Service Experiences with Cracking in T23 Weldments

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ABSTRACT

For over 50 years, the conventional Cr-Mo steels, such as Grades 11 and 22 have been used in large utility-type boilers throughout the world with notable success. From this solid base of experience there has emerged a new group of high-strength ferritic materials that offer substantial improvements in elevated temperature performance through the judicious addition of a range of precipitate-forming elements, such as columbium, vanadium, titanium, tungsten, nitrogen, and boron. Following in the footsteps of the German X20 material, Grade 91 rivals TP304H in high-temperature strength up to approximately 1150°F. A more recent addition is the low carbon modifications of Grade 22, designated Grades 23 and 24, which were developed to be highly weldable grades that could be left in the as-welded condition, in contrast to Grade 91. Laboratory tests have confirmed the improved weldability of Grade 23, with relatively low hardness values possible in as-welded condition. However, service experience with this alloy has been very limited, except for tightly controlled trial applications conducted by the OEM/steel mill partners. As a consequence, its behavior outside of the laboratory, under the less felicitous conditions that typically prevail in a modern power plant, naturally is of some interest.

With increasing applications of T23, cracking issues in Grade 23 welds have become a "hot topic" over the entire utility industry. During the recent commissioning of a new supercritical utility boiler with a portion of the furnace constructed using T23 tubing, a number of problems were encountered in the furnace that largely were confined to the T23 tubing. Subsequent analysis of samples of failed tubing proved conclusively that the problems encountered did not reflect an inherent weakness of the T23 material, but that problems would have occurred to some degree had one of the standard alloy steels been installed at the failure locations under similar conditions of processing. The analysis did suggest, however, that claims made by the tube supplier regarding the virtual immunity of the as-welded material to damage such as welding "cold" cracks or stress-corrosion cracking were exaggerated. In particular, it was found that under exceptional conditions T23 material in the fully hardened condition could attain hardness levels sufficiently high to render the material susceptible either to hydrogen-assisted cold cracking or to stress-corrosion cracking. In the following discussion, the history of some T23 weld cracking incidents is recounted, and the results of the analysis of the damaged tubing are reviewed in detail.

1.0 INTRODUCTION

To a cynic, the US power industry's enthusiastic adoption of the "new" generation of high strength ferritic steels inevitably calls to mind Shaw's comments on second marriages - that they represent the triumph of hope over reason. It certainly is true that this group of materials offers substantial improvements in elevated temperature performance compared to the conventional Cr-Mo steels, such as Grade 9, Grade 11, and Grade 22, improvements based on the judicious addition of a range of precipitate-forming elements, most notably columbium, vanadium, titanium, tungsten, nitrogen, and boron. An example often cited is the fact that the modified 9Cr alloy, designated as Grade 91, is comparable in strength to TP304H up to a temperature of approximately 1150°F. These enhanced grades have been marketed, therefore, not only as the necessary successors to the conventional steels for use in the proposed ultra-supercritical boilers, but also as cost-effective replacements for the standard grades of low alloy steel in

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the existing fleet of older utility boilers. Their use, we have been told, for SH or RH tubing can minimize or completely eliminate the need for the austenitic stainless grades, thereby avoiding dissimilar metal welds. Because of their superior strength, thick-walled pressure parts can be designed to be thinner and, therefore, more tolerant of thermal cycling.

Sales brochures notwithstanding, the growing number of unexpected failures in pressure parts fabricated from Grade 91 has drawn attention to the fact that the benefits of these enhanced grades carry a price that goes beyond the direct material cost from the supplier. At least a part of this price is the requirement for substantially more rigorous process control than has been necessary for the conventional grades to insure the development of the specific microstructural condition that, in every case, is the basis for the enhanced grade's improved strength. The full extent of the control required for any given alloy is not always well understood, and in certain areas, such as the effects of cold work on rupture strength and ductility, there simply is not enough information available to establish well-defined limits.

