A Simple Test for Dissimilar-Metal Welds

Using a simple fixture, it is possible to quickly develop cracks similar to those found in steam tube welds after long-time elevated temperature service

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ABSTRACT. A simplified accelerated test procedure has been developed for testing dissimilar-metal welds between austenitic stainless steels and low-alloy ferritic steels. The failure of these welded joints in operating steam generators of fossil-fired power plants has become an increasing problem for the utility industry. The proposed test is a three-point loading, bent-beam test that uses sheet specimens taken from a dissimilar-metal weldment. Tests were conducted in a simple test fixture where the specimens are loaded with a set-screw.

To determine whether the test produces the same type of failure as those produced in a power plant, tests were conducted on specimens taken from a weld between Type 316 stainless steel and 2¼ Cr-1 Mo steel plates using Type 309 stainless steel filler metal. The specimens were loaded in the test fixture at room temperature and then thermally cycled between room temperature and 593°C (1099°F) by placing the test apparatus in a box furnace (thermal cycling during power plant operation plays a major role in the weld failure during service). The specimens were kept in the furnace for 20 to 70 hours (h), cooled to room temperature, and then the cycle was repeated.

Metallographic examination of specimens cycled as few as 64 times with a total of 2300 h at 593°C revealed that the specimens contained cracks similar to the cracks observed on dissimilar-metal welds cut from steam tubes after long-time elevated-temperature service in a fossil-fired steam generator. All indications are that this simple accelerated test could be used as a screening procedure to compare the relative behavior of "improved" welds in future research and development programs.

Introduction

For more than 40 years, both ferritic heat-resisting steels and austenitic stainless steels have been used for fossil-fired boilers. Primary boilers and heat exchangers operate at temperatures and environmental conditions that make low-alloy ferritic steels the best choice for the structural material. Because of their oxidation resistance and creep strength, the Cr-Mo steels, especially 2¼ Cr-1 Mo steel, have been used extensively. Superheaters, reheater tubes, and the hot-reheat steam pipes operate at elevated temperatures where austenitic stainless steels become the necessary choice. The use of these two materials within the system leads to the need for a transition joint.

The problems inherent in such dissimilar-metal weld joints have long been recognized (Ref. 1-5). Recently, the utility industry has experienced a rash of transition-joint weld failures in fossil-fired steam plants. These failures often occur after 15 to 20 years of operation, well before the lifetime of the tubing has been exhausted. Because of the economic consequences of a power plant shutdown, the need for an improved dissimilar-metal weld is obvious. As pointed out in a recent paper by Holko and Li, the problem has led to research and development programs in the United Kingdom, Canada, Japan, the Netherlands, and the United States (Ref. 6).

Almost all of the austenitic-ferritic, dissimilar-alloy weld failures that have occurred in service (Ref. 6-8) or in test programs (Ref. 1-5,9) were in the ferritic alloy. Most of the service failures occurred with 2¼ Cr-1 Mo steel tubing and piping as the ferritic alloy—primarily because most fossil-fired power plants contain this widely used Cr-Mo steel.

Factors that contribute to dissimilar-alloy weld failures in fossil-fired plants have long been understood (Ref. 1-5). Tucker and Eberle (Ref. 4) summarized them as:

1. Cyclic thermal stresses.
2. Low oxidation resistance of the low-alloy ferritic steel.
3. Carbon migration.
4. Metallurgical deterioration caused by elevated-temperature exposure.

During the operation of a power plant, numerous startups and shutdowns occur. Because of the differences in coefficients of thermal expansion for the three components in a joint (the ferritic and austenitic alloys and the weld metal), the startups and shutdowns generate thermal stresses within the joint. These cyclic stresses superimposed on the residual welding stresses, external loads, and internal steam pressure are believed to be the ultimate cause of the failure.

Although it has generally been thought that a cyclic stress is required to produce this type of dissimilar-metal weld failure, several investigations have produced such failures in a creep-rupture test (Ref. 9,10). It is agreed, however, that in an operating steam plant the stresses responsible for dissimilar-metal weld failures are due to the thermal cycling when the plant is started and stopped.

