Growing experience with P91/T91 forcing essential code changes

By Jeffrey F Henry, Alstom Power Inc and ASME Task Group

1. Grade 91 increasingly is being used in combined-cycle steam systems because of its greater resistance to thermal fatigue and enhanced creep strength compared to alternatives. However, manufacturers, constructors, and HRSG users often are unwittingly damaging the microstructure, and thereby degrading the material's mechanical properties

With today's combined-cycle powerplants operating at more demanding steam conditions and in more rigorous cycling duty than facilities built only a few years ago, designers increasingly are specifying creep-strength-enhanced ferritic steels—such as the modified 9Cr-1Mo alloy—for use in critical sections of the steam plant and heat-recovery steam generator (HRSG).

Use of the modified 9Cr-1Mo alloy, commonly referred to as Grade 91 ("P91" for piping and "T91" for tubing), for high-temperature applications can result in substantial reductions in component thickness compared to weaker alloys, such as Grade 22. The thinner wall produces substantially reduced thermal stresses and thereby improves service life.

Unfortunately, there is a lack of understanding of the significant differences in the handling of Grade 91 versus the low-alloy steels traditionally used in the power industry. This lack of understanding—which extends from the purchasers, through the manufacturers, to the constructors, and all the way to the plant owner/operators—is imposing substantial costs on the industry in terms of premature failure of components, excessive forced outages, and extensive rework.

In response, key sections of the ASME Boiler & Pressure Vessel Code currently are being revised to better define the proper heat treatment, chemical composition, contamination limits, cold working, and joint design of Grade 91, as well as other creep-strength-enhanced ferritic steels. It is imperative for all industry participants to understand and comply with the new code requirements as they are published. In addition, plant owners and operators need to substantially upgrade their current quality-assurance (QA) practices in order to detect

the problems known to exist with these materials.

Super material for superheaters

The frequent startups, shutdowns, and load changes imposed by cycling duty typically cause only minor trouble for a combined-cycle plant's gas turbine, but they pose very serious challenges to the HRSG. The most serious is thermal fatigue. Cycling causes rapid rates of change in steam temperatures, creating severe thermal gradients in thick-walled HRSG components—such as main steam piping and superheater headers. If the thermal gradients are large enough and are repeated a sufficient number of times, the result is thermal-fatigue cracking (Fig 1).

One effective way to fight thermal fatigue is to use higher-strength materials, such as Grade 91, which allow pressure-containing components to be made in thinner sections. Thinner components have smaller temperature gradients across the wall thickness and require less time to reach thermal equilibrium, thus they are less prone to thermal-fatigue damage.

Many existing plants are using, or planning to use, Grade 91 as a replacement material for failed components, and virtually all manufacturers now use the alloy for the superheater sections in new HRSGs. In addition to thermal fatigue induced by rapid changes in steam conditions, the superheater sections suffer creep damage because of the high metal temperatures at which they operate. Fortunately, Grade 91 also offers superior resistance to creep, compared to traditional low-alloy steels. For a typical superheater header, an upgrade from the traditional P22 alloy to P91 can:

- Reduce wall thickness by nearly two-thirds, and component weight by 60%.
- Raise allowable strength in the 950F-1100 F range by up to 150%.
- Raise the oxidation limit by 100 deg F, enabling a lower corrosion allowance.
- Increase thermal-fatigue life by a factor of 10 to 12.

Microstructure is key

Many in the industry are rightfully impressed with these mechanical properties, but they fail to grasp one fundamental principle: The superior properties of Grade 91 depend entirely on the creation, by heat treatment, of a precise condition of microstructure, and the maintenance of this microstructure throughout its service life. Specifically, the properties require the creation and maintenance of a tempered martensitic structure, which underpins the steel's high tensile strength at elevated temperatures and its high creep resistance (see sidebar).

Failure to obtain this precise microstructure during original steel production, or any subsequent action that alters the microstructure of the steel—such as the hot bending, forging, and welding that regularly occurs during component fabrication, plant construction, and steam-plant repairs—will seriously degrade the alloy's high-temperature properties. Making matters worse, particularly for end users, is the fact that this degradation in high-temperature properties is not always detectable with the standard QA tests.

