Welding “Grade 91” Alloy Steel

A material that has become commonplace over the last 20 year through the piping and boiler industry is an alloy that is referred to in various specifications as “T-91, “P-91, “F-91” and “Grade 91.” This is a specially modified and heat-treated 9% chromium, 1% Molybdenum, Vanadium enhanced (9Cr-1MoV) steel that performs quite well at elevated temperature – 1050°F and higher. It was first used in the mid-1980s and has “picked up steam” since then. If you are going to weld or fabricate Grade 91 alloys, beware! These are not your father’s chrome-moly steels!

Development of Grade 91 began in 1978 by Oak Ridge National Labs for the breeder reactor and further developed by other researchers since then. Other grades such as grade 92, 23, 24, 911 and others are also under development, and the guidelines in this paper should be followed for those materials until the industry gains experience that may dictate other practices. This class of materials even has it’s own name: “Creep Strength Enhanced Ferritic Steels (CSEFS). CSEFS are a family of ferritic steels whose creep temperature strength is enhanced by the creation of a precise condition of microstructure, specifically martensite or bainite, which is stabilized during tempering by controlled precipitation of temper-resistant carbides, carbo-nitrides, or other stable and/or meta-stable phases.

Since P/T-91 is modified with vanadium, nickel, aluminum, niobium and nitrogen, it develops very high hardness. Tramp residual elements in this steel, such as phosphorous, sulfur, lead, tin, copper, antimony and other elements will segregate to the grain boundaries during solidification of the weld, and, since the weld metal is very hard, it will crack quite easily. It is, therefore, very important to use low residual filler metal.

For SMAW, E9015-B9 electrodes are preferred. EXX15 type electrodes have no extra iron powder in the coating like EXX18 electrodes, eliminating one source of contaminants. While electrode manufacturers have recently improved awareness of the need to make clean E9018-B9 electrodes, if you occasionally get crater cracks (also known as “solidification anomalies” and “rogue weld metal’), the filler is not low in residuals and you should send it back (or at least get some good stuff). Look carefully for crater cracks, and keep in mind that one batch of electrodes from a manufacturer may crack and another batch not crack. Keep an eye on it. Two trade names of electrodes and filler that have low residuals are Metrode Chromet 9B9 electrode and Euroweld ER90S-B9. The wire is suitable for GTAW, GMAW and SAW (with a suitable flux, such as Lincoln MIL800H, Lincoln 882, Thyssen Marathon 543, Bavaria-Schweisstechnik WP380. Welding Grade 91 using FCAW requires even a little more care since some FCAW wires do not provide adequate toughness at 70°F (the lowest hydrostatic test temperature permitted by ASME); Metrode’s Supercore F91 does exhibit good toughness at 70°F, as do many other. The above electrodes and filler metals are available from stock at Euroweld at 1-704-662-3993 or www.euroweld.com.

The performance of Grade 91 welds depends entirely on having the correct chemical analysis and microstructure in the weld metal; therefore, electrodes and filler metals should always be purchased with *test reports* showing *actual chemical analysis* for the specific heat/lot combination that one has purchased. In addition, a minimum carbon content of 0.09%, a minimum niobium content of 0.03%, and a minimum nitrogen of 0.02% should be specified to ensure adequate creep strength in the weld metal. A slightly lower niobium level can be accepted with flux cored wire if titanium is added; titanium is an effective substitute for niobium, but the titanium should not exceed 0.010% since titanium will also combine with nitrogen, reducing nitrogen’s effectiveness as a creep strength enhancer.) In addition, the sum of Mn + Ni should not exceed 1.5%. Manganese and nickel depress the lower transformation temperature, and when this sum exceeds 1.5%, the lower transformation temperature drops to around 1450ºF, narrowing the range in which heat treatment can be done without damaging the creep properties of the weld. In addition, the Martensite finish (Mf) temperature also goes down when the Ni+Mn goes over 1.5%, increasing the possibility of retained austenite after PWHT. Risk of damaging the weld during PWHT is minimized when the Ni+Mn is less than 1.05%

When using SAW, a basic flux is preferred since other flux types will burn out carbon and permit elevated oxygen and nitrogen levels reducing the strength and toughness of the weld metal.

