Ontario Hydro Experience with Dissimilar Metal Welds in Boiler Tubing

Transition weld damage mechanisms include creep-fatigue interaction and stress-assisted oxidation

R. B. DOOLEY, G. G. STEPHENSON, M. J. TINKLER, M. D. C. MOLES, AND H. J. WESTWOOD

ABSTRACT. Failures of Type 309 stainless steel-filled transition welds between austenitic and ferritic superheater tubes in two 300 MW units stimulated a program aimed at identifying the critical parameters governing the failure mechanism. Nondestructive testing and temperature monitoring have been employed, and heavy emphasis has been placed on detailed metallographic examination of welds removed from service. Transition welds made with Type 309 stainless filler have shown microcracking as have welds made by pressure bonding; welds with nickel-base filler (Inconel 92 and 182)* have been damage free.

A discriminatory laboratory test has been developed in which welded tube sections are subjected to realistically simulated but accelerated service conditions, including cyclic or "two-shift" operation. Using this approach, the long-term integrity of transition welds has been compared with service experience; most recently, a service-type failure has been reproduced in a test on Type 309 stainless welds subjected to pressure/temperature cycling and bending stress. These tests are reviewed and future work outlined.

Introduction

Low-alloy ferritic steel tubing is extensively employed in superheater and re heater sections of fossil-fueled power boilers. Additionally, the high metal temperatures associated with the final steam conditions — up to 17.2 MPa (2500 psi) and 538°C (1000°F) — require the more oxidation- and creep-resistant austenitic stainless steels for the finishing sections. Accordingly, dissimilar metal transition welds (henceforth referred to as transition welds) are needed. However, these

Nickel-base welds are also widely employed and, in OH, joints with Inconel 92 GTA root and Inconel 182 SMAW filler have so far been trouble-free. Again in line with general experience, other utilities have had similar experiences with Inconel 82 and Inco Weld A welds, but some failures in Inconel 132 welds have been reported (Ref. 4). A third design extensively used within OH is a pressure weld, made by hot upsetting to austenitic and ferritic tube ends together. No failures have been experienced by OH in these welds, although significant damage has been observed in some cases as reported elsewhere in this paper.

The total transition weld inventory within OH is shown in Table 1. The spool pieces referred to are used in some cases to accommodate wall thickness differences between the two tube materials.

Transition Weld Failures in OH

To date, out of approximately 31,000 welds, 5 failures have occurred, all in Type 309 stainless welds in two 300 MW units at station A. These units have accumulated ~50,000 operating hours (h) with ~350 starts.

Details of the failure location are given in Fig. 1, which shows one of the 120 parallel platens making up the final section of the secondary superheater. Steam flows towards the outlet header and tube material changes from 21/4 Cr-1 Mo (T22) to 321H for the final stage within the furnace. After passing through the front wall, a transition back to T22 is made within the vestibule before the tube-to-header joint.

There are as shown, 4 transition welds per platent. Of the 5 failures, 4 occurred within the furnace, 1 in the vestibule region. Subsequent dye penetrant inspection indicated that over 50% of the transition welds apparently had incipient cracks; this led to a decision to replace all the welds in the two units.

The first indication as to the cause of these failures came from consideration of the tube support details as shown in Fig. 1. Fracture of the sliding support/spacer pieces had occurred in service, resulting

*Registered Trademark of International Nickel Co., Ltd
*Inconel 132, Inco Weld A and Inconel 182 conform to the AWS/ASME SFA-5.11 SMA electrode specifications ENCrFe-1, ENCrFe-2 and ENCrFe-3, respectively. Inconel 82 and Inconel 92 are bare wire products conforming to the AWS/ASME SFA-5.14 bare wire specifications ERNiCr-3 and ERNiCrFe-6.
in loss of support and imposition of large bending stresses on the transition welds. Clear evidence of bending stress was provided by the appearance of the failed welds, as shown in Fig. 2.