This dependency on a precise microstructure represents a major difference from the traditional carbon and low-alloy steels that have for decades shaped the habits of the power industry. With traditional low-alloy steels—such as Grades 11 and 22—operating at the low stresses typical of power applications, the microstructure produced during processing was of only minor importance. In fact, for these materials it was found that a wide range of microstructures produced by both authorized and prohibited heat treatments would still provide satisfactory service.

The sensitivity of the Grade 91 microstructure recently was demonstrated at two combined-cycle plants in the Southeast. The owner detected several locations, in both bends and straight pipe, where material specified to be P91 was actually in the over-tempered condition rather than in the optimal tempered martensitic condition. In the over-tempered condition, this 9Cr material will exhibit a substantially higher creep rate at the plant's operating temperature of 1050F, and a much lower hardness value (<180 on the Vickers Hardness scale or HV, instead of the expected 200+ HV).

Significantly, this unacceptable material condition was discovered, not through the standard QA procedures conducted by the pipe fabricators or plant constructors, but only by special metallurgical replication ordered by a very concerned and vigilant owner. Subsequent investigation revealed that the post-bending tempering procedure had caused these sections of piping to cool far too slowly, with the inevitable result that the structure was over-tempered. Symptomatic of the industry's "business-as-usual" nonchalance toward Grade 91, the heat-treatment procedure used by the plants' contractor was similar to the one they had used for decades with P22.

"Code-compliant" is no guarantee

When users discover problems such as these, they're often surprised and frustrated because they specified compliance with the appropriate codes—ASME Boiler & Pressure Vessel Code Sections I and VIII for HRSG design, and ASME B31.1 for power piping systems. Being code-compliant, the users assume, should have prevented such problems. But this assumption represents a critical change in the perceived role of the ASME codes.

Throughout virtually all of its history, the sole purpose of ASME codes was to ensure safety—to prevent catastrophic failures and the resultant loss of life, injury, and property. Only in recent years have users come to view the codes as some sort of "design and construction handbook," in which they believe is distilled the essence of 100 years

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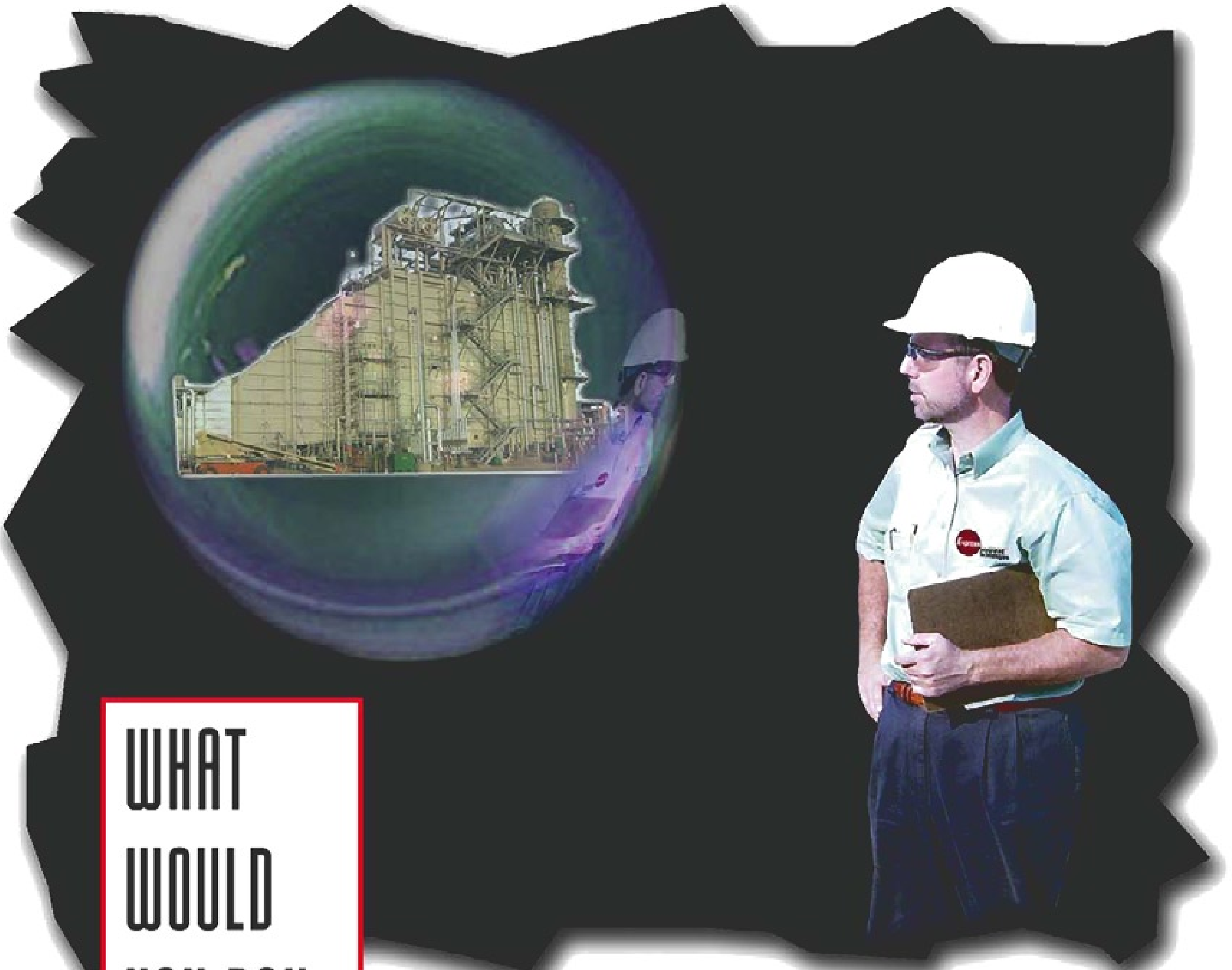


