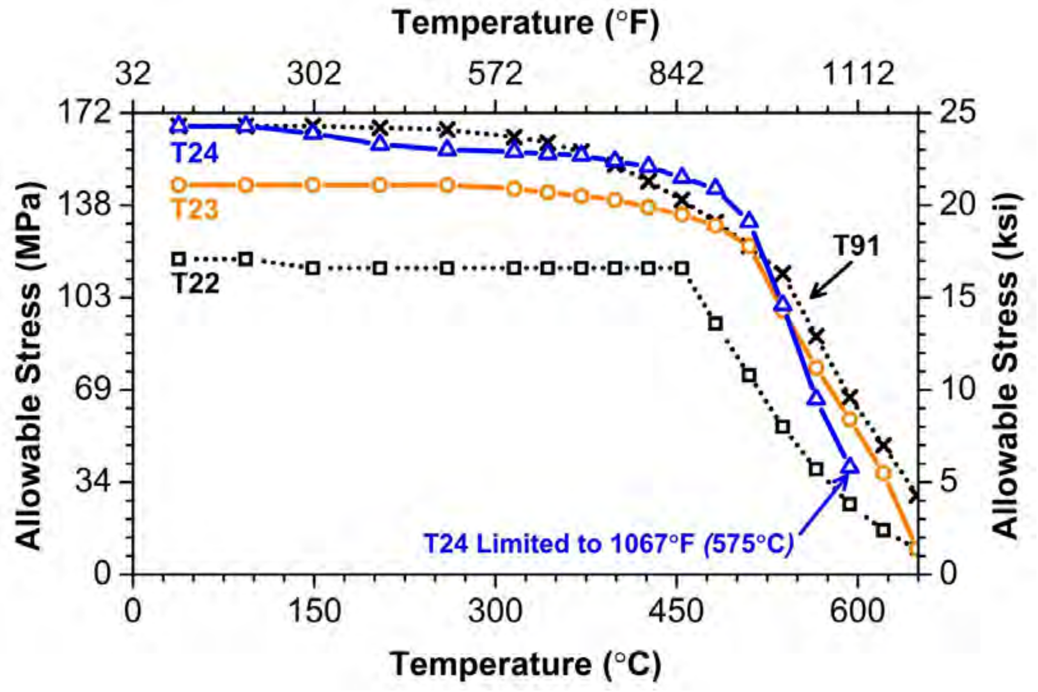

Figure 1: Allowable Stress Values for T23 and T24, as compared to T22 and T91 [1-3]

The increased susceptibility to cracking for the bainitic class of CSEF steels may arise, at least in part, from the fact that these materials accumulate higher levels of residual stress on-cooling from welding thermal cycles than their martensitic counterparts. Figure 2 shows a comparison of stress accumulation for representative bainitic (T22), martensitic (T9) and austenitic (316) materials, as determined using the Satoh Test [8]. Grades 23 and 24, like 2.25Cr-1Mo, predominately consist of bainite. The reported transformation temperatures for Grades 23 and 24 are shown in Table 2 [9, 10]. The transformation to martensite or bainite compensates for the thermal contraction strains that accumulate on-cooling and the observed re-accumulation of stress occurs following the completion of the transformation [8]. Similar shear components (0.22 for bainite and 0.24 for martensite) suggest that the magnitude of the transformation plasticity on-cooling should be nearly identical for both phase transformations. Because of this, the major consideration which affects the accumulation of residual stress on-cooling is the temperature at which the transformation occurs. The higher transformation temperatures (start and finish) of bainite results in a higher accumulation of residual stress from thermal cycles (such as in welding) exceeding the A_1 temperature. This phenomenon is complicated by the fact that bainitic materials do not require PWHT in thin sections (regardless of applied extrinsic restraint) and therefore may enter service with high residual stress resulting from welding.

The accumulation of residual stresses from welding will have an adverse affect on the susceptibility of bainitic materials to cracking mechanisms that are highly influenced by the residual stress state. These cracking mechanisms include hydrogen induced cracking, stress corrosion cracking and reheat cracking. Both Grades 23 and 24 have demonstrated susceptibility to these cracking mechanisms in the fabrication and erection of modern power plant components. As with most cracking mechanisms, there are other complicating factors that affect the global susceptibility of a given material to these mechanisms. However, it is interesting to note that martensitic CSEF materials are generally not susceptible to the previously mentioned cracking mechanisms. In the case of HIC, susceptibility to cracking likelihood is substantially reduced because pre and post weld heat treatments are typically required. This is can be attributed to two important factors: First, regardless of application or component thickness, preheat and PWHT have always been required for martensitic CSEF steels. Second, as described above, martensitic materials accumulate less residual stress during welding.

