Optimizing the fabrication sequence for composite-to-carbon steel field welds in recovery boiler tubing

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Four welding and inspection sequences used for joining composite tubes to carbon steel tubes were evaluated for advantages and limitations. One design was superior to all others.

The trend in the last two decades of using composite tubing in the lower furnace section of recovery boilers has dramatically increased the number of composite tube welds that have been made. Boiler bottom replacement with composite tubes usually requires 300–600 composite-to-carbon steel tube butt-welds. There are two major types of composite tube butt-welds in recovery boilers, one joining composite tubing to itself and the other joining composite and carbon steel tubing. This paper concentrates on the composite-to-carbon steel joints made in the field because these welds have the most direct influence on the downtime required to replace the bottom of a recovery boiler or to install a significant number of composite tubes.

A simple and efficient welding and inspection sequence (WAIS), using "fabrication friendly" processes, is essential to minimize downtime while welding and inspecting these joints, especially in light of the thorough radiographic examination given to every weld. Furthermore, it is best to perform time and quality intensive operations in the shop to improve field fabrication efficiency. Thus, more sophisticated joint preparation can be done in the shop to simplify subsequent field procedures.

The overall goals of the WAIS development effort for wall tube butt-welds were to:

- Minimize the total amount of welding required (i.e., weld volume and number of weld repairs)
- Minimize the number of welding processes and electrodes or filler metals
- Minimize the time for and maximize the effectiveness of weld inspection
- Optimize the metallurgical nature of the weld
- Maximize weld quality and minimize reject rate by making the WAIS "fabrication friendly."

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Weld joints where carbon steel and stainless steel both may be mixed in the molten weld metal result in a dissimilar metal weld. This occurs either when stainless weld metal is diluted with carbon steel or when carbon steel weld metal is diluted with stainless steel. This raises a number of concerns regarding the range and the control of chemical composition in the solidified weld. The range in chemical compositions is of concern because the metallurgical, physical, and mechanical properties of mixed carbon-stainless welds can increase the potential for in-service problems (mechanical, thermal, corrosion, etc.).

These problems usually are minimized by controlling weld chemistry through the essential welding variables such as welding process, joint detail, consumables, etc. However, because it is also important in recovery boiler tube butt-welds to get these field welds made as defect-free and as rapidly as possible, identification of a production optimized WAIS is essential.

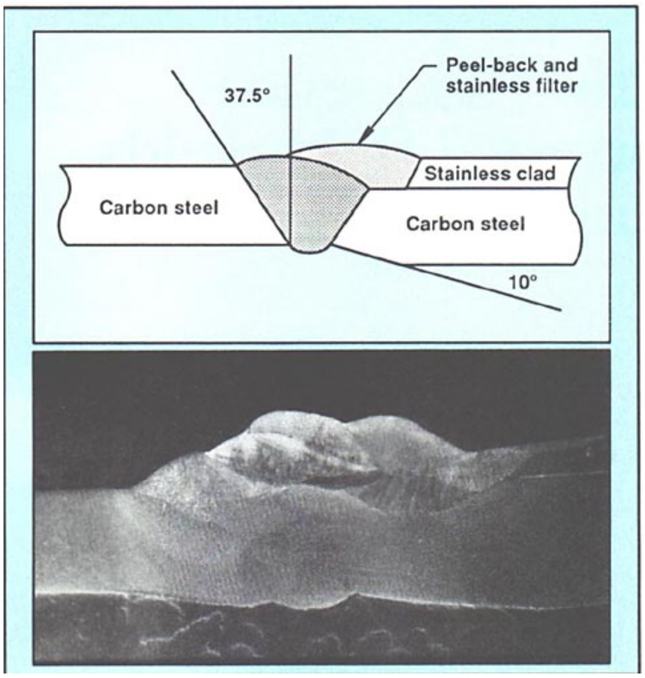
Whichever type of field-weld joint design is used, the joint detail also depends on the respective diameters and thicknesses of the tubes to be jointed. For replacement of the bottom of an existing boiler, the dimensions of the carbon steel tubing at the cut line are predetermined, and the actual tube-wall thicknesses should be measured by ultrasonic testing to ensure proper joint design. The joint detail should not require extensive fit-up because that makes it more difficult to complete the WAIS in a timely fashion.