One of the more recent additions to this group of alloys is the low carbon modification of Grade 22, which has been designated Grade 23 [1-3]. This alloy was developed to be highly weldable and, unlike the modified 9Cr and 12Cr alloys, capable of being left in the as-welded condition; the strength levels approach those of Grade 91 up to approximately 1150°F [1-6]. Grade 23 differs from Grade 22 through additions of tungsten (1.6%), vanadium, columbium, and boron, with a reduction of molybdenum (0.20%) and control of carbon content to less than 0.10% (0.04-0.10). After proper heat treatment (N&T or Q&T), a tempered bainitic-martensitic microstructure with optimum precipitates is produced in the material, which contributes to the enhanced creep strength and the resulting higher allowable stresses. The improved weldability is based on the reduced carbon content, which has been reported to allow the hardness to remain below 350 HV in the as-welded condition. Extensive laboratory testing has confirmed the material's superior weldability, based on the relatively low hardness values that can be achieved in the as-welded condition. However, except for precisely controlled trials conducted by the OEM/steel mill partners, the service experience with this alloy has been limited to date, and its behavior outside of the laboratory, under the less felicitous conditions that are likely to prevail in a modern power plant, is of more than passing interest.

The failures of T23 components served as a wake-up call throughout the entire power industry; T23 in an actual component can behave differently relative to its base metal in a precisely controlled laboratory testing during which T23 material had been developed. Numerous leaks in T23 furnace wall tubing during hydro-tests [8, 9] due to stress-corrosion cracking are a good example. The majority of these leaks had developed at butt welds at one elevation in the furnace, and most of the leaks had occurred in welds joining T23 tubing. The other mode of damage observed in the same case was "cold" cracking, which was confined to a few welds in one specific area of the furnace where the assemblies were highly restrained. In addition, Grade 23 is known to be vulnerable to reheat cracking with the addition of W, V, Nb, N and B [12-15]. The degree of susceptibility varies significantly from heat to heat. The failures of T23 components due to reheat cracking have been experienced during the component manufacture and during service. In the last two decades, there have been a number of failures in Grade 23 pressure parts attributed to reheat cracking [16-20].

This paper summarized some cracking incidents in T23 welded components and shared our service experience with this alloy in the modern power industry applications. The optimistic claims made for T23 may not be true under certain conditions. Fundamental understanding of T23 metallurgy is the basis for successful applications.

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2.0 T23 COMPONENT CRACKING ISSUES – CASE STUDIES

2.1. Case 1-Stress Corrosion Cracking in T23 Tubing [8-11]

During the commissioning of a supercritical coal-fired utility-type boiler, multiple leaks occurred in tubing in the rear wall of the furnace over a period of approximately two months. In all cases the tubing in which the leaks had occurred was SA213, T23 material, the enhanced 2-1/4Cr alloy covered by Code Case 2199. By design, the T23 tubing had been used only to construct the rear wall of the furnace, with SA-213, T12 tubing being used for the rest of the furnace. Of nineteen tubes in which leaks were detected, three of the leaks were located at the site of temporary welded erection lugs, fifteen leaks were located at girth butt welds (T23-to-T23 or T23-to-T12 welds), and one leak was located at a tube bend in the upper nose arch in the center of the rear wall. Figure 1 shows an example of one of the leak sites at a temporary erection lug weld; the through-wall crack can be seen on the transverse cross-section of the tube. These lugs had been installed temporarily in the shop to assist in the alignment of the furnace wall panels prior to the final assembly welding of the panels. Once the panels were installed, the lugs were removed from the tubes at the site by flame cutting and the tube surface was ground smooth. A typical composition for the T23 material in which the leaks had developed is presented in Table 1, together with the ASME specification for SA213, T23 for comparison.

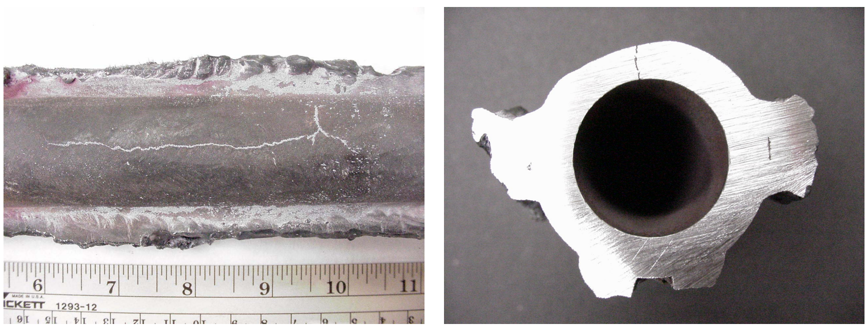

Figure 1. Example of T23 tube leaks at a temporary omega lug weld.