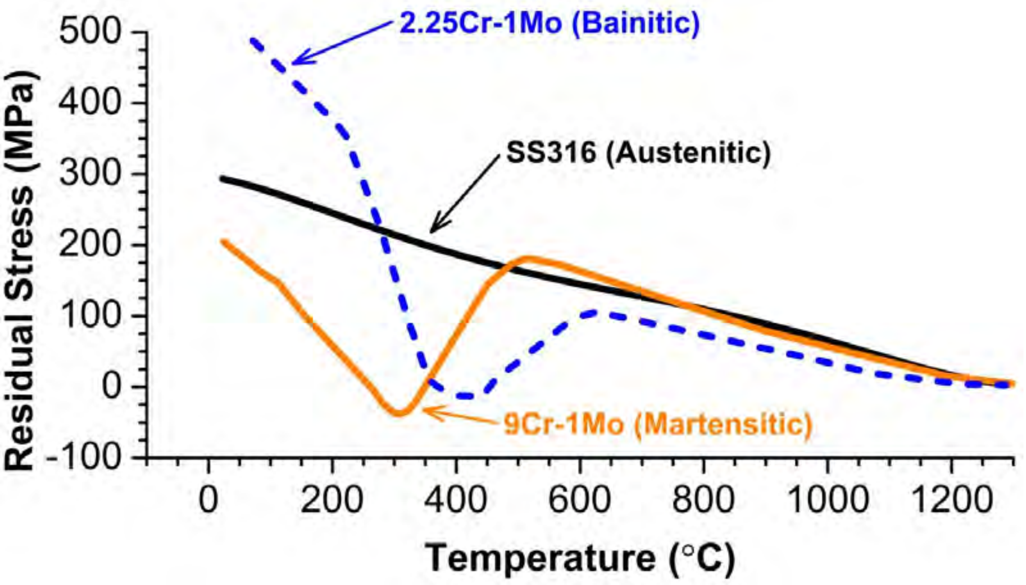

Figure 2: Interpretation of experimental data (determined using Satoh Test) showing how residual stresses develop on cooling for an austenitic steel (no transformation), a bainitic low alloy steel (relatively high temperature of transformation) and a martensitic steel (relatively low temperature of transformation). Adapted from [8].

Table 2: Transformation Temperatures of Grade 23 and 24 Base Material, as Compared to Grade 91 Base and Weld Metal [9, 10]

Grade	M_S		M_F		B_S		A_1	
	°F	°C	°F	°C	°F	°C	°F	°C
23 (Base)	999	537	615	324	1148	~620	1490	810
24 (Base)	860	460	500	260	1022	~550	1499	815
91 (Base)	702-740	372-393	318-385	159-196	N/A		1450-1495	788-813
91 (Weld)	734-784	390-418	392-459	200-237			1418-1474	770-801

SERVICE EXPERIENCE

A range of cracking phenomena during fabrication, field erection, commissioning and repair have been observed in Grades 23 and 24 including stress corrosion cracking (SCC), hydrogen induced cracking (HIC), reheat cracking (RHC) and crater cracking. In addition to these identified issues, fabrication-related difficulties have been highlighted such as flame heating/straightening, excessive grinding, weld repair, brittle fracture and ferritic dissimilar metal welds. Examples for each of these difficulties will be briefly detailed in subsequent sections.

Stress Corrosion Cracking (SCC)

SCC has been documented in waterwall panels constructed from both Grades 23 and 24 [11-17]. Detailed material testing in a variety of environments suggests that either or both acid cleaning and water chemistry plays an important role in the susceptibility of these materials to SCC during the commissioning phase of the boiler [13-16]. The influence of these two processes in the commissioning phase remains a highly debated topic. On-going research is working to define which step(s) in the acid cleaning procedure cause SCC as well as identification of specific corrosive media (and content) in the water chemistry that influences susceptibility to SCC. In Figure 3, an example of SCC is shown in a T23 waterwall panel tube to tube butt weld. In this image, it can be seen that cracking initiates from the root (ID, water touched surface) and in the coarse grained heat affected zone (CGHAZ) near the fusion line and propagates intergranularly through the CGHAZ and weld metal.