Original joint designs and WAIS

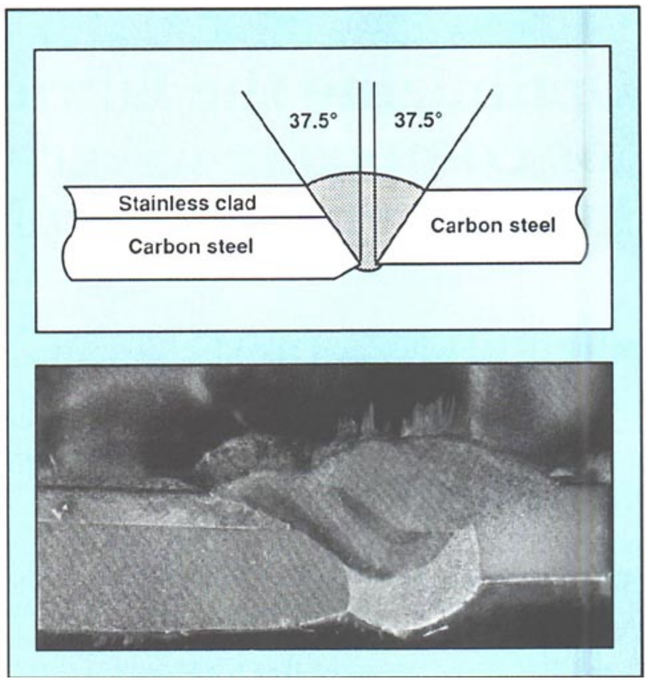
Type I: peel-back and stainless overlay

One original, composite-to-carbon steel, butt-weld joint design (here called Type I) is shown in **Fig. 1**. This "peel-back and overlay" design was provided by boiler manufacturers and used by Champion in boiler bottom replacements up to 1989. Joint preparation included a conventional peel back of the stainless cladding to avoid dissolving any of it into the carbon steel weld metal.

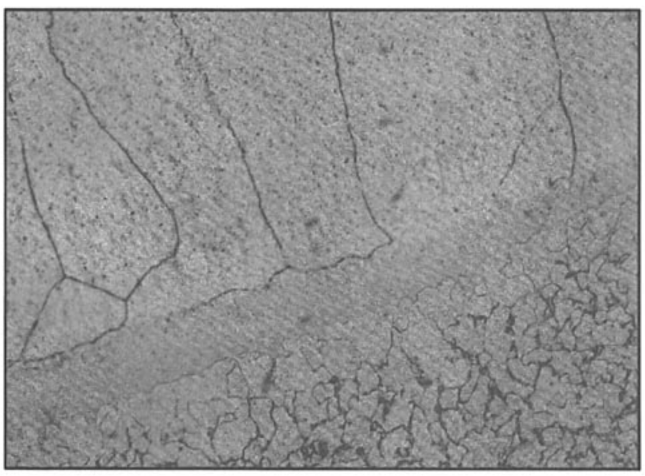
1. Type I WAIS. Note peel-back and I.D. mismatch on preparation and stainless penetration and inhomogeneous dilution revealed by differential etching (photo 3X).



3. Type II WAIS. Note lack of peel-back and all carbon steel filler, as well as inhomogeneous dilution of the carbon steel weld with stainless cladding as revealed by differential etching (photo 3X).



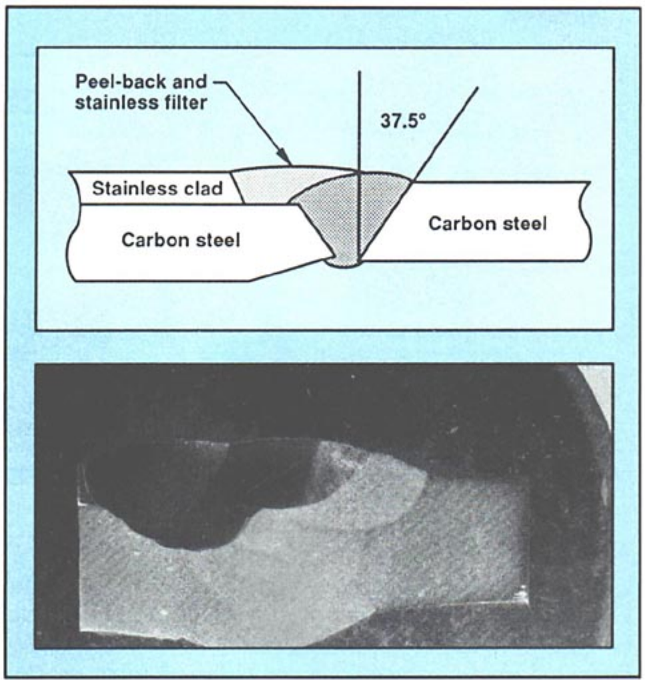
2. Fusion line between stainless weld and carbon steel shows a thin, hard, unmixed zone of carbon steel when a Type I design is used (400X).