Since this is a highly-hardenable alloy, it is subject to hydrogen cracking. Purchase of E9015-B9-H4 electrode is recommended. The "H4" designation indicates that the electrode exhibits less than 4 ml of hydrogen per 100 grams of weld metal. This is truly a very low hydrogen electrode – exactly what is best for welding highly-hardenable steel like Grade 91. Even with diffusible hydrogen control of the electrodes, it is recommended that the electrodes be stored in heated portable rod boxes at the welding location rather than just distributed in the normal fashion. SAW wire/flux combinations and FCAW wire should be ordered with "-H4" (or "-H5" for European specification products) designations also, although FCAW wire may not be available except as H-8.

Preheat and interpass temperature are very important. A range of 400 to 550°F is recommended, After welding is completed, the joint should be allowed to cool slowly to at least 200°F after welding is completed to be sure that all the austenite has been transformed to martensite prior to postweld heat treatment (PWHT). If this is not done, there is risk of martensite formation after PWHT; this will result in hard, brittle welds. For the metallurgists out there, the M_f temperature is above 212°F, varying some with the grain size. This problem largely goes away when the weld metal Mn+Ni is less than 1.0%

When using welded lugs (dogs) for alignment, preheating should also be used, and any jacking or wedging to achieve alignment should be done while the parts are still warm, if possible. If alignment lugs are left in the as-welded condition and moisture condenses on the lug, there is some risk of stress-corrosion cracking of the HAZs particularly if the lugs are stressed while cold and damp. See the discussion of SCC below. The safest procedure to follow when using welded alignment lugs is to preheat the pipe, attach the lugs, do whatever jacking or wedging is needed to get alignment, make the tack welds (making them large enough to not crack after the lugs are removed) and remove the lugs and grind the surfaces flat – all while the pipe is still hot. Finally, after the lugs are removed and the pipe has been allowed to cool to room temperature, the lug weld areas should be examined using magnetic particle examination. Obviously, the filler metal used should be B9 electrode, and the lug weld areas should be included in the heated band when the weld is heat treated.

The welding technique is also important. Since a wide, flat bead is best, a slight weave technique is preferred. Ropy beads are bad since tall, narrow beads tend to crack. Concave beads should also be avoided, particularly with SAW. Bead thickness should not exceed 1/8 in. for SMAW and FCAW to promote tempering of previous passes. These conditions of welding should specified in the WPS to provide correct guidance to welders, not to give them a hard time. Be sure that your welders have been trained regarding these special requirements and that they comply with them.

Finally, postweld heat treatment is mandatory for Grade 91 steels, regardless of what construction codes may permit. The holding range should be 1375 to 1425°F for a minimum of 2 hours. Even on small superheater tubes, a long time at temperature PWHT temperature is necessary to form the required weld structure, to ensure adequate toughness during hydrostatic testing and to ensure adequate service life. The lower transformation temperature can be as low as 1450°F if the Ni+Mn is near 1.5% and 1470°F when the Ni+Mn is less than 1.05%; if these temperatures are reached during PWHT, the weld should be allowed to cool to below 200°F and the condition of the joints should be evaluated by hardness testing.

Refer to AWS D10.10, *Recommended Practice for Local Heating of Welds in Piping and Tubing*, for excellent direction on locating and attachment of thermocouples, the extent of insulation needed, heating coils arrangement, etc. if local heating (preheat, postweld baking, PWHT, etc) is going to be done.