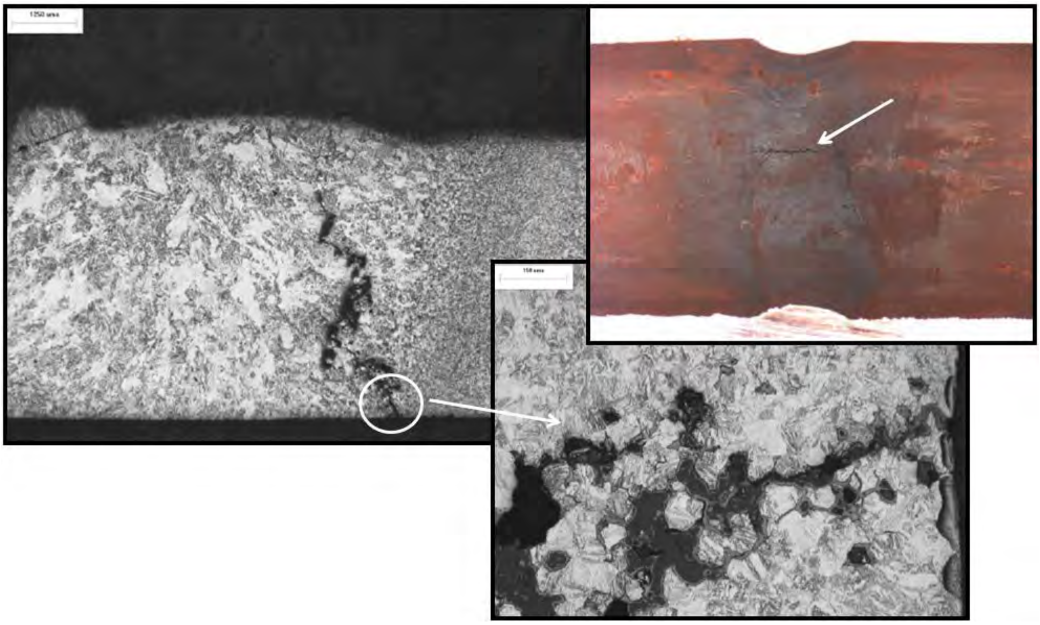

Figure 3: Example of Stress Corrosion Cracking (SCC) in a Grade 23 Tube to Tube Butt Weld

Hydrogen Induced Cracking (HIC)

HIC has been observed in various components including tube to tube butt welds in Grade 23 and tube to fin waterwall welds in Grades 23 and 24. Initially, both Grades 23 and 24 were reported to be weldable without an applied and controlled preheat temperature. Despite this early guidance, it is clear from field and fabrication experience that a controlled preheat temperature is required for both materials to avoid HIC. In Figure 4, HIC in waterwall panels was identified near tube to tube butt welds where inserts were welded to seal around the field tube to tube butt welds. These inserts were fairly small and as such, were susceptible to creating high levels of localized residual stresses. In this instance, cracking was isolated primarily to the CGAHZ, propagated in a transgranular fashion and exhibited some branching consistent with HIC.