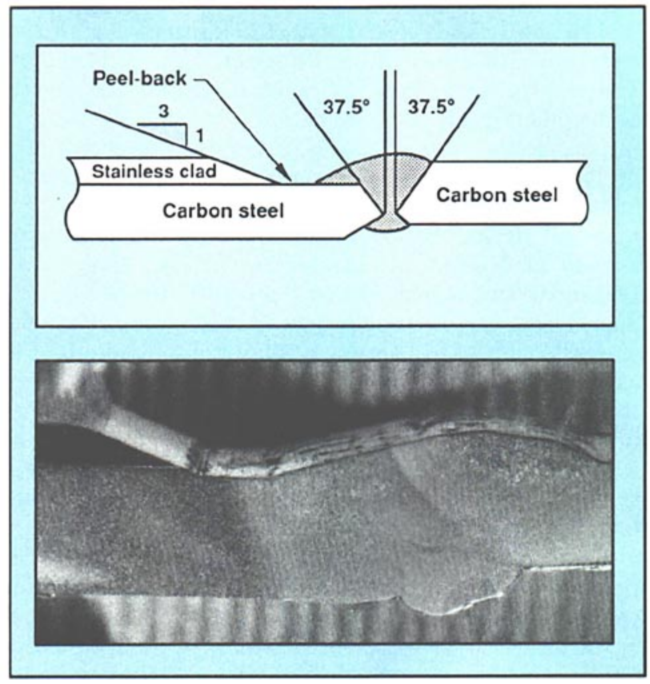
4. A Type II metallographic specimen has hard martensite structure (42 R_c) in the fusion zone next to the stainless cladding (400X).

Welding was done in a conventional manner, with carbon steel root and hot passes made by the gas tungsten arc welding (GTAW) process. Shielded metal arc welding (SMAW) was used for the carbon steel fill passes and the stainless steel half-cap overlay. Carbon steel was the filler metal used on the root and hot passes; E-7018 and E-309L electrodes were used for the fill and overlay passes, respectively. However, because composite-to-carbon steel tube welds do not need to be more corrosion resistant than the immediately adjacent carbon steel tubing, overlaying these welds with stainless steel seemed unnecessary. In addition, quality control problems were encountered with meeting minimum design wall thicknesses with this weld detail because it was difficult to keep the 10° tapered, internal joint preparation concentric.

Quality control for field welding this joint is excessively complicated due to the use of three different welding rods, two of which require moisture control with ovens. Furthermore, since weld inspection is done first by radiographic testing (RT) on the carbon steel portion of the weld and then by penetrant testing after the stainless steel overlay is completed, extra time is needed for inspections, communication, repair, etc. Metallographic examination revealed a hard, unmixed zone between the stainless overlay and carbon steel base metal (**Fig. 2**), as reported by others (30-40 R_C) (*1*). These factors provided a strong incentive for eliminating the stainless steel



5. Type III WAIS. Note peel-back and better I.D. matchup as well as depth of stainless penetration and inhomogeneous dilution of the stainless weld.



6. Type IV WAIS. Note extended peel-back, more sophisticated joint preparation, and undiluted carbon steel weld (photo 3X).

overlay to save substantial field time and to look for a better joint design and WAIS than this original, complicated type.

Type II: no peel-back, all carbon steel

An alternative, original, composite-to-carbon steel tube butt-weld design used by one boiler manufacturer is shown in **Fig. 3**. We call it Type II. It is simpler than Type I because it uses only carbon steel as filler metal for the complete weld even though the stainless clad layer is not peeled back (not conventional) (*2*).