Table 1. Typical Composition of T23 Material Related to The Leaks

	C	Mn	Si	P	S	Cr	Mo	V	W	Nb	B
Tube	0.0648	0.46	0.32	0.001	0.001	2.12	0.172	0.262	1.74	0.033	0.0036
ASME SA213, T23	0.04-0.10	0.10-0.60	0.50 max	0.030 max	0.010 max	1.9-2.6	0.05-0.30	0.20-0.30	1.45-1.75	0.03-0.08	0.0005-0.0060

Destructive analysis of the failed tubing established that the leaks in rear wall tubing were the result of caustic-induced stress corrosion cracking (SCC), with the cracks exhibiting the transgranular/intergranular branched fracture path characteristic of this type of damage. All cracks had initiated on the inside surface of the tube. Evidence of the SCC was found on both the furnace side and the backside ID surface of the tubing. Figures 2 and 3 record typical macrostructural and microstructural features of the SCC as it appeared at the temporary erection lugs and at girth butt welds. An examination of other tubes in the same area that had not leaked confirmed the presence of SCC attack in a number of these tubes, as well, with cracks of sufficient depth in some to insure imminent failure of the tube, as shown in Figure 4.

A detailed review of the procedures used during both manufacturing and erection of the boiler uncovered several practices that contributed to the stress corrosion cracking problem. First, during the removal of the erection lugs, the grinding had not been controlled, so that on a number of the tubes extensive weld repair was necessary to repair local grinding damage to the tube wall. In several cases the weld repair extended completely through the wall of the tube. There was no pre-heat or post-weld heat treatment (PWHT) applied in the course of making the weld repairs, and hardness in the weld Heat-Affected Zones was measured to be as high as 370HV. With regard to the girth butt welds, similar welding practice had been followed in making these welds (i.e., no pre-heat and no PWHT), and hardness levels in the HAZ were

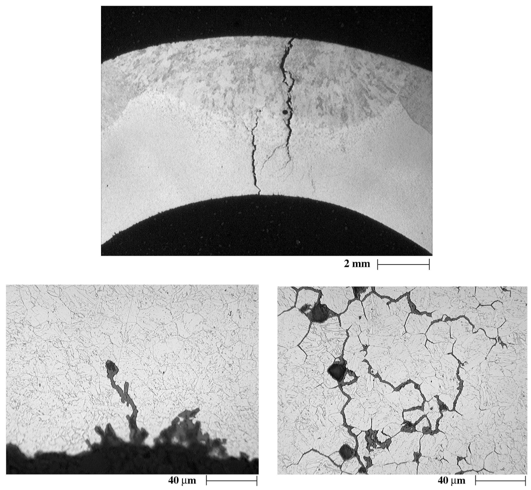

Figure 2. Stress corrosion cracking at a temporary erection lug weld.

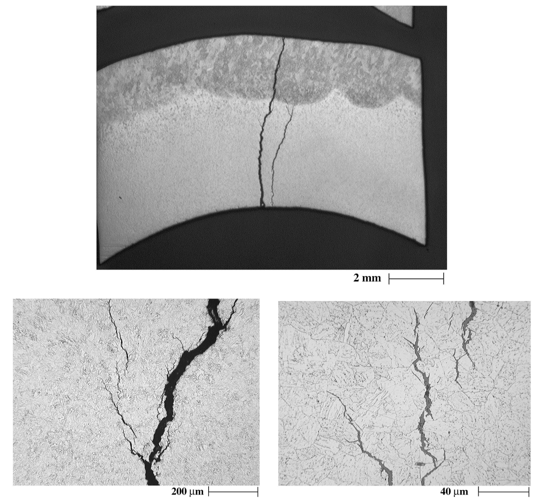

Figure 3. Stress corrosion cracking at a girth butt weld.

comparable to those measured in the weld repair HAZ. With regard to the leak in the bent tube at the nose arch, it was found that in this case a small area of the tube wall had been re-austenitized by torch heating to facilitate minor adjustments to the alignment of the tube in the panel. Hardness within this locally re-austenitized region was measured to be approximately 325HV.