The through-wall circumferential crack on the ferritic side of the weld is shown in profile in Fig. 3. Close examination shows that the crack path was not along the weld fusion line, but within the ferritic material. Detailed microstructural examination and microhardness measurements confirmed that the crack had propagated through a carbon-depleted zone. Two distinct mechanisms of crack propagation are shown in Fig. 4, i.e., oxide notch penetration from the outside surface and creep-type cavitation on prior austenitic boundaries within the tube wall. Both damage forms were associated with the carbon-depletion, indirect evidence for which is the presence of a band of carbides just beyond the fusion boundary in the stainless weld metal. The orientation of the cavities relative to the fusion line is indicative of shear stresses resulting from the coefficient of expansion differential between austenitic and ferritic materials.

Similarly oriented, but more extensive cavitation damage in Fig. 5; this is from a pressure transition weld. It is noteworthy that, although this cavitation extended through more than 50% of the tube wall, complete link-up of cavitated grain boundaries to form a major crack had not occurred. This was possibly due to the large prior austenite grain size, apparently typical of pressure welds.

The importance of the support design in minimizing bending stress was shown by examination of transition welds from 500 MW units at station B. Details of the platen configuration are given in Fig. 6. The most significant difference from the station A design is the use of “ladder-type” supports which permit free lateral expansion, whilst providing reliable support. None of the welds examined showed significant damage after a similar operating history, only minimal oxide notching and the earliest stages of cavitation being observed in the worst cases.

**Operational Temperature Cycles**

The differential thermal stresses inherent in austenitic-ferritic joints clearly arise during temperature changes. For this reason, it was decided to monitor tubes with thermocouples in order to determine temperature ranges to which transition welds are subjected in normal operation.

Figure 7 shows results of such monitoring at station A, the temperatures being measured during a “two-shift” or hot start cycle, i.e., on-load for 16 h (two shifts) with an 8 h overnight shutdown. The principal observations were:

1. Tubes in the furnace were generally 30-50°C (54-90°F) hotter than those in the vestibule.
2. Ramp rates of up to 300°C (540°F)/h occur during start-up.

Similar monitoring at station B showed almost identical temperature characteristics. This suggested that temperature cycling alone was not responsible for the station A failures and supported the belief...
that extraneous (bending) stresses were more important.

Research Program

Research work, which is on-going, includes detailed metallographic examination of welds removed from service and laboratory tests of transition welds subjected to realistically simulated operational conditions. In the service-simulated test program, two major investigations have been undertaken and reported in some detail (Ref. 5,6). The main aspects of these tests are reviewed. Then, some metallographic work on Inconel welds removed from service is reported, and the implications are discussed.

Test Philosophy and Objectives

Essentially, a laboratory test was required in which representative transition weld designs could be subjected to stresses, temperatures, and environments—simulating, as closely as was practical, the operational situation. Additionally, it was necessary to accelerate the simulated service exposure in order to obtain results in reasonable time. The objectives were to reproduce service-type damage in test welds and to compare the susceptibility to such damage of various weld designs.

Because of the previously explained association of differential thermal stresses with temperature changes, it was decided that the test should be cyclic in nature. Furthermore, with the growing industry-wide trend towards "two-shift" operation of fossil-fueled power plants, it was considered most relevant to perform the tests under simulated "two-shift" conditions involving cyclic temperature and stress.

Test Method

Tests were performed in a tube burst test facility in which boiler tube sections up to ~500 mm (~20 in.) length could be subjected to cyclic temperature and internal steam pressure with a hold period, thus simulating the operational start up, full-load, shutdown cycle (Ref. 5). To accelerate the cycle from the operational value of 24 h to a test cycle of 30 minutes (min), the overtemperature method was adopted, i.e., the hold time temperature was higher than operational, the value being determined using the Larson-Miller extrapolation (Ref. 7).

Steam pressure was made equal to the operational value. This was done because there is evidence that overtemperature acceleration of creep is valid but overstress acceleration is not, at least for ferritic alloys (Ref. 8).