In a previous paper the results of studies on failed and unfailed dissimilar-metal welds taken from fossil-fired steam generators were used to postulate a failure mechanism (Ref. 8). To test such a mechanism or any other proposed mechanisms, a simple test procedure is required, one that produces accelerated failures under conditions similar to those experienced by a transition joint in an operating plant. Several experimental programs now under way have as their objective the development of an "improved" transition joint (Ref. 6). It would be extremely useful to have a simple procedure where large numbers of such welds could be simultaneously tested and compared.

Although stress-rupture tests are quite

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simple and can be used to test large numbers of specimens, such tests are relatively expensive and many test machines are required. Furthermore, the effect of thermal cycling in such a test is probably not the same as that experienced during service. Moles, *et al.* have developed a test procedure on tubes that employs thermal cycles to produce part of the imposed stress (Ref. 11). However, the test is quite complicated (expensive) and does not lend itself to a large test program.

In this paper a simple test procedure for dissimilar-metal welds is described, and it is demonstrated that the failures produced in that test are similar to those observed in operating fossil-fired plants.

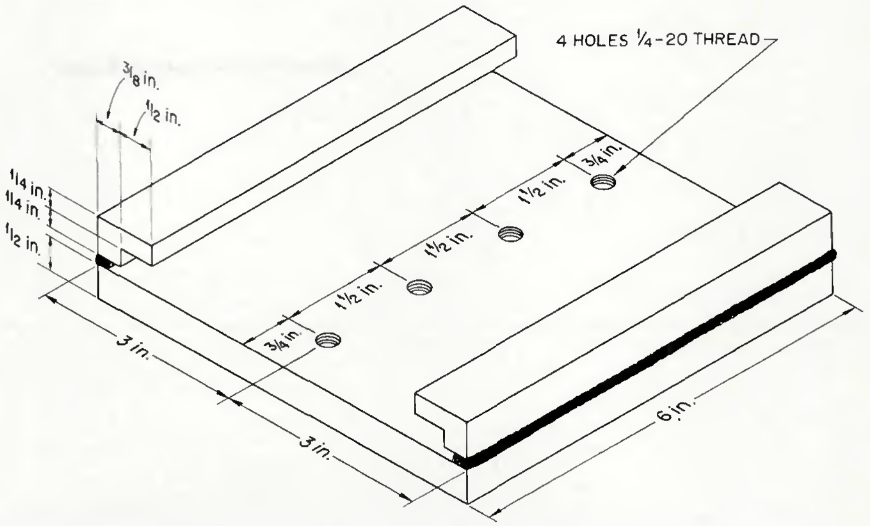

Fig. 2 — Dimensioned drawing of the three-point-loaded, bent-beam test apparatus

Test Apparatus

The stresses on dissimilar-metal weld transition joints in steam tubes of operating power plants include the internal steam pressure, cyclic thermal stresses, residual welding stresses, and external loading stresses. The internal steam pressure is generally small compared to the strength of the joint materials.

Cyclic thermal stresses are generated during plant startup and shutdown because of differences in thermal coefficients of expansion for the joint materials. Residual welding stresses should tend to relax out during elevated-temperature service. External loading (bending) stresses are the biggest unknown, and may be most deleterious. Such stresses arise because of plant design and construction and have been shown to have an effect in some dissimilar-metal weld failures (Ref. 11).

To try and simulate the conditions for a dissimilar-metal weld in a steam generator, a simple three-point loading, bent-beam test apparatus was designed; it uses a procedure similar to that used for stress-corrosion cracking studies (Ref. 12) — Fig. 1. On a specimen thus loaded, there is a stress gradient through the thickness, varying from a maximum tension stress on the top (convex) surface to a maximum compression stress on the bottom (concave) surface. The stress also varies along the specimen length: It is a maximum at the center and decreases linearly to zero at the outer supports.

The elastic stress at the midspan on the outer fibers is given by:

$$\sigma = \frac{6Ety}{L^2} \qquad (1)$$

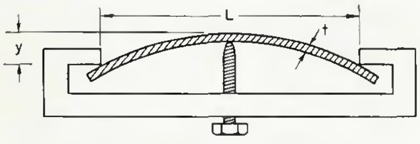

Fig. 1 — Schematic of three-point-loaded, bent-beam test apparatus

where σ is the maximum stress, y the displacement of the outer fiber normal to the surface at the center of the specimen, E the modulus of elasticity, t the specimen thickness, and L the distance between the outer supports.