The operator's reaction to these failures was to call into question the use of the T23 tubing for the construction of a portion of the furnace. He argued that the fact that virtually all failures had occurred in T23 tubing, while the T12 tubing in other areas of the furnace was largely untouched, proved that the T23 was unusually susceptible to SCC and that, therefore, all T23 tubing should be replaced. The limited operational experience with the T23 material only served to reinforce his belief that he was the unwitting victim of a failed "experiment." Despite the fact there was so little experience with the material, it was believed that the customer's fears were unfounded for two fundamental reasons. First, not all of the T23 welds had failed. In fact, there were a large number of butt welds in T23 tubing in the rear wall that showed no signs of distress, this despite the fact that they had been welded in exactly the same manner as the failed welds and had been exposed to the same environment. When the failure locations were plotted with respect to their elevation in the furnace, it was found that all failures were located within a well-defined band on the rear wall. It then was discovered that during start-up of the unit, it was possible to operate the unit in such a way that local boiling could take place on the rear wall of the furnace. Since it was necessary to identify a

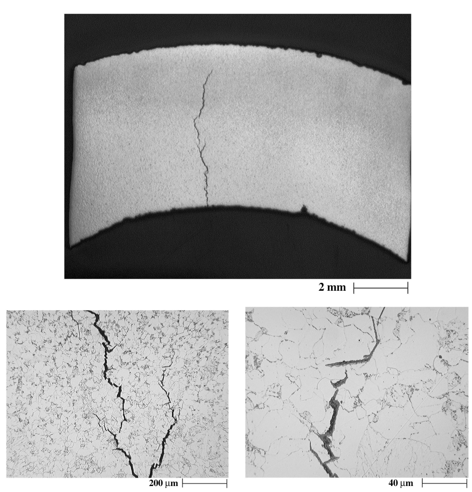

Figure 4. Stress corrosion cracking in a non-leak T23 tube.

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concentrating mechanism, if the contamination had, in fact, occurred during operation, the discovery of a potential for local boiling during start-up provided an explanation for the localized nature of the failures. The location in the furnace of this “dry-out” condition corresponded with the area in which the failures had occurred.

The other basis for the belief that the T23 was not unusually susceptible to damage compared to the conventional low alloy steels was the fact that the as-welded hardness of the T23 tubing was no greater than the hardness that could be developed in those alloys when left in the as-welded condition. Since hardness, coupled with the influence of residual or applied tensile stress, dictates relative susceptibility to SCC, it was believed that relative susceptibility to SCC would not vary significantly between these alloys, the only possible difference being the higher yield stress of the T23 alloy. In order to define the SCC sensitivity of T23 material relative to T12 or T22, a series of SCC tests was conducted on GTA welds made in T23, T12, and T22 tubing using an ER90S-B3 filler material [11]. The SCC test specimens represented welds in the as-welded, the stress-relieved (1325°F/1hr), and the N&T (1700°F/1hr + 1325°F/1hr) conditions. The specimens were configured to produce yield-level tensile stresses at the exposed surface of the weldment. Based on the physical evidence of caustic stress corrosion cracking obtained during the metallographic investigation of the T23 tube failures, the test solution selected was caustic in nature, consisting of a 33% sodium hydroxide solution to which 0.1% lead oxide had been added in order to shift the electrochemical potential into a region where intergranular cracking was expected. In addition, a “pure” water test, reflecting purity levels established for higher pressure boilers, also was conducted on as-welded T23 and T12 coupons to establish the relative SCC sensitivity base line. The SCC testing was conducted at the test solution boiling temperature for 96 hours. The SCC damage level in either the base metal, weld metal or HAZ was destructively examined after testing, and the relative SCC sensitivity was classified according to a qualitative damage ranking scheme. Accordingly, a ranking of “1” represented the lowest damage level, consisting of a few small microfissures extending no more than one to two grains in depth, while a ranking of “5” represented the highest damage level, consisting a large number of cracks extending through or nearly through the full thickness of the test coupon. The SCC test results are summarized in Table 2.

Table 2. Summary of SCC Test Results

Conditions	Test Materials and Regions					
	T23		T12		T22	
	WM	HAZ	WM	HAZ	WM	HAZ
As-welded	5	5	5	4	5	5
As-welded	5	5	5	4	---	---
Stress-relieved	3	1	3	3	---	---
Stress-relieved	3	2	NC	NC	---	---
N&T	1	NC	1	2	---	---
N&T	NC	NC	1	3	---	---
*As-welded**	NC	NC	NC	NC	---	---

* SCC test was conducted in pure water.
NC: No Cracks WM: Weld Metal HAZ: Heat-Affected Zone

Following the damage evaluation, hardness testing also was conducted to identify the maximum level of material hardness in the base metal, weld metal, and Heat-Affected Zone (HAZ) for each SCC sample. The results are presented in Table 3.

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Results of these SCC tests demonstrated that the T23 tubing material is not unusually susceptible to caustic stress corrosion cracking compared to common boiler tubing materials, such as Grade 12 and Grade 22 when properly welded and heat-treated. The tests confirmed that the combined influence of hardness and residual plus applied stress at a specific location play a decisive role in determining a material's susceptibility to SCC in a caustic environment.