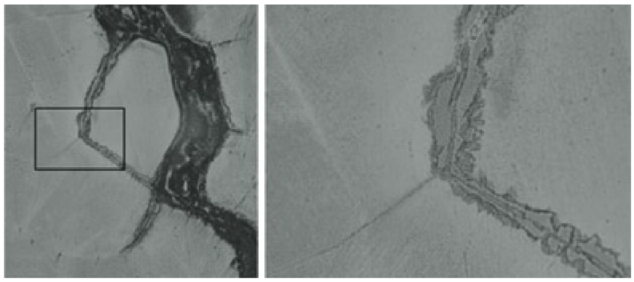
Metallurgy primer for P91/T91 users

To better understand Grade 91 alloy, and the procedures needed for its inspection and maintenance in the field, over 100 HRSG users, manufacturers, and consultants gathered in October 2003 for a Maintenance Workshop sponsored by the HRSG User's Group. The following metallurgy principles were discussed during the workshop by Jeff Henry, Alstom Power Inc, Chattanooga, and Ron Munson, Mechanical & Materials Engineering, Austin:

- **Production of Grade 91.** This advanced alloy is produced by first heating the 9Cr-1Mo material to approximately 100 deg F above its upper critical transformation temperature (AC_3) until it is fully austenitic. Next, the steel is cooled in air to below 400F, at which point the austenite is fully transformed into untempered martensite. This precise heating and cooling process, referred to as "normalizing," produces a structure that is very strong, but brittle. The material then is reheated—or "tempered"—at a temperature around 1400F to improve ductility and toughness, and to induce the formation of critical carbide and carbo-nitride precipitates. These strengthening precipitates form at the sites of crystalline defects, which had been produced during the martensite transformation.
- **Chemical composition.** The critical transformation temperatures for Grade 91—including AC_1, AC_3, and the martensite start and finish temperatures—can vary significantly depending on small changes in the material's chemical composition. For example, nickel and manganese—two common alloying elements—suppress the transformation temperatures. As a result the concentrations of these elements must be controlled when formulating weld-filler materials, and the precise amounts of the elements present in a Grade 91 component must be known so that the appropriate PWHT temperature range can be identified.
- **Creep.** Steel under stress at high temperature—such as power piping exposed to 1050F steam during steady-state operation—will experience plastic deformation, even when the stress level is lower than the steel's measured yield strength at temperature. This deformation is called creep. The rate at which a given material will creep will be governed by the stress and temperature to which the material is subjected.
- **Hardness is not an intrinsic material property** dictated by precise definitions, in terms of fundamental units of mass, length, and time. Instead, "hardness" is the result of a specific measurement method. For practical reasons, the available methods are divided into a range of scales, defined by a combination of applied load and indenter geometry. Commonly used hardness-test methods include the Rockwell Hardness Test, the Brinell Hardness Test, the Vickers Hardness Test, and the Moh's Hardness Test.
- **Stress-corrosion cracking.** The combined effects of stress and corrosion can result in a special type of failure known as stress-corrosion cracking (SCC). This arises under a particular set of circumstances for a given alloy. Although the specific conditions under which SCC will occur in Grade 91 have not been fully defined, it is known that the mechanism requires some combination of a susceptible microstructure, a high local tensile stress, and the introduction of contaminants. It appears that mere condensation from exposure to a moist atmosphere may allow sufficient contamination to produce SCC in Grade 91 components left in the untempered condition.