Equation (1) is only applicable for stresses below the elastic limit. At stresses above the elastic limit but below the engineering yield strength, the errors involved in the use of the formula are small.

A simple test apparatus made of Type 304 stainless steel was constructed — Fig. 2. It consisted of a 12.7 mm (0.5 in.) thick plate to which an L-bracket was welded to each side. Four 1/4-20 threaded holes were placed along the center of the plate. These holes were fitted with rounded Allen-head setscrews, which are turned against the center of the specimen to get the desired specimen displacement (y of Fig. 1) for a given stress estimated from equation (1). The displacement at the center of the specimen was determined using a dial gage that measured displacements with a sensitivity of 0.3 μm.

In Fig. 3, three specimens are shown loaded in a test fixture (a vacant test position is also shown). The base of the fixture consists of two 12.7 mm (1/2 in.) OD stainless steel tubes that were welded to the plate — Fig. 3. A two-pronged "fork" was made to be inserted into these tubes for easy handling when the apparatus was placed in or taken from the test furnace.

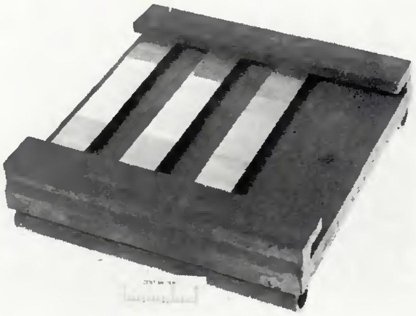

Fig. 3 — Bent-beam test apparatus containing three test specimens

When the loaded test apparatus is heated or cooled to or from the test temperature, the specimens will expand or contract. This gives rise to stresses different from those calculated from the bending at room temperature, the temperature at which the specimens were loaded in the test apparatus. Likewise, the stress on the specimen at the test temperature will be less than the calculated stress, because stress relaxation at the 593°C (1099°F) elevated test temperature should quickly reduce the applied stress. During thermal cycling, however, the stresses imposed on the joint caused by the expansion and contraction of the specimen should be similar to the type of stress imposed on a dissimilar-metal weld in an operating power plant during startup and shutdown.

Because the present study was concerned with developing an accelerated test to produce "typical" dissimilar-metal weld failures, no stress analysis was attempted.

Test Procedure

It has been found that dissimilar-metal welds between austenitic stainless steel and ferritic steel made with Type 309 stainless steel filler metals are more prone to failure than those made with a nickel-base filler metal (Ref. 4,5). Because of this, test welds were made with Type 309 stainless steel.

A 12.7 mm (0.5 in.) thick plate of Type 316 stainless steel was welded to a 12.7 mm (0.5 in.) thick plate of 2 1/4 Cr-1 Mo steel using the gas tungsten arc process.

Table 1—Test Conditions for Dissimilar-Metal Weld Tests[a]

Postweld heat treatment	Center deflection, mm	Estimated stress, MPa
5 h at 732°C	0.28	69
10 h at 732°C	0.28	69
None	0.55	138
1 h at 732°C	0.55	138
5 h at 732°C	0.55	138
10 h at 732°C	0.55	138
None	0.83	207
1 h at 732°C	0.83	207

(a) Conversions: 732°C = 1350°F; in. = 25.4 mm; ksi = MPa ÷ 6.895.

Fig. 4—Apparatus with four specimens that were tested at 593°C (1099°F) for approximately 2300 h and 64 thermal cycles

The plate was end-milled to a thickness of 3.2 mm (0.125 in.). Specimen blanks 127 mm × 19.1 mm × 3.2 mm (5 in. × 0.75 in. × 0.125 in.) were cut from the plate; the weld was in the center of the blank. A length of approximately 50 mm (2 in.) in the specimen center was ground to 16 μin. to give a suitable finish for the specimen test section.

There has been speculation that elevated-temperature service exposure (thermal aging) or a postweld heat treatment changes the microstructure so as to increase susceptibility to failure (Ref. 4, 5). Therefore, specimens were placed in test after various postweld heat treatments. Specimens were annealed for 0, 1, 5, and 10 hours (h) at 732°C (1350°F).

The 5 and 10 h heat treatments were not meant to be typical of postweld tempering treatments. Rather, they were meant to simulate an aged microstructure that will be obtained after long-time elevated-temperature exposure during service.