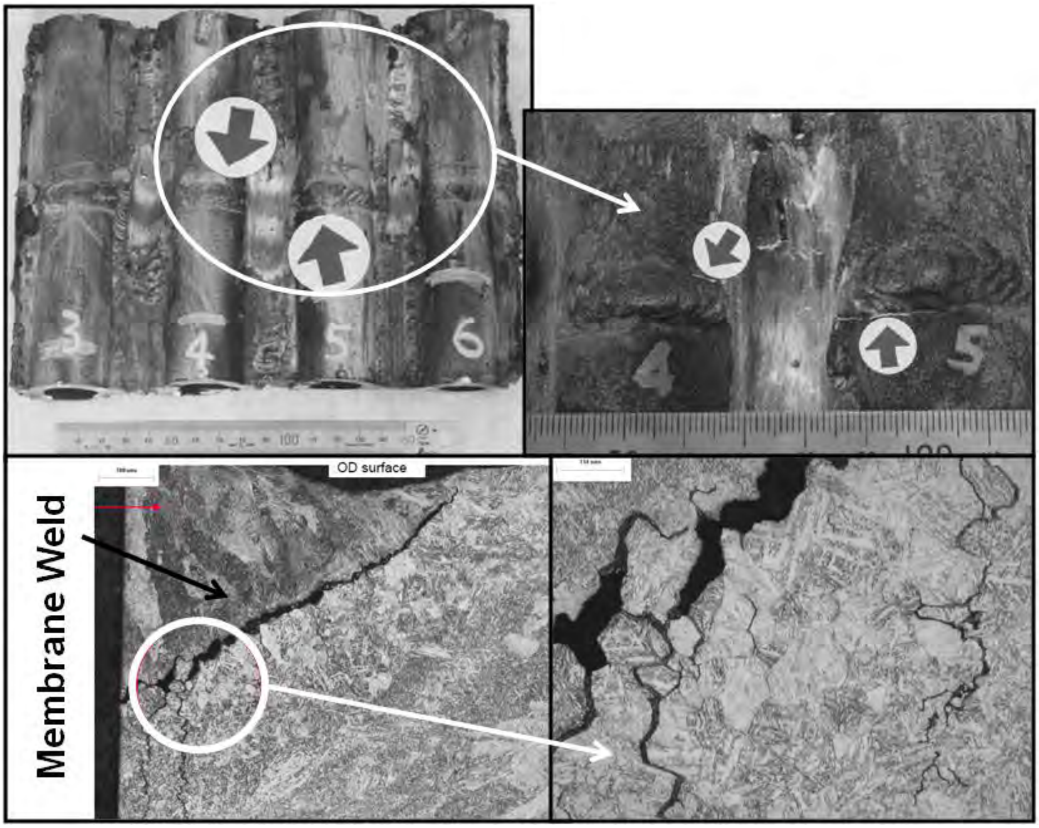

Figure 4: Example of Hydrogen Induced Cracking in Grade 23 Waterwall Panel Note: HIC in this instance is observed between the membrane to fin weld and adjacent to highly restrained field-welded inserts. These inserts were utilized to seal the region around the tube to tube butt welds made between adjoining waterwall panels [17]

Reheat Cracking (RHC)

RHC has been observed in a variety of highly restrained Grade 23 components including high crown seal welds, thick-section girth welds and stub to header welds. Grade 23 was shown to be potentially susceptible to reheat cracking in early screening tests using both the Belgian Welding Institute controlled strain rate tensile test and in more controlled Gleeble relaxation tests [18-20]. RHC can be difficult to avoid and overcome, although from the CrMoV experience it is generally accepted that highly controlled welding procedures to create a refined grain structure in the CGHAZ and weld metal are beneficial in resisting this form of cracking. Additionally, RHC may be controlled by careful compositional refinement, as detailed in [7]. It should be noted that the sensitivity to alloy and weld metal chemistry in Grades 23 and 24 has not been exhaustively studied. This is a particularly important point as research on CrMoV indicates that the chemical composition (such as As, Sn, Sb, Si, Al and N) played an important role in defining the RHC susceptibility of this material [21-22]. Limited research in Grade 23 base material and weld metal suggest that similar influences may play a role in the RHC tendency of this material [7, 23].

Figure 5 shows an example of a RHC in a high crown seal where the seal weld was made using a –B3 (matching to Grade 22) filler metal around T23 material. The cracking morphology included classic signs of RHC such as cavitation ahead and isolated from the main crack tip as well as cracking isolated to the CGHAZ and immediately adjacent to the fusion line. Reported fabrication experience of thick-section girth welds, the development of Grade 23 consumables and the welding of stub to header welds suggests that fabrication of thick-section components from Grade 23 must be appropriately considered [23-24]. Lastly, although initial data developed using the BWI controlled strain rate test suggested Grade 24 was immune from RHC, more recent data obtained from higher carbon Grade 24 has shown this material to be potentially susceptible to RHC [25]. Thus, RHC must be considered prior to welding both steels in either thick-sections or in highly restrained situations.