- **The "Type" of a crack** provides some idea of the relative location and orientation of the crack. For example, Type I cracks are oriented transverse or longitudinal, and are located in the weldment itself. A Type II crack is similar to a Type I crack, but it grows out of and extends beyond the weldment. A Type III crack is located in the coarse-grained heat-affected zone of a weld. Type IV cracking takes place in the fine-grained section on the base-metal side of the heat-affected zone. Grade 91 is classified as a "creep-strength-enhanced" ferritic steel, and like all ferritic steels, it remains susceptible to Type IV cracking.

Stress Engineering Services Inc

A. Metallurgical replication revealed the crack in this nozzle adjacent to the weld's heat-affected zone and through the base metal. Here, the actual metal surfaces are prepared non-destructively using grinding and polishing disks



Stress Engineering Services Inc

B. The microstructure of a suspect metal surface is revealed on a cellulose acetate film, or "replica." The replica can be studied at the plant to provide prompt results, or it can be sent to a lab for even more sophisticated evaluation using special microscopes

NDE techniques

Perhaps the most important "take-away" from the 2003 Maintenance Workshop on P91/T91 was the need to closely monitor these advanced materials throughout their service lives. To support this effort, the HRSG User's Group focused much of its next Maintenance Workshop on nondestructive evaluation (NDE) techniques that users can deploy.

NDE kit. James Yavelak, manager of fossil services,

Special from the HRSG User's Group

Aptech Engineering Services Inc, Sunnyvale, Calif, advised attendees of the 2004 workshop to use an "NDE kit" that comprises at least: a digital camera wielded by plant personnel; visual inspection by qualified inspectors; magnetic-particle and liquid-penetrant testing to identify cracking in tube-to-header weld joints and downcomer-to-evaporator distribution pipes; and ultrasonic (UT) tools to check tube, header, and riser-pipe wall thickness. Other items that might be appropriate for a plant's NDE kit, using subcontracted specialists, include radiography, eddy-current, and pulsed eddy-current tests.

For HRSG users, Yavelak conceded, there are limitations to NDE. For starters, HRSG access is tightly constrained, compared to conventional fossil boilers, so users may not be able to perform certain tests that would give the most insightful results. The presence of finned tubing poses another problem for HRSG users, because it severely limits the use of UT for tube-thickness measurement. For owners of P91/T91 components, there is yet another limitation: The common NDE tests typically will not detect the degradation in high-temperature properties to which this alloy is vulnerable.

Metallurgical replication. Fortunately, a less common method of non-destructive testing called "metallurgical replication" can help. The method, explains Leo Vega, associate metallurgical engineer, Stress Engineering Services Inc, Houston, examines the actual microstructure of a suspect metal surface. It can be used as a complement to standard NDE techniques—to confirm observations made by such methods as ultrasonic or penetrant testing—but it also can go much further to detect early stages of creep damage and cracking, and to identify the specific nature of a flaw.

The technique begins with abrasive preparation of the suspect metal surface using successively finer grits of grinding and polishing disks, followed by a final diamond-impregnated cloth (Fig A). A sampling procedure then records and preserves the topography of the metallographic specimen as a negative relief on a cellulose acetate film or replica.