It should be noted that the Codes specify an upper temperature limit of 1425°F (775°C) for PWHT of Grade 91 type materials. If this temperature is exceeded (as sometimes may happen due to errant thermocouples, power surge or temporary insanity by the operator), the effect on Grade 91 type materials is dramatic and warrants evaluation. For most materials, including your father's Cr-Mo steels, excursions above the lower transformation temperature have little consequence since the material properties return to practically their original condition when the material cools down from such an excursion. The worst case scenario for the old Cr-Mo steels -- the WPS might have to be requalified since the lower transformation temperature was exceeded. However, high-performance Cr-Mo steels develop their properties via normalizing and tempering; this results in the precipitation of the carbides that give these materials their superior elevated-temperature performance characteristics. If the lower transformation temperature is exceeded (depending on the chemical makup of the alloy, it can be as low as 1450°F), the carbide matrix is destroyed and the material loses its elevated temperature strength. Since it is not possible to reform the normalized and tempered microstructure using local heating (there is always a temperature gradient beyond the band that is being normalized that contains damaged material), it is necessary to cut out and replace the weld joint, including a minimum of 3 inches of base metal on each side of the joint that was overheated. Alternative solutions include normalizing and tempering of the entire assembly and justifying use of the weld based on properties of the material in the annealed condition (e.g., using the allowable stress values for Grade 9 instead of those for Grade 91 for the joint and surrounding material). Good luck on getting an engineer to agree to the latter. Note that what is permitted when Grade 91 is overheated during PWHT is specified in precise detail and consistent with the above in both ASME Section I, PG-5.6 and in Table PW-39-5 and also in B31.1, Table 132 notes for P-number 15E materials.

When joining the high-chromium alloys to lower-chromium alloys or carbon steel, carbon in the lower-chromium steels will migrate to the higher-chromium steel during PWHT. This will result in a soft zone in the lower chromium steel. Accordingly, the filler metal to weld with can match either side, and the selection will determine which side of the weld metal the carbon diffuses to, but it makes little difference in performance of the weld. The higher the PWHT temperature and the longer the joint is held at PWHT temperature, the more diffusion occurs and the bigger the soft zone becomes. While the minimum PWHT temperature for welds involving Grade 91 welded to itself have been increased over the last few years, the PHWT temperature for dissimilar joints remains at 1300°F (705°C) to minimize this undesirable effect. To minimize the size of the soft zone, do not heat treat dissimilar metal joints at temperatures much over minimum, and don't hold them at temperature longer than is required by the applicable Code. Recently introduced is EPRI P87 electrode for joining P-91 to stainless steel and nickel alloys; this alloy eliminates the issue of carbon migration by having a sufficiently high carbon content.

After PWHT, the weld hardness should be in the range of 190 to 275 Brinnell. Hardness up to 300 Brinnell may be accepted, but any hardness over 300 is an indication of inadequate PWHT. SMAW and SAW weld metal will typically exhibit higher hardness when compared to GTAW and FCAW. Hardness below 175 indicates overheating of the joint or other incorrect heat treatment, and such joints should metallographically evaluated; if a mixed microstructure is found be replaced or the part should be normalized and tempered.

Do not perform hardness tests that will leave deep impressions in the surface of thin tubes. When performing hardness tests, it is important to prepare the surface properly. Since the base metal may have a layer of decaraburization on the surface, about 1/32 inch of metal should be removed by grinding, and that should be followed by polishing to a 120 grit finish. This preparation will also make readings more consistent and should also be followed when measuring the hardness of the weld metal.

Grade 91 can be hot bent using furnace heating or induction heating between 1600 and 2000°F, but the low end of this range is preferred. Pipes that are hot bent should be given a full-furnace normalizing heat treatment at 1900 to 1950°F for 30 minutes per inch of wall thickness, air cooled to below 200°F and tempered in the PWHT range of 1375 to 1425°F for 1 hour per inch of thickness. Cold bent pipe should be given a stress-relieving heat treatment at the above tempering temperature if the strain exceeds 5%. If the strain exceeds 20%, the bend should be normalized and tempered if the design temperature exceeds 1200°F (540°C).