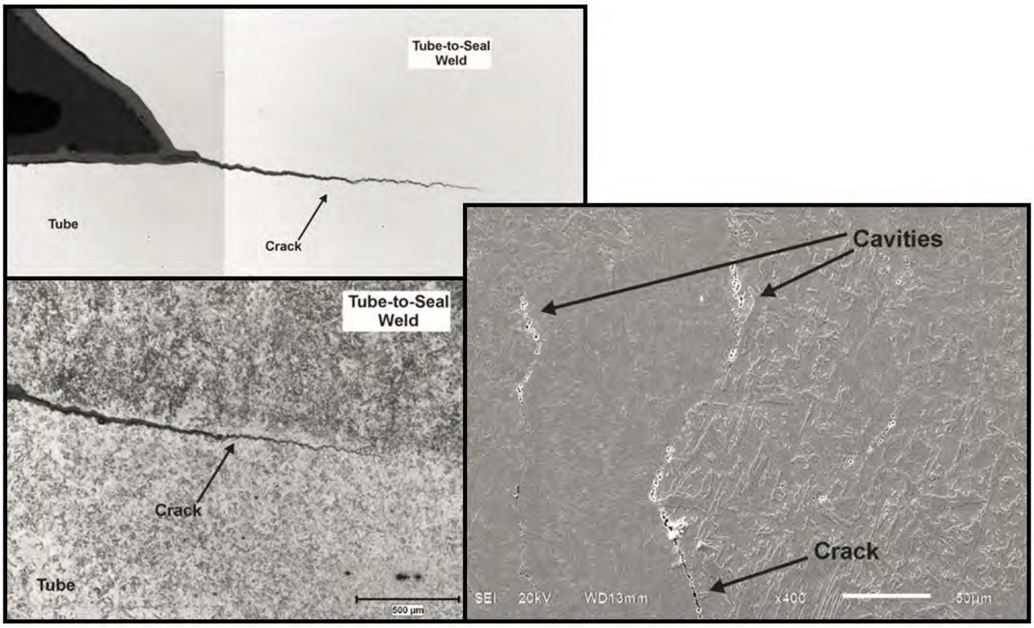

Figure 5: Example of Reheat Cracking in Grade 23 High Crown Seal Weld

Crater Cracking

Crater cracking has been observed in tube to fin waterwall welds and tube to tube butt welds in Grade 24. Controlled welding parameters during the submerged arc welding (SAW) process of tube to fin seal welds in waterwall panel fabrication has eliminated this issue [26-27]. More recently, extensive issues have been reported in crater cracking of tube to tube butt welds in Grade 24 and revised welding techniques (i.e. a controlled ramp down and extinguishing of the arc near the sidewall) are required to avoid this phenomenon [27-28]. Crater cracking has not yet been detailed as a widespread issue in Grade 23.

Flame Heating and Straightening

Flame heating and straightening are routinely used processes in fabrication and field construction such as in the modification of waterwall panels or for preheat. The cracked tube shown in Figure

6 was attributed to a retransformed region in the tube caused by the hot straightening that resulted in stress corrosion cracking. Uncontrolled hot straightening and/or flame heating will re-austenitize the microstructure. The austenite on-cooling will transform to fresh bainite and/or martensite. Fresh bainite and martensite will have elevated levels of hardness and cause an accumulation of localized residual stress. This scenario creates a condition in which a base material may become susceptible to SCC, RHC or brittle fracture.

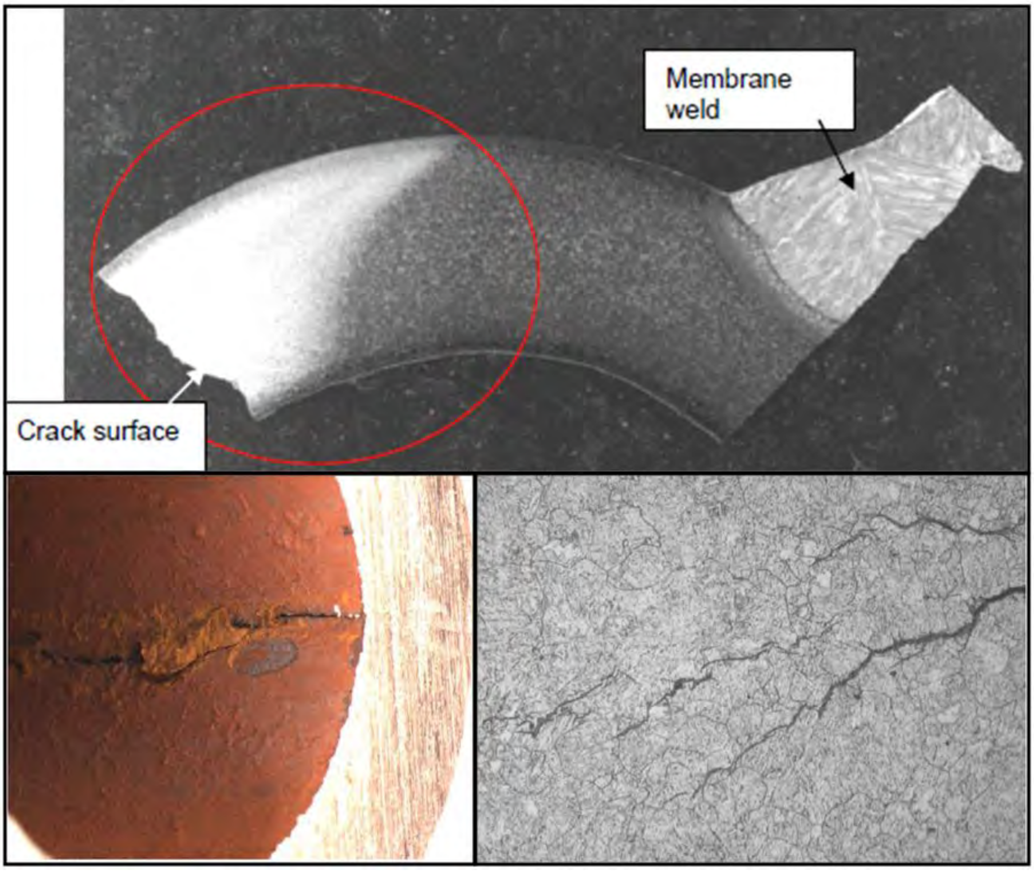

Figure 6: Example of Improper Flame Heating Leading to Re-Transformation of the Microstructure and Ultimately Failure by Stress Corrosion Cracking