Vega says that a portable microscope with up to 400X magnification can be used in the powerplant to study the prepared metal surfaces, as well as to confirm the quality of the replica. These results can be presented to plant personnel during the on-site visit, so the technique saves a lot of time during a shutdown. For even more sophisticated evaluation, the metallurgical replica can be sent to a laboratory to be studied with a light optical microscope or a scanning electron microscope (Fig B).

Replication provides the metallurgist with a two-dimensional view of the microstructure, similar to that observed in a laboratory metallographic specimen. Such microstructure details as grain size, grain orientation, carbides, and cracks are easily identifiable to the trained professional. In addition to piping failures, Vega has used metallurgical replication to detect the following: manufacturing flaws in reciprocating-engine cylinder heads; cracking in the heat-affected zone of a compressor wheel; thermal-fatigue failures in a turbocharger exhaust wheel; and very early signs of creep degradation in gas-turbine components.

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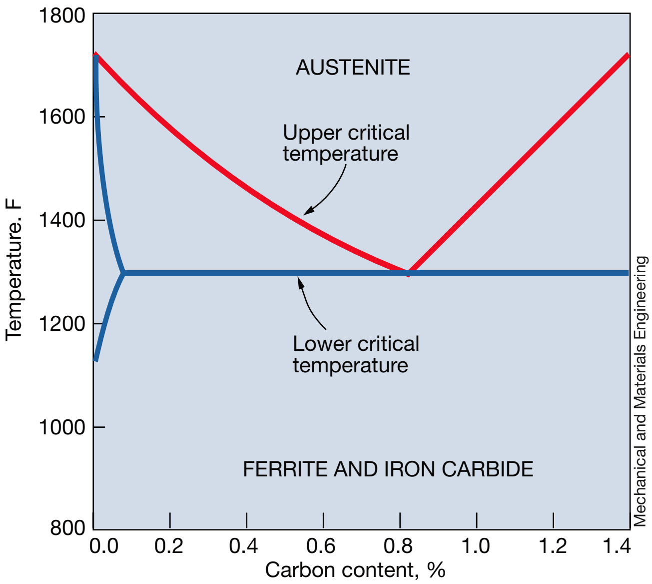
of experience in the fabrication and operation of equipment. As the codes currently are written, this expectation is not truly fulfilled for any powerplant materials, and certainly not for advanced materials like Grade 91.

Fortunately, responsible parties within the industry recognize the discrepancy between user expectations and ASME-code reality, and have begun to take action. The chairman of Section II (Materials) of the ASME Boiler & Pressure Vessel Code has convened a Task Group of leading specialists to address the unique problems posed by Grade 91, as well as the four other creep-strength-enhanced ferritic alloys that have been approved for code use to date.



2. Two important parameters for Grade 91 components are (1) the lower critical transformation temperature (AC_1), above which the alloy's phase transformation from martensite back into austenite begins, and (2) the upper critical transformation temperature, above which the phase transformation to austenite is complete