Another strange phenomenon with Grade 91 is that it is subject to stress-corrosion cracking in the as-welded condition. The media that causes this has not been identified as yet, and it does not happen for several days after the weld has cooled to ambient, but it does happen. It also appears to occur if the joint is allowed to get damp, such as might occur if the part gets cold and moisture condenses on it; keeping joints that have not been given PWHT warm and dry seems to preclude this cracking. Of specific concern is shop-fabricated pipe which may get moved around in a shop for a few days before heat treatment. With Grade 91, heat treat welds as soon as practical after welding. Contamination with sulfur-bearing compounds (cutting fluids, lubricants, markers, air condensation, bird droppings, etc.) will cause transgranular cracking, so they should not be used around Grade 91 in the as-welded condition.

Hot bend pipe *must* be renormalized and tempered since hot bending destroys the structure that gives Grade 91 its enhanced creep properties. Cooling rates after hot bending are typically too slow to achieve a uniform martensitic microstructure, or, when induction heating is used, there is a temperature gradient that contains sections of pipe that are overtempered. The same thing happens if one performs local normalizing and tempering of a bend. Normalize and temper any hot bends, and that includes the entire assembly, not just the bend area.

Local heating (such as during square-up) using a rosebud or other heating torch is acceptable, but the temperature must be monitored and not ever allowed to exceed 1300ºF in order to stay below the lower transformation temperature and out of danger of overtempering the pipe. Such heating should be limited to making small changes in dimensions; if large changes are needed, pipe should be cut and rewelded.

Cold deformation (such as occurs during cold bending) should be limited to not more than 10% strain in the metal, and if this limit is exceeded, the part should be renormalized and tempered. The strain formula is % strain = 100 r/R where R is the radius of the bend and r is the radius of the pipe.

For dissimilar metal welds between Grade 91 and lower chrome-moly steels, use filler metals that match either the lower chromium grade or the Grade 91. A large difference in chromium causes a gradient that pulls carbon out of the lower-chromium steel causing a depleted carbon band in the lower-chromium side of the joint and a higher-carbon band in the Grade 91 side of the joint. This happens during welding and cannot be avoided; however, has been shown to have no significant effect on creep behavior when heat treatment time and temperature are not excessive. The width of the band can be increased by excessively high or long PWHT temperatures, so PHWT should be done following typical requirements for the lower-chromium steel rather than those of the Grade 91. Use regular carbon grade filler metal, not low carbon grades.

For welds to austenitic stainless, use nickel-based filler metals ENiCrFe-2, ENiCrFe-3 or ERNiCr-3. If the stainless is a stabilized grade or a low-carbon grade, the completed joint can be given standard PWHT. If the stainless is not a stabilized or low-carbon grade, the P/T-91 side of the joint should be buttered with at least 1/4" of nickel-alloy weld metal and heat treated in the normal fashion. The buttered and heat treated end can then be welded to the stainless steel using nickel alloy filler metal without preheat or PWHT. Don't even think of welding nickel overlay with stainless -- the weld metal will be fully austenitic and crack.

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Preheating to 300°F is recommended when thermal cutting or using carbon or plasma arc gouging.

A NOTE OF CAUTION: When performing hydrostatic testing, there is always danger of brittle failure due to the presence of flaws and inadequate toughness of the metal. Weld metal can be somewhat unpredictable in toughness due to variations in welding techniques by different welders and the possibility of weld discontinuities. Accordingly, Grade 91 should be hydrostatically tested at 70°F (19°C) or higher to be sure that the weld metal is above 15 ft-lbs or 15 mils lateral expansion. This is usually adequate toughness to ensure failure by leak-before-break rather than brittle failure.

For more information about P/T91 metals and also T-23 and T24 metals, convenient (and free to likely customers) reference books are available from:

V&M Tubes Corporation (Vallourec & Mannesmann)
1990 Post Oak Boulevard, Suite 1400
Houston, TX 77056
713-479-3200
FAX 713-479-3202
e-mail: ken.brown@vmtubes.com

References

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