Root and hot-pass welding were done with GTAW with carbon steel filler; the remaining passes were made with the SMAW process using E-7018 A-1 electrodes. There is no stainless overlay, so this joint is more easily repaired and is examined only once, by RT after all welding is completed.

However, because some carbon steel weld capping passes are diluted with the stainless steel clad layer, this weld design has raised concerns about the metallurgical properties and increased potential for problems in this area. Metallographic examination of a typical weld sample revealed partially mixed zones of stainless and carbon steel in the capping passes (Fig. 3). Higher magnification showed zones of martensite in the capping passes (**Fig. 4**) where dilution of the carbon steel weld occurred, and microhardness testing showed values up to 42R_C in these martensitic areas. However, the heat affected zone of the weld showed lower, normal hardnesses.

Despite reports by the manufacturer of many years of satisfactory industry experience with such welds, we remain concerned about the undesirable metallurgical structures in some zones of these welds. Also, additional welding is required in this Type II joint design to give the completed weld the appropriate profile. This would not be necessary if the stainless clad layer was peeled back a short distance from the joint.

Type III: carbon steel safe-end

Shop welding of carbon steel safe-ends on composite tubes is another way of simplifying the WAIS for field fabrication (*1, 3*). This technique offers improved control of the transition in wall thickness and diameter and metallurgy between the composite and carbon steel tubing and is a classical way of eradicating dissimilar metal field welding. End preparation has a slight peel-back of the stainless (**Fig. 5**), and welding usually is done with an automatic orbital GTAW process with carbon steel filler metal for the root, hot, and fill passes, and stainless steel for the overlap cap passes.

Safe ends are attached in the shop on loose tubes before membrane welding. Because safe-end welding is automated, it usually has a low reject rate and provides better control of chemical and metallurgical aspects (*1*). This alternative adds one more shop butt-weld to each tube length, resulting in a cost increase and more boiler tube welds to worry about, even though they have been RT inspected. Although the use of automatic welding equipment provides better control of the welding, the fusion zone of the stainless overlay to carbon steel weld metal has hardened martensitic areas (35–43 R_C) similar to those described for the Type I joint design.

Current joint design and WAIS: Type IV

The numerous advantages and disadvantages described above led us to develop the joint design shown in **Fig. 6**, which we call Type IV. This "extended peel-back, all carbon steel" weld joint has more extensive peel-back of the stainless steel layer and a more gradual taper in the transition area of the clad layer. The primary appeal of this joint design is that it makes the composite-to-carbon steel field welds just like conventional carbon steel-to-carbon steel field welds, without concerns for mixed metallurgy (inhomogeneous dilution) of the weld metal. The WAIS for a Type IV joint meets all the WAIS development goals listed earlier.

Because the wall thickness of the carbon steel in the peeled-back portion of the composite tube is not subsequently overlaid, its thickness there must be sufficient to meet all design requirements, such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section I pressure design, plus an appropriate corrosion allowance. A machining tolerance of ± 0.25 mm (0.010 in.) is typically obtainable for the carbon steel wall thickness in the peeled-back portion of the tube. The stainless cladding edge is machined to a 3:1 taper to lessen stress concentration and to allow easy visual inspection of the transition from carbon steel to stainless steel. The internal surface of the composite tube end can be (usually is) tapered to accommodate I.D. mismatch. It also is important to verify by actual RT test that the weld preparation details do not produce a finished weld joint geometry that produces spurious RT indications.

We prefer to have the entire weld (root, hot pass, fill, and cap) made using the GTAW process because it usually produces a higher quality weld with fewer rejects. Using only one process reduces the number of power supplies and leads, although care should be taken to avoid pinching of shielding gas lines. Control of consumables is simplified since only one filler metal is required for GTAW welding, and electrode moisture control (rod ovens) is not necessary.

This WAIS allows the field welds to be made with less welding (i.e., smaller weld size) and only requires RT inspection once the weld is complete. Weld repairs are conventional and made with the same procedure used for original welding. The all-carbon steel weld and HAZ microstructure contains no unusual or hard metallurgical phases or zones.