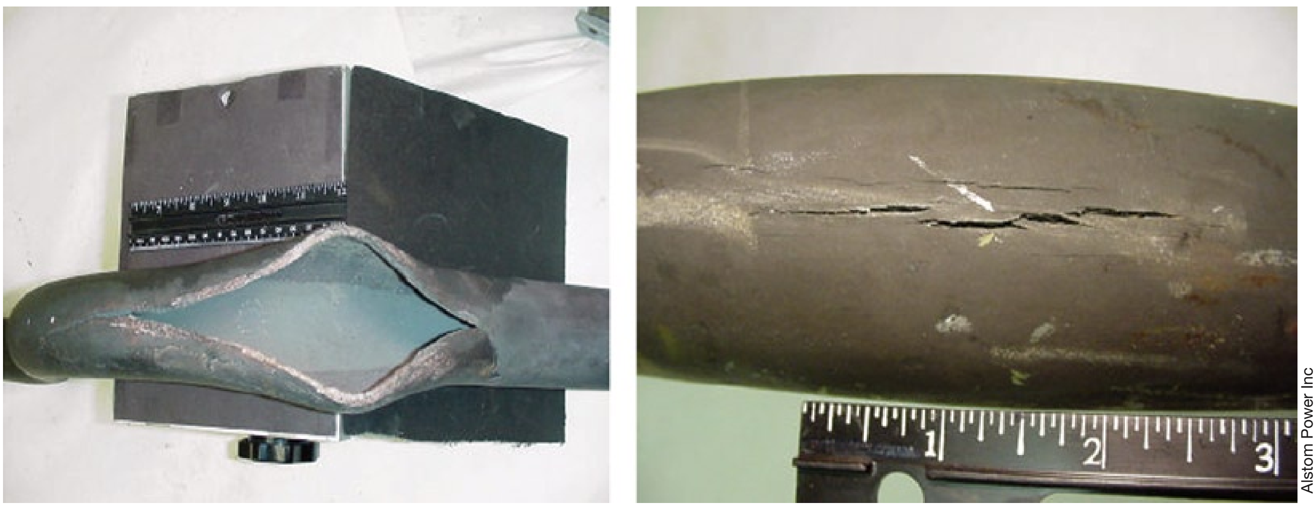
Thermal processing

A Task Group priority is to establish more rigorous rules for proper thermal processing of these materials. "Thermal processing" refers to any heating process that has the potential to alter the microstructure of the material. Problems that can significantly impair the creep-rupture strength of these alloys are over-tempering, under-tempering, and exposure to temperatures in the intercritical region.

Over-tempering causes a coarsening of critical precipitates, with a corresponding loss in creep-rupture strength because of the loss of the restraining influence of these precipitates. *Under-tempering* also can jeopardize the high-temperature properties, since the required precipitation does not go to completion, and the precipitates either are absent or are of insufficient size to stabilize the structure. Other complications associated with under-tempering—such as the risk of brittle fracture and stress-corrosion cracking—also must be considered.

Perhaps the most common problem with Grade 91 is post-production exposure to temperatures in the *intercritical* region—above the temperature where the tempered martensite begins to transform back into austenite (referred to as the lower critical transformation temperature or AC_1) and below the temperature where phase transformation is complete (the upper critical transformational temperature, AC_3). When Grade 91 is heated into this intercritical region, the material partially re-austenitizes, and the resulting structure will have substantially reduced creep-rupture strength (Fig 2). In the worst case, this material will have lower creep-rupture strength than that of traditional Grade 22.

It is this intercritical heating—rather than the over-tempering often cited in the literature—that



3. These superheater tubes fabricated from Grade 91 material failed after only four years of service in a conventional fossil-fired boiler. The lot of tubing from which they were fabricated had been exposed to improper intercritical heat treatment causes the substantial reduction in strength observed in the Type IV (refer to sidebar for definition) region of welds made using these alloys (Fig 3). In a Type IV failure, cracking takes place in the fine-grained section of the heat-affected zone of a weldment. There have been about a dozen such failures in P91/T91 components, mostly in the UK, where the alloy has been in service longer than in the US. These failures are a matter of significant concern because they have occurred at a relatively early stage in component life—20,000 to 40,000 hours—and at lower operating temperatures than the maximum design temperature of 1110F.

In response to these problems, the Task Group has made several recommendations for new rules governing the thermal processing of Grade 91. These recommendations, which are awaiting action by approving committees, include:

- Normalizing in a tightly defined temperature range of 1900F-1975F. The minimum temperature limit for normalizing will be established to insure complete re-solution of the most temper-resistant of the precipitates, while the maximum temperature limit will be imposed to minimize detrimental grain coarsening.
- Tempering in a tightly defined temperature range of 1350F-1470F. The minimum temperature limit for tempering will be established to ensure that sufficient precipitation is induced to stabilize the structure, and that a reasonable level of ductility is imparted to the material. The maximum temperature limit will be established to minimize the risk of the reduction in rupture strength that can occur when heating above AC_1.
- During the course of their work, the Task Group learned that some US manufacturers had adopted the practice of hot-bending thick-walled pipe at temperatures above AC_3, and then performing a local re-normalization and tempering of the bend area. Since this practice leaves a broad zone of material on either side of the heated area that has been intercritically heated, the Task Group has further recommended that if any component fabricated from Grade 91 is "locally" heated above 1470F, then either the entire component must be re-normalized and tempered, or the heated section must be removed from the component in its entirety, re-normalized and tempered, and then re-inserted into the component by whatever means is appropriate.