Table 3. Hardness Testing Results of SCC Samples

Conditions	Hardness (HV)		
	Base Metal	CGHAZ	Weld Metal
T23 As-welded	188	347	328
T12 As-welded	159	336	306
T22 As-welded	186	368	365
T23 Stress-relieved	191	333	314
T12 Stress-relieved	159	264	262
T23 N&T	212	274	226
T12 N&T	164	229	219

2.2 Case 2-Cold Cracking on T23 Girth Butt Welds [8-10]

During a unit restart of the same boiler, several tube leaks were detected in field butt welds at the same elevation on the furnace rear wall. The leaks were traced to circumferential cracks at the toe of the weld on the furnace side of the assembly, as indicated in Figure 5. The tubing material SA213, T23 with dimensions of 1.375" OD x 0.220" MWT.

Metallographic examination revealed that the cracks had initiated in and propagated through the coarse-grained region of the HAZ and exhibited a fracture morphology that differed markedly from the caustic stress-corrosion cracking observed at other locations on the rear wall of the furnace. In particular, the cracks at these leak sites proved to be predominantly transgranular, with substantially different branching characteristics. The maximum HAZ hardness was measured to be at the level of 370HV. The distinctive microstructural features of the cracking, and the localized nature of the damage in an area where the welds were highly restrained by large welded attachments, suggested that this damage was the result of hydrogen-induced or "cold" cracking. (Access to sample material, unfortunately, has been limited, so that documentation of the cracking cannot be provided at this time. However, all pertinent information related to this damage, including the welding procedures, the component configuration, and the microstructural features of the damage were reviewed by materials engineers representing the operator, the tubing supplier, and the boiler manufacturer, all of whom agreed in the diagnosis of "cold" cracking).

Figure 5. Documenting the Circumferential Cracking observed along the toe of the girth butt welds on the FS of the tubing.

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With regard to the issue of pre-heat of T23 tubing material, it has been claimed by suppliers that for tubing the T23 alloy can be welded without either pre-heat or postweld heat treatment. This claim likely is true when welding conditions are properly controlled during fabrication and when the degree of restraint on the joint is relatively low. However, any deviation from conditions of proper control (e.g. wet rods, poor gas shielding, etc.) may render the material susceptible to "cold" cracking in the absence of pre-heat, depending on the degree of restraint. The basis for this susceptibility is a level of hardness in excess of 350 HV that may be achieved with some heats of the T23 material, even when the carbon and alloy contents are near or only slightly above mid-range for the alloy. It is for this reason that the application of the ASME Boiler Code requirement for the pre-heating of welds made in T23 tubing at a minimum temperature of 300°F, or the postweld heat treating at a minimum temperature of 1250°F is prudent in certain applications.

2.3 Case 3-Reheat Cracking on T23 High Crown-Seal Weld [19]

During the normal operation of a CFB boiler, a tube leak occurred in high crown-seal area of the superheat wingwall assembly. The leak was traced to the root of the high crown-seal weld on the furnace side of the assembly, as indicated in Figure 6. The tubing material SA213, T23 with dimensions of 1.75" OD x 0.165" MWT. Metallographic examination revealed that the cracks had initiated in and propagated through the coarse-grained region of the HAZ (CGHAZ) as documented in Figure 7. In addition to the intergranular cracking, extensive cavitated grain boundaries were also observed in the CGHAZ. The maximum weld deposit hardness was measured to be at the level of 300HV, indicating that either the welds had not been post-weld heat treated or that the temperature used for the PWHT was relatively low. SEM fractographic examination exhibited the intergranular fracture with cavitated grain boundary facets as exhibited in Figure 8. The distinctive microstructural features of the cracking, and the localized nature of the damage in an area where the welds were highly restrained by high crown-seal structure, suggested that this damage was the result of the reheat cracking.

Figure 6. Documenting the cracking observed along the root of the high crown-seal weld.