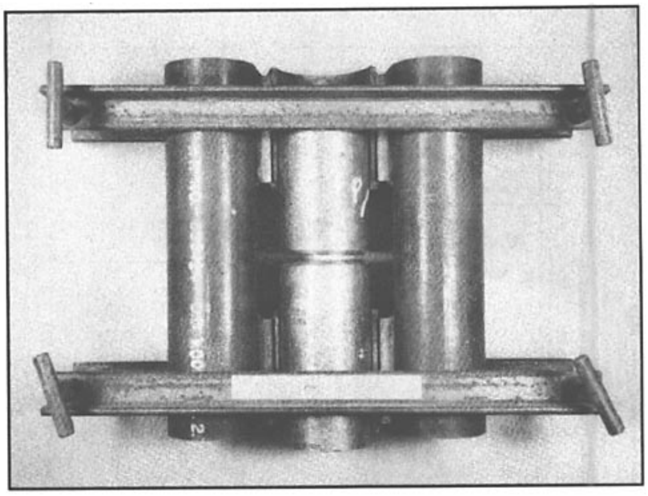
Additional considerations

Welding processes

The reasons for selecting GTAW as the preferred welding process for Type IV joints include: higher weld quality (lower rejects) and therefore higher productivity, simplified electrode selection and control, one set of power supplies/leads per welder, and the much smoother surface profile possible with GTAW than with SMAW. Smoother welds often make RT easier and reduce the geometric stress concentration. The ability to better control weld profile with GTAW also makes this a better process for producing smoother weld transitions between tubes with different outside diameters.

A high number of rejects have occurred with SMAW in the membrane area and are typically characterized as gross porosity in the cap or fill passes from loss of shielding. This is primarily a technique problem due to long arcing, carrying the electrode too far around (past the optimum pick-up point), or placing the electrode at too sharp an angle. Although such technique errors with SMAW can be corrected, experience has shown they are not easily eliminated and are prone to reoccur.

7. Simulator jig for welder qualification. The qualification coupon is secured between the two outside tubes to simulate interference that will be experienced on the job.



Welder qualification and performance

Qualification of welders in accordance with ASME Section IX requirements has not always ensured weld reject rates low enough for acceptable welder productivity. As indicated above, most of the welds in the furnace walls are rejected by radiographic testing due to defects in the membrane (tube tangent) area of the weld. Welding access is difficult in this area because of the adjacent tubes. To best evaluate a welder's skill for welding on the actual boiler tubes, and especially for avoiding defects at the membrane, we require that welders qualify (on site) by welding a coupon that is fixed in a "jig" that simulates the actual tube arrangement (**Fig.** 7).

It is valuable to communicate to the welders the cause(s) of rejection of their welds so corrective action may be taken. (This may include showing the welder the radiographic film and providing additional training.) The job should have an experienced welding technician on site to help the welders identify the causes of rejects and to recommend corrective action. Furthermore, since weld repair for these welds requires skill that only certain welders possess, the welder(s) assigned to repairs should be specifically selected.

Some contractors offer bonus payments to welders for defect-free welds, in combination with a forfeiture for making welds that need to be repaired, or other incentives as a way of motivating high productivity and high quality in tandem.

Radiographic examination techniques

The technique selected to radiographically test composite-to-carbon steel field welds can have a significant effect on the time required to complete a boiler bottom replacement project. We are convinced of the merit and importance of radiographing 100% of the length of every "critical" wall tube butt-weld, as recommended by the Black Liquor Recovery Boiler Committee. This means that two radiographs are required for each furnace wall butt-weld, making the time needed for each radiograph more important.

Our experience has shown that the two-shots per weld, elliptical RT technique can examine about 3-5 welds per hour (per source). On the other hand, the contact RT technique, which examines two half tubes with each shot, can examine 4–5 times as many welds (per source) in the same time and provides a more readable film image. The lower strength sources used for the contact technique also make radiation safety easier and decrease the area that must be roped off, resulting in improved productivity.

Conclusions

Elimination of the stainless steel clad layer from the weld joint in composite-to-carbon steel butt-welds significantly reduces the complexity of the welding and inspection sequence.

Peeling back the stainless cladding, using GTAW welding, testing welders in simulators, and using contact RT inspection maximized the production rates and quality aspects of field welding for composite bottom replacement projects.

Elimination of stainless steel from the joint avoids the undesirable, mixed metallurgy zones in these welds and decreases the potential for in-service problems.□

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