Post-weld heat treatment

The ASME Task Group also is studying specific changes to the post-weld heat treatment (PWHT) rules. Proper PWHT is essential in order to temper Grade 91 material and to eliminate the risk of stress-corrosion cracking (SCC). The rule changes are needed both because of the risk of tempering at too high a temperature and because recent studies have shown that certain alloying elements—principally nickel and manganese—alter the transformation characteristics of the materials.

The new recommendations, which recently were adopted by the ASME Boiler & Pressure Vessel Code, state that the maximum PWHT temperature for P-No. 5B, Group 2 materials will be 1425F, except as indicated below:

- If Ni + Mn < 1.5% but ≥ 1.0%, the maximum PWHT temperature is 1450F.
- If Ni + Mn < 1.0%, the maximum PWHT temperature will be 1470F.

The new rules also make some provision for microstructure recovery if these limits are exceeded during processing.

SCC in weldments

During the period when materials such as Grade 91 are left in the untempered or as-welded condition, they can be susceptible to the severe problem of SCC. Although case histories of this failure mechanism in Grade 91 are still rare and the specific conditions under which SCC will occur have not been fully defined, it is known that the mechanism requires some combination of a susceptible microstructure, a high local tensile stress, and the introduction of a contaminant. In fact, it appears that mere condensation from exposure to a moist atmosphere may concentrate sufficient contaminant under certain circumstances to produce SCC in P91 piping left in the as-welded condition.

While further study of this failure mechanism is still needed, the Task Group is concerned because current industry practice in both shop and field fabrication of P91 piping does not guard against this SCC risk. Batches of piping welds often are left in the as-welded condition for weeks, months, even up to a year where the welds are exposed to the elements, until a convenient number are ready for furnace or localized PWHT.

To eliminate the risk of SCC in P91, the Task Group is considering amendments to code rules to keep the weldment sufficiently hot to prevent condensation between the completion of welding and the initiation of PWHT. A disadvantage of this option, however, is that it might prevent users from performing the radiographic testing typically performed on welds prior to PWHT. Mandating a sufficiently dry environment, rather than an elevated temperature, may be an alternative way to eliminate SCC while still allowing pre-PWHT radiographic testing.

If hot or dry conditions cannot be assured, it would be prudent to limit the time between completion of welding and initiation of PWHT, to minimize the time that contaminants can enter the weldment. The risk of undetected SCC also can be minimized by inspecting the weldment via liquid-penetrant or magnetic-particle testing following completion of PWHT. Because SCC can initiate on both the inner- and outer-diameter, these nondestructive tests should be performed on all surfaces of the weldment.

Cold working

Recent studies have indicated that cold strain can adversely affect the creep-rupture strength of creep-strength-enhanced ferritic alloys. Even at low levels of cold strain, there is a discernable reduction in Grade 91's creep-rupture strength. Based on the results of the studies, the Task Group is considering action that will establish maximum limits for cold strain, above which it will be necessary to re-normalize and temper the full extent of the strained component. The likely maximum limit for cold strain, based on the available data, will be around 15% to 20% for Grade 91.

Proper joint design

Yet one more problem that has been experienced in the field is imprudent joining of Grade 91 materials to dissimilar alloys—typically to Grade 11, 22, or austenitic stainless steels. One plant owner in the US was forced to rework the welded connection between the main-steam piping and the steam-turbine stop valve—not on one, but on three of its 500-MW, F-class combined-cycle plants.

The oldest plant, which had fewer than 5000 service hours, found a through-wall crack 135 deg around the circumference of the weld, and 24.5 in. long, while the steam line was in service. The second oldest plant used liquid-penetrant testing to find a crack that was 20 deg around the joint but had not yet penetrated the wall. The youngest of the three plants could not detect a crack with liquid-penetrant testing, but replaced the weld anyway because its joint design was the same as that for the other two plants.