Excessive Grinding

Excessive grinding has been reported in the removal of erection lugs, Figure 7. The consequence of excessive grinding is two-fold. In the instance where excessive grinding may occur and does not violate minimum tube or pipe wall thickness, the grinding operation may cause localized heating and re-transformation of the surrounding microstructure to fresh bainite and/or martensite. As previously discussed, such an occurrence would result in a localized region of base material with high levels of hardness and residual stress. This localized region will be susceptible to stress corrosion cracking, reheat cracking or brittle fracture. In the second scenario, excessive grinding results in the need for weld repair to restore the needed material; this example is detailed in the following section. Weld repair will not only result in the formation of fresh bainite and/or martensite, but successful implementation of weld repairs remains a challenging prospect.

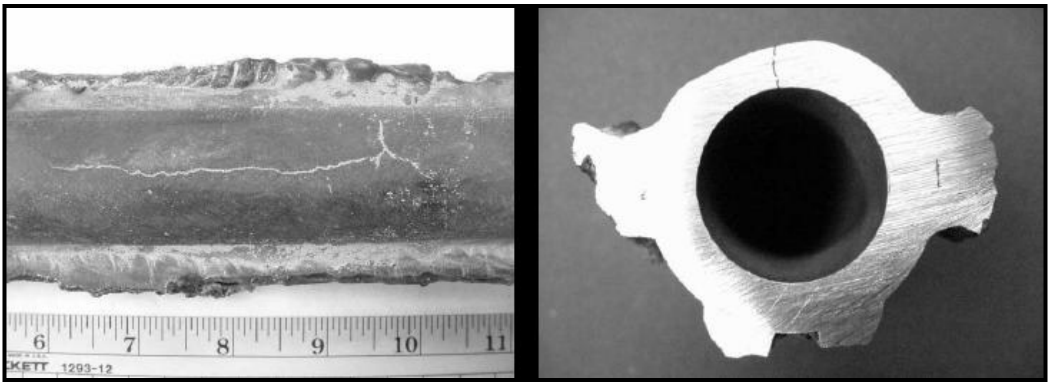

Figure 7: Example of Excessive Grinding Following Removal of an Erection Lug Note: The outside diameter has been removed below minimum wall and cracking originated from the inside diameter due to stress corrosion cracking [17]

Weld Repair of Identified Defects

In Figure 8, weld repair was required to restore material removed from the outside diameter of tubing due to excessive grinding. Elevated levels of residual stress and a susceptible microstructure resulted from the weld repair and SCC was observed in these regions. From a more strategic point of view, weld repair of Grades 23 and 24 has not been extensively addressed. Due to the differences in the microstructure constituents, alloying content and material behavior in various CSEF steel grades, weld repair techniques developed for one steel may not be applicable to others in this family of materials. An intense effort at the former Central Electricity Generating Board (CEGB) in the UK resulted in acceptable repair techniques for CrMoV piping systems involving carefully controlled temperbead weld repairs. Such techniques may be applicable to Grades 23 and 24, but have yet to be developed and instituted.

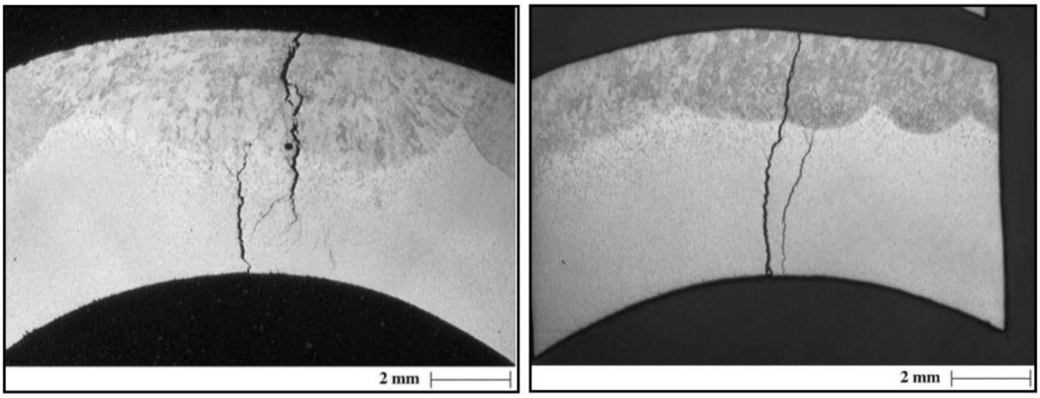

Figure 8: Example of Stress Corrosion Cracking Initiation at a Weld Repair Performed where Excessive Grinding had occurred [17]