Specimens were tested at starting stresses (at the center of the specimen) of 69, 138, and 207 MPa (10, 20, and 30 ksi) as calculated from equation (1).* Note that, although these stresses are relatively high compared to ASME allowable stresses, the specimens stressed to 69 MPa (10 ksi) were stressed below the 593°C (1099°F) yield stress for all three alloys in the joint. This is probably also true at 138 MPa (20 ksi). The high stresses are necessary for an accelerated test, just as high stresses are necessary in a stress-rupture test. Table 1 lists the test conditions.

Tests were conducted in air at 593°C (1099°F). The test apparatus was placed in a box furnace and kept at the test temperature for ~20-22 h, after which it was removed from the furnace and allowed to cool to room temperature. Cooling was complete in ~2 h, after which the specimen was reinserted in the furnace. Once a week (the weekend), the specimens remained in the furnace for ~70 h.

After the specimens had been exposed at 593°C (1099°F) for ~2300 h and had experienced 64 temperature cycles, they were removed from the test apparatus and a lengthwise slice ~1.6 mm (0.06 in.) thick was removed for metallographic examination. The specimens, now 1.6 mm (0.06 in.) reduced in width, were again placed in test at the same deflections they had before they were removed. Similar 1.6 mm (0.06 in.) slices were taken for metallography after a total of ~5000 h at 593°C, i.e., 1099°F, (130 cycles) and ~9000 h (249 cycles).

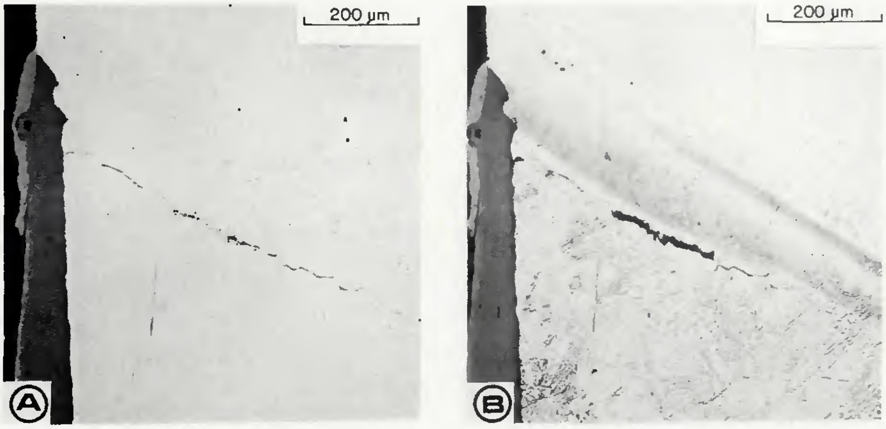

Fig. 5—Crack formed in specimen tests at 207 MPa (30 ksi) for 2300 h at 593°C (1099°F) and 64 cycles. Before testing, the specimen was tempered 1h at 732°C (1350°F). A—unetched; B—etched in 2% nital

Results and Discussion

The objective of the present tests was to demonstrate that the accelerated test procedure could be used to develop failures similar to those observed on steam tubes taken from fossil-fired steam plants. For that reason, no effort was made to delineate the effect of stress or the heat treatment prior to test. Service failures generally occur by the formation of a crack at the external surface that propagates into the tube; the crack forms

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**It should be noted that "typical" failures occur in the 2¼ Cr-1 Mo steel very near the weld interface. This region was not at the center of the specimen and was thus not tested at the maximum stress.*