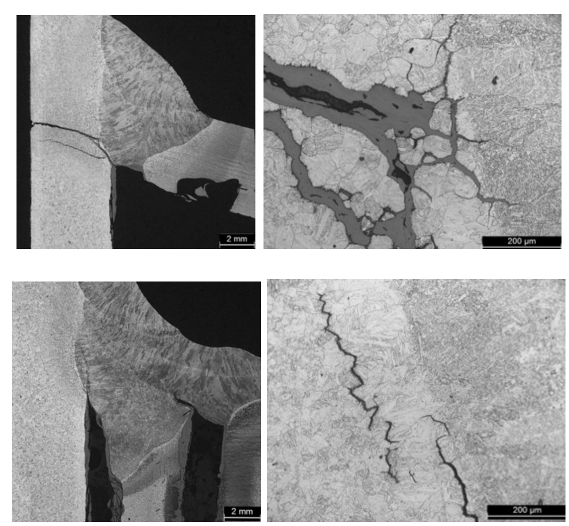

Figure 7. Documenting the metallographic features of cracking in the CGHAZ of crown-seal weld.

Reheat cracking is a unique type of creep damage that occurs in certain precipitation-strengthened alloys, such as Grade 23, due to rapid strengthening of intragranular structure either during heat-up to stress-relieving temperature or during operation. Intragranular structure is substantially strengthened due to formation of very fine precipitates at defect sites created during warm or cold working, resulting in concentration of all strain associated with stress relief

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into grain boundaries. In the as-welded condition, the CGHAZ region can contains a significant amount of precipitation-strengthening elements, such as V, Ti and Nb, are still in solid solution, and a considerable level of warm-working is also available in the CGHAZ associated with shrinkage during solidification of the weld deposit. when such welds are heated into an "unfavorable" temperature range, either during a sub-critical heat treatment (e.g., PWHT) or during elevated temperature service. Reheat cracking often occurs in the CGHAZ of welds due to its unique metallurgical condition. In general, three metallurgical factors influence the reheat cracking susceptibility of a steel:

- Susceptible chemistry: Grade 23 is known to be vulnerable to reheat cracking with the addition of W, V, Nb N and B. The degree of susceptibility varies significantly from heat to heat. The cleanness of the heat, such as Sn, Sb, As, Pb, Bi, S, and P contents, also has a significant effect on the reheat cracking behavior and susceptibility.

- Cold or warm work: The shrinkage stresses associated with solidification and cooling of weld metal provides sufficient "working" of weldment, especially in the CGHAZ, to result in high level of deformation to (i.e., high concentration of defects in) material substructure.

- High level of restraint: The high crown-seal arrangement induces high degree of restraint in the area of crown-seal weld, concentrating strain within weldment during stress relief attempts.

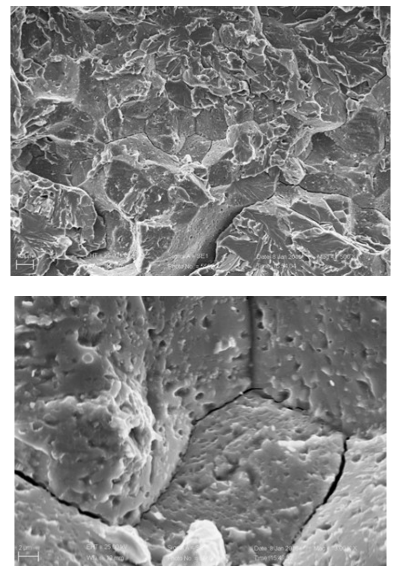

Figure 8. Documenting the SEM fractographic features of cracking in the CGHAZ of crown-seal weld.

In summary, there have been optimistic claims made for the Grade 23 alloy that it is virtually immune to such problems as stress-corrosion cracking and "cold" cracking due to the relatively low hardness that is developed in the bainitic/martensitic structure in the fully hardened condition. Recent field experience with the alloy, however, suggests that under certain conditions the material hardness can reach levels sufficiently high so that the material is vulnerable to both types of damage. As such, any attempt to weld or fully harden this material without the implementation of precautions that would minimize susceptibility to SCC or "cold" cracking should take into account the potentially adverse effects of a material hardness greater than 350HV and high levels of restraint or reaction loading on the alloy's crack sensitivity.

Grade 23 is known to be vulnerable to reheat cracking with the addition of W, V, Nb, N and B. The degree of susceptibility varies significantly from heat to heat. The failures of T23 components due to reheat cracking have been experienced during the component manufacture and during service. In the last two decades, there have been a number of failures in Grade 23 pressure parts attributed to reheat cracking. Unfortunately, there is no general remedy to reheat cracking, and the solution to the issue is always case-based. In addition to the effect of steel chemistry, weld joint design, welding parameters, weld sequence, filler meal selection, PWHT parameter and procedure, and component geometry and restraint all can have significant influence on reheat cracking behavior of Grade 23 welds.

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