In addition to pressure stresses, boiler tubes are also subjected to thermal stresses due to steady-state through-wall temperature gradients and it was considered necessary to reproduce these stresses in the test. This was accomplished by means of an internal cooling system in the test vessel (Ref. 5).

The first test was carried out under two-shift simulated conditions, as described. With the second test, however, an additional parameter, i.e., bending stress, was incorporated.

1st Test—Testing 3 Transition Weld Designs Under Simulated Two-Shift Conditions

In this test, the three most common transition weld types in OH service (i.e., Type 309 stainless pressure and Inconel) were incorporated into a test vessel and subjected to simulated two-shift pressure-temperature cycles. Details of the welds are given in Fig. 8.

For the fusion welds, the ferritic sections were preheated to 230°C (446°F) before welding and no postweld heat treatment was applied; the pressure weld was postweld heat treated and the external upset ground off. The pressure-temperature-time cycles are shown in Fig. 9. During the hold period, the maximum temperatures of the welds were equal within ±3°C (5.4°F) and the through-wall temperature gradient was ~20°C (36°F).

The test was run for 4062 cycles, simulating 100,000 h (~11 years) of two-shifting or 65,000 h at 553°C (using the Larson-Miller extrapolation). After test, the three welds were removed and examined metallographically to determine the extent, if any, of damage.
Failure. The weld experiencing the highest temperature and the bending stresses for welds in test 2 are shown in Fig. 13. A section through the failure is shown in Fig. 11. In the pressure weld, as shown in Fig. 12, some apparent intergranular decohesion and some intergranular damage was present. No damage was observed in the Inconel weld.

In general, the damage (or absence of damage) observed was of the same form as that seen in service transition welds from the better supported elements of station B. This confirmed the validity of the test method and showed that thermal cycling in itself can only produce incipient damage. The extent of damage was less severe, suggesting that, although two-shifting is detrimental, other factors such as extraneous bending stresses had been involved in service failures.

2nd Test—Testing 309 Stainless Welds under Combined Two-Shifting and Bending Stresses

For the second test, it was decided to concentrate on Type 309 stainless steel welds, three of which were incorporated into a test vessel suitably modified to facilitate loading as a cantilever by suspending a suitable weight from one end while the other end was rigidly supported. This was an effort to reproduce service failures which were believed to have been promoted by bending stress. The 309 stainless steel weld was chosen because it had been best documented and the testing could be directly compared with service failure experience.

The three welds were subjected to different bending moments which were constant during the two-shift simulated cycle. The pressure-temperature-time cycles were similar to those in the first test, but the hold-time temperatures of the three welds were not equal. These temperatures and the bending stresses are shown in Fig. 13.

After 2960 cycles, a through-wall failure occurred in the weld which had experienced the highest temperature and the intermediate bending stress (weld B in Fig. 13). A section through the failure is shown in Fig. 14; comparison with Fig. 3 shows striking similarity with the service failure. The weld experiencing the highest bending stress and second highest temperature (weld A) was also damaged, as shown in Fig. 15. In this section, the two damage forms (oxide notching and internal cavitation) are clearly exhibited and are similar to those in service welds—Fig. 4. No evidence of any damage was found in the third weld, which had experienced the lowest bending stress and significantly lower temperature.

Detailed metallographic examination showed that, in the damaged but unfailed weld (weld A), internal damage involved cavitation with intercavity linkage by narrow or "lace-work" cracking. This damage morphology is shown in Fig. 16; it is typical of that frequently observed in service welds. The cavity linkage was thought to be fatigue-induced, i.e., to be associated with the two-shifting. In the failed weld (B, shown in Fig. 17), this apparent fatigue component was much less evident, the cavitation being more typical of creep damage. This observation suggested that the overtemperature acceleration may tend to shift the balance towards the creep side of the creep-fatigue spectrum.