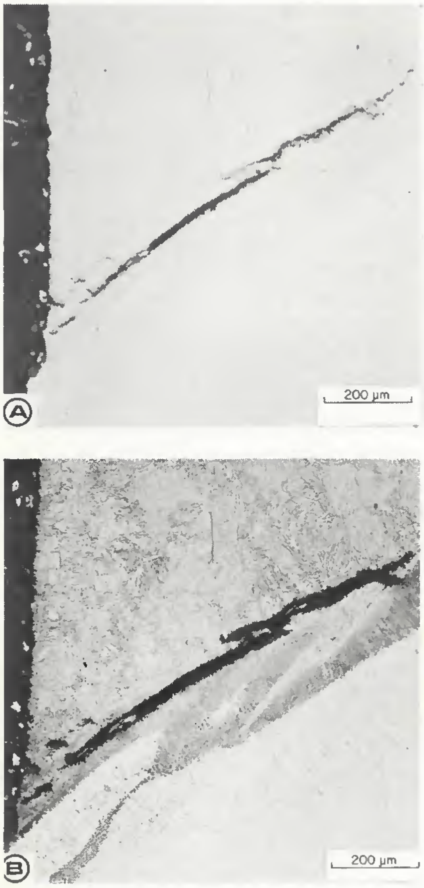

Fig. 6 — Same specimen as in Fig. 5, but after testing for approximately 5000 h and 123 cycles. A — unetched; B — etched in 2% nital

in the heat-affected zone of the 2¼ Cr-1 Mo steel very near the weld interface. Metallography was used to determine if such failures occurred on specimens tested in the new apparatus.

In Fig. 4 the specimens are shown in the test apparatus after the first 64 cycles. A large oxide buildup occurred on the 2¼ Cr-1 Mo steel. The oxide was very nonadherent; it was thickest adjacent to the weld interface and decreased in thickness with distance from the fusion line. This probably indicates an effect of stress, as the stress decreases with distance from the center of the specimen.

After the first test exposure ($\sim$2300 h at 593°C, i.e., 1099°F, and 64 cycles), cracks were observed metallographically on all specimens. Upon further exposure, the extent of cracking (depth and width of cracks) increased, but there was no noticeable change in the general characteristics of the cracks. Examples of the observed cracks are shown in the micrographs of Figs. 5 to 8.

Oxide-filled cracks were observed to start at the external surface of the specimen and propagate into the interior in the 2¼ Cr-1 Mo steel heat-affected zone very near the weld interface. The cracks started on only one surface of the specimen, the surface that had maximum tensile stress imposed on it (the top surface of Figs. 1 and 3). This was true for the specimens after all three test sequences. In a few instances, it appeared that there was a start of attack on the surface under the compressive stress, but in all cases these were quite superficial penetrations, especially when compared to the penetrations observed on the surface under the tensile stress.

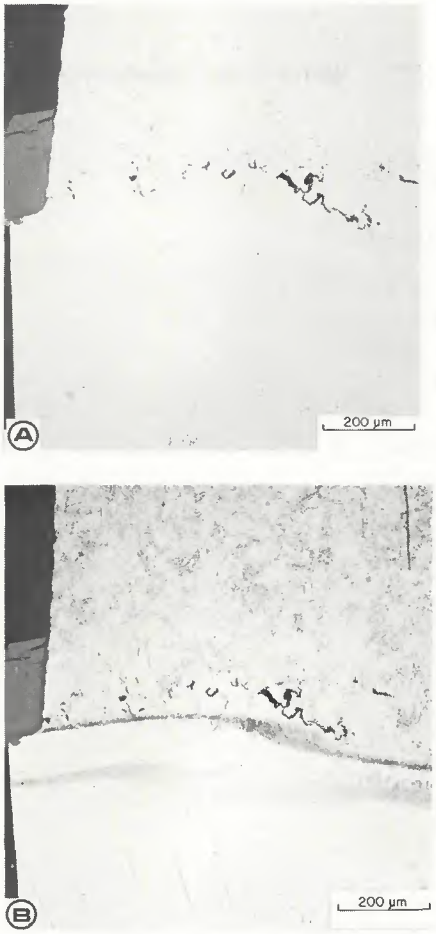

Fig. 7 — Cracks formed in specimen tested at 138 MPA at 593°C (1099°F) for 2300 h and 64 cycles. Before test, specimen was tempered 10 h at 732°C (1350°F). A — unetched; B — etched in 2% nital

Most of the penetrations had the appearance of a single continuous crack proceeding in from the specimen surface — Figs. 5-7. However, several penetrations took more tortuous routes in from the surface — Fig. 8. These penetrations were found to follow 2¼ Cr-1 Mo steel grain boundaries, but at a somewhat greater distance from the fusion line than did the penetrations having a single-crack appearance.