Brittle Fracture

Brittle fracture has been reported in tube bends and swages. Specifically, brittle fracture in swages was recently reported during the weld repair roof tubing near high crown seals, Figure 9. In this instance, cracking initiated from these welds and propagated across the roof tubing panels through T23 swages. Some of the T23 swages exhibited charpy impact toughness values below 10 ft-lbs. Such low values indicate that the swages were improperly manufactured, inappropriately renormalized and tempered, or some combination of fabrication and heat treatment resulted in non-optimum microstructures.

Figure 9: Brittle Fracture through T23 Swages and T23 Welds in the Vicinity of High Crown Seals

Ferritic Dissimilar Metal Welds (DMWs)

The inability to procure Grade 23 plate material manufactured to SA387 (or similar specifications) has resulted in Grade 23 headers being manufactured with Grade 91 end-caps. The use of a matching filler material to either Grade 23 or Grade 91 is insignificant; the difference in chromium between these two materials will result in carbon migration during welding, post weld heat treatment and service in either filler metal selection. If a filler metal matching to Grade 23 is used, this carbon migration will result in a carbon-denuded, creep weak region in the deposited Grade 23 filler metal and adjacent to the fusion line. If a filler metal matching to Grade 91 is used, the creep weak region will be located in the Grade 23 base material and adjacent to the fusion line. When specifying Grade 23 or Grade 24 components, and especially in the instance of replacement parts, it is critical to ensure that ferritic DMWs are minimized and that the design of unavoidable ferritic DMWs is given proper engineering consideration with respect to filler material and post-weld heat treatment.

ON-GOING AND FUTURE WORK

EPRI is working closely with its membership to collaborate with industry and recognized world experts in Grades 23 and 24 to address the fundamental issues which challenge successful use of these materials. Regardless of material, there are three key issues that material users must address when these two materials are utilized in their plant components: procurement of acceptable material through more tightly controlled specifications, life assessment of components and weld repair of existing components. To address these key, underlining issues, a multitude of studies are being conducted through EPRI, Lehigh University, Oak Ridge National Laboratories and RIF to examine fundamental material behavior, susceptibility to stress corrosion cracking in a variety of environmental conditions, accumulation of residual stresses in weldments, tempering behavior of weldments and creep crack growth behavior.

CONCLUSIONS

In general, few issues have been reported in Grades 23 and 24 when welded in “loose” tubing applications such as in reheaters and/or superheaters. More extensive issues in tubing applications have been reported where highly restrained welds have been made in waterwall panels, roof tubing, high crown seals, and erection lugs. Additional problems in welding these materials have been documented in stub to header welds and girth welds in thick-section components. Challenges with common fabrication techniques like flame heating, flame straightening, grinding and weld repair have been detailed. The issues in these two materials demonstrate the need to better understand these complex steels from a fundamental standpoint to address needs surrounding material specification, life assessment and weld repair.

REFERENCES

[1] “Code Case 2199.” *ASME Boiler and Pressure Vessel Code*. Approved June 28th, 2012.

[2] “Code Case 2540.” *ASME Boiler and Pressure Vessel Code*. Approved June 28th, 2012.

[3] *ASM E Boiler & Pressure Vessel Code, ASME B&PV II, Part D: Properties* (Table 1A), 2010. New York: ASME.

[4] Masuyama, F. and Mitsuura, H. “High Strength Heat-Resistant Low Alloy Steels.” Patent 5,084,238. January 28, 1992.

[5] Iseda, A., Sawaragi, Y., Masuyama, F., and Yokoyama, T. “Low-Alloy Heat-Resistant Steel Having Improved Creep Strength and Toughness.” Patent 5,211,909. May 18, 1993.

[6] Iseda, A., Sawaragi, Y., Masuyama, F., and Yokoyama, T. “Low-Chromium Ferritic Heat-Resistant Steel with Improved Toughness and Creep Strength.” Patent 5,407,635. April 18, 1995.

[7] Komai, N., Masuyama, F., Yokoyama, T., Hirata, H., Kawano, K., and Kan, T. “High Strength, Low Alloy, Heat Resistant Steel.” Patent 6,379,611. April 30, 2002.