The failed weld connected an 18-in.-diameter P91 pipe with a wall thickness of 1.562 in. to a valve casing made of 1.25Cr-1Mo-0.2V with a wall thickness of 3.000 in. The filler selected was B3 (2.25Cr-1Mo) with no dimensional transition piece. An investigation confirmed that no codes were violated in the welding or PWHT procedures.

But the failure mechanism was determined to be initiation and propagation of the crack through the carbon-depleted zone that is an inevitable feature of welds joining materials of different chromium content. In other words, the joint design, with its lack of a dimensional transition piece between P91 and a dissimilar alloy, was entirely inappropriate and was guaranteed to fail prematurely, yet it did not violate existing code rules.

At all three plants, the joint was replaced with a P91 dimensional transition piece, which matched the pipe-wall thickness at one end and the valve nozzle at the other. The piece featured a P91-to-P91 weld at the thin end, and a P91 to 1.25Cr-1Mo-0.2V weld at the thick end using B9 filler. This new joint design placed the weakened but inevitable carbon-depleted zone in the thicker section of the joint where the stresses were lower and more favorably distributed.

During the root-cause analysis of this piping failure, investigators learned that many, if not all, P91 piping systems are installed without "cold spring." This common practice once again demonstrates the industry's "business-as-usual" approach toward Grade 91, because it is based on the faulty assumption that Grade 91, like traditional alloys, will relieve high-temperature steady-state stresses by creep relaxation during the early stages of operation.

In many cases, however, the high-temperature creep strength of the Grade 91 material is such that at normal operating temperatures the material will not "relax" sufficiently fast to relieve these stresses. This can lead to a condition of "elastic follow-up" in which the joint is subjected to a secondary stress that behaves like a primary stress. Thus, a better industry practice would be to install P91 piping with cold spring, so that the piping system is not stressed when at elevated temperatures, where accelerated creep damage will occur.

QA testing

To determine whether the processing of creep-strength-enhanced ferritic steels has been performed correctly, users need tools that can quickly and inexpensively provide information on the overall condition of the material. Because hardness provides a direct indication of a material's room-temperature tensile strength, which can be used to roughly estimate its elevated-temperature properties, portable hardness testing has been used as one such tool.

However, this has created significant problems because of a lack of understanding of the variables that can affect the accuracy of hardness readings. For example, there are several types of portable hardness testers available that operate on entirely different principles, each of which exhibits certain peculiarities that are capable of influencing the accuracy of the measurements relative to testing with a laboratory instrument. In addition, the condition of the work piece itself can create considerable difficulty in accurately assessing the hardness.

For example, it is not uncommon for the surfaces of tubing and piping to be decarburized to varying degrees as a result of mill heat treatments. If the decarburized layer is not completely removed prior to testing, the hardness measured will be reduced by some amount corresponding to the depth of the layer affected and the depletion of the carbon.

One possible action that could be taken would be to identify a recommended hardness range for each grade that would be considered acceptable for all applications, with the stipulation that hardness readings outside of that range would require evaluation to determine (1) accuracy of the measurement and (2) fitness for service. It also should be emphasized that, for Grade 91 material that has been heated into the intercritical temperature range, the hardness may not be adequate to indicate damage, since the re-formed martensite can mask the effects of the undesirable heat treatment. CCJ

P91/T91 Technical Workshop 2005

Grade 91 Code Revisions

The ASME Boiler & Pressure Vessel Code is being changed substantially as it pertains to P91/T91 materials, based on recent problems identified in the combined-cycle industry and the results of new studies. The revised rules will specify the proper heat treatment, chemical composition, contamination limits, cold working, and joint design of this strong but easily degraded alloy.

All members of the power plant community—from the purchasers, through the manufacturers, to the constructors, the pipe fabricators, the outage-service contractors, and all the way to the plant owners and operators—need to understand and comply with these new rules.

To communicate these code changes to the power industry as they are made available, the HRSG User's Group will host a special Technical Workshop in the summer of 2005. If you deal with P91 piping or T91 tubing—whether in a combined-cycle, a fossil-boiler, or a nuclear plant—then this meeting is a MUST-ATTEND!

For details on agenda, location, and dates, visit www.HRSGusers.org, send an e-mail request to info@HRSGusers.org, or call 406-582-8655.

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