A third damage morphology was observed in sections from welds A and B where the oxide notch had linked up with internal damage. Figure 18 is a scanning electron micrograph showing a fine network of small cracks surrounding the main crack. This is also typically observed in service welds; it appears to be stress-assisted grain boundary oxidation and suggests that, although the oxide notch is independent of the cavitation/fatigue mechanism, linking of the two damage forms does result in acceleration to failure.

Inconel Transition Welds

In principle, nickel-base transition welds should be immune to the damage experienced by austenitic welds for two reasons:

1. Carbon-depleted zones do not develop.
2. The coefficient of expansion difference between T22 and Inconel is only about 20% of that between T22 and 309 stainless.

Failures have occurred, however, in Inconel 132 welds in the U.S. (Ref. 4). The failure mechanism appears to involve the
formation of a semi-continuous M_{23}C_{6} precipitate at the interface, at which cavities can initiate (Ref. 9). Initiation of cavities at similar precipitates has been observed in Inco Weld A service welds (Ref. 10), implying the potential for a similar kind of failure in this kind of weld.

To the authors' knowledge, no such failures have occurred in Inconel 182 welds. In OH experience, in fact, several T22 tube failures due to excessive fireside oxidation have occurred. Metal temperatures up to 629°C (1164°F) have been measured at the transition, demonstrating the integrity of these welds at above-design temperatures.

Despite this apparent integrity of Inconel transition welds, there is some concern that failures could occur by other than conventional transition weld type mechanisms. Thus, recent metallographic examination of welds removed from service has revealed a large incidence of welding defects, a typical example of lack of fusion or root penetration being shown in Fig. 19.

The difficulties of making sound dissimilar metal welds using Inconel-type filler metal are well known. Welding-related defects have been observed in weld metal or at either interface in nearly one third of the 13 Inconel welds examined. Although, as previously noted, there is little thermal mismatch at the ferritic-Inconel interface, there is a significant expansion differential between Inconel and austenitic stainless which will induce significant thermal stresses along this interface (Ref. 3).

The concern is that these stresses could be concentrated by welding defects, leading to failure on the stainless side of the transition joint. There is some suspicion that two recent transition weld failures at Station A could have been on the stainless side of Inconel 182 welds—unfortunately these welds were repaired in situ and returned to service before metallographic examination was possible.

Recognizing the problems of making sound Inconel welds, particularly under field conditions, current OH practice is to use short spool pieces incorporating a shop-weld between T22 and 321 stainless, so that only similar-metal welds are made in the boiler. Inconel 182 SMA filler metal is used, but the GTA root pass is made with In82, which is now preferred to In92 because it does not age-harden in service. To ensure the integrity of the welds, radiographic examination is performed.

**Future Work**

The next service-simulation test will again combine two-shifting and bending stresses, but the three welds will be of the Inconel 92/182 type. Subsequent tests have yet to be decided. However, one possibility is a non-cycled test in order to determine the integrity of welds under pure creep conditions.

In transition weld development, attention is being given to automatic GTA and friction welding techniques. Another area of interest is the separation of austenitic and ferritic tube sections by a spool piece of intermediate expansion coefficient, i.e., Incoloy 800 or Inconel 600. T9 (9 Cr-1 Mo) is also being considered due to its good creep ductility and resistance to carbon depletion. Assessment of such new designs will be facilitated by service-simulation testing and in-service monitoring. There is also a need for development of nondestructive evaluation techniques which can detect damage in service welds.

**Conclusions**

1. Type 309 stainless steel and pressure transition welds are susceptible to damage in service.
2. Transition weld damage mechanisms include creep-fatigue interaction and stress-assisted oxidation.
3. Although cyclic or two-shift operation promotes some damage, extraneous bending stress and maximum service temperature are also important damaging parameters.
4. A laboratory test has been developed in which service-type failures can be reproduced on an accelerated time scale.
5. Although nickel-base welds appear most damage-resistant, they are particularly prone to welding defects.

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**References**