[8] H. K. D. H. Bhadeshia. ‘Effect of Materials and Processing: Material Factors’, *Handbook of Residual Stress and Deformation of Steel*, 2002. ASM International, Ohio, USA.

[9] Alexandrov, B. A. and Lippold, J. C. “Phase Transformation Behavior in CSEF Steel Welds.” *Proceedings of the Sixth International Conference on Advances in Materials Technology*, August 31 – September 3, 2010, Santa Fe, NM.

[10] Arndt., J., Bendick, W., Deshayes, F., Haarmann, K., Kottmann, G., and Valliant, J. C. *The T23/T24 Book*, 1998. Vallourec and Mannesmann Tubes.

[11] Private Correspondence with Eric DuPont, 7/7/2011.

[12] Private Correspondence with Frank Moore, 10/31/2012.

[13] “T24 Experience: An Hitachi Power Europe Perspective.” *Modern Power Systems*, October 2012. pp. 38-40.

[14] Nowack, R., Gotte, C. and Heckmann, S. “Quality Management at RWE Using T24 Boiler Material as an Example.” *VGB PowerTech Publication*, November 2011.

[15] Ullrich, C., Heckmann, S., Tillmann, W., Bodmer, T., Neumann, F., Rademacher, H., and Gierschner, G. “T24 – Investigation Program and Derived Measures.” *38th MPA-Seminar*, October 1-2, 2012, Stuggart, Germany.

[16] Ludenbach, G. “Stress Corrosion Cracking of T24.” *VGB PowerTech e.V.,* Mannheim, 2012.

[17] Fishburn, J. D., Henry, J. F., and Zhou, G. "Service Experience with T23 Material." *Proceedings of the 9Cr Materials Fabrication and Joining Technologies*, July 10-11, 2001, Myrtle Beach, SC.

[18] Dhooge, A. and Vekeman, J. "New Generation $2^{1/4}$Cr Steels T/P 23 and T/P 24 Weldability and High Temperature Properties." *Welding in the World* (49); 2005, pp. 75-93.

[19] DuPont, J. N., Marder, A. R., Nawrocki, J. G., Puskar, J. D., and Robino, C. V. "The Mechanism of Stress-Relief Cracking in a Ferritic Alloy Steel." *Welding Journal 82* (2), pp. 25-s – 35-s.

[20] DuPont, J. N., Marder, A. R., Nawrocki, J. G., and Robino, C. V. "The Stress Relief Cracking Susceptibility of a New Ferritic Steel – Part 1: Single-Pass Heat Affected Zone Simulations." *Welding Journal 79* (12), pp. 355-s – 362-s.

[21] Barbaro, F. J., Gunn, K. W., and Edwards, R. H. "Stress Relief Cracking in CrMoV Steels." *Metals Forum* 5 (2), 1982, pp. 119-129.

[22] King, B. L. "Intergranular Embrittlement in CrMoV Steels: An Assessment of the Effects of Residual Impurity Elements on High Temperature Ductility and Crack Growth." *Philosophical Transactions of the Royal Society A* 295 (1413), 1980, pp. 235-251.

[23] Park, K., Kim, S., Chang J., Lee, C. "Post-weld heat Treatment Cracking Susceptibility of T23 Weld Metals for Fossil Fuel Applications." *Materials and Design* 34 (2012), pp. 699-706.

[24] R. Fuchs, B. Hahn, and H. Heuser, "Affect of inexpert working of heat resistant steels to the serviceability," in *Proceedings of the Sixth International Conference on Welding and Repair Technology for Power Plants*, Sandestin, FL, 2004.

[25] Huysmans, S., De Bruycker, E., and Vanderlinden, F. "Complementary Research Related to SCC Sensitivity of T24 Boiler Tubing." Presented at the *VGB Materials and Quality Assurance Workshop*, June 19, 2013, Essen, Germany.

[26] J. Adamiec and A. Hernas. "Experiences in Welding of Membrane Panels Made of 7CrMoVTiB 10-10 (T24) Steel." *Proceedings of the Trends in the Development of Machinery of Associated Technology*, Mediterranean Cruise, 2010. pp. 57–60.

[27] L. Mraz, P. Brziak, P. Bernasovsky, P. Zifcak, J. Kotora, D. Krajci, M. Mraz, J. Pecha, J. Robinson, and D. Tanner, "Experience with Utility Properties of T24 Steel." *Proceedings of the 9th International Trends in Welding Conference 2012*, June 4-8, 2012, Chicago, IL. pp. 1003-1010.

[28] Heuser, H. "Welding of Ferritic Steel T/P24." Presented at *V&M Powergen Technical Seminar*, Orlando, FL, December 13, 2012.