To compare the observed penetrations with observations on dissimilar-metal welds taken from steam tubes that had been in service in a power plant, several micrographs for such tubes are presented in Figs. 9 to 11. These are austenitic stainless steel tubes that were joined

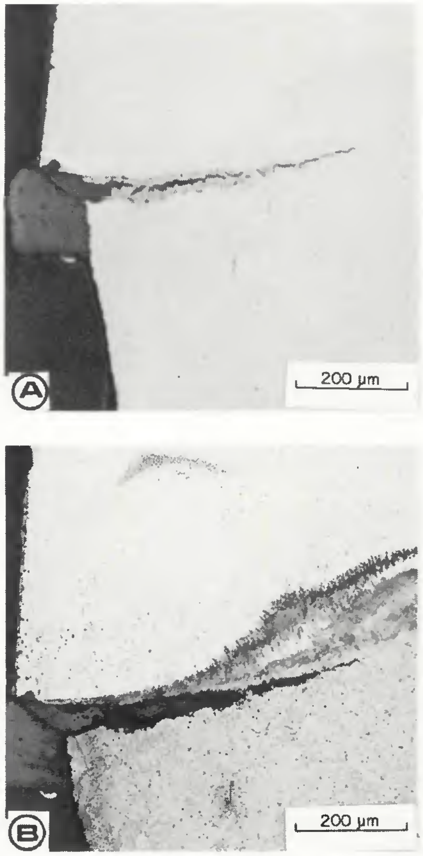

Fig. 8 — Cracks formed in specimen tested at 207 MPa (30 ksi) at 593°C (1099°F) for 5000 h and 123 cycles. The specimen was not tempered prior to test. A — unetched; B — etched in 2% nital

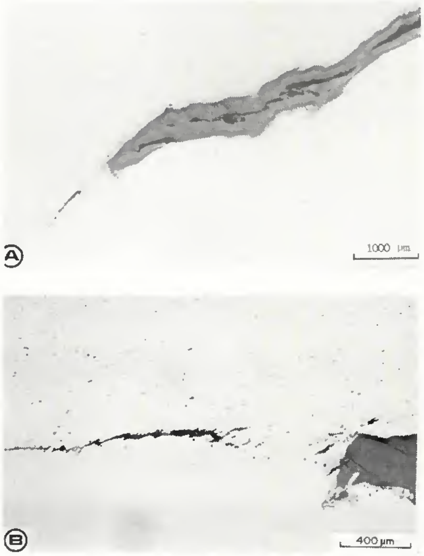

Fig. 9 — An oxide-filled crack that formed in a dissimilar metal weld between an austenitic stainless steel tube and a 2¼ Cr-1 Mo steel tube with Type 309 stainless steel filler metal (the weld was in service near 560°C, i.e., 1040°F, for over 50,000 h). A — entire crack; B — crack tip

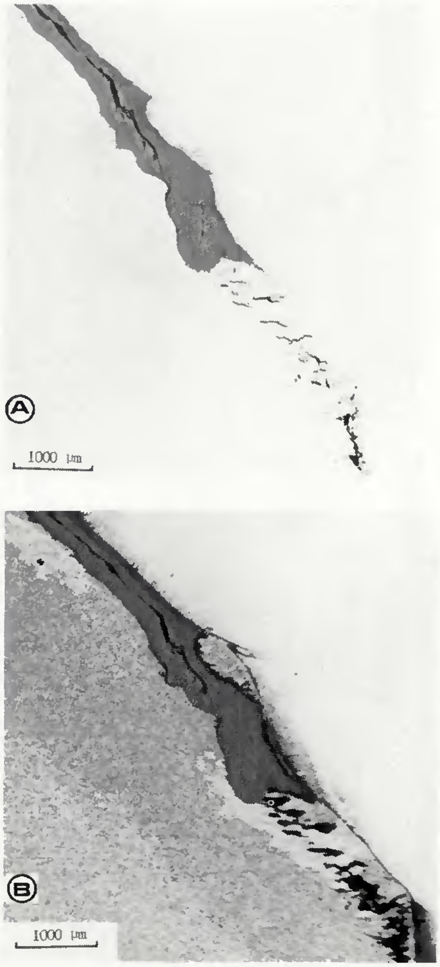

Fig. 10 — Cracks in a dissimilar-metal weld between an austenitic stainless steel tube and a 2¼ Cr-1 Mo steel tube with Type 309 stainless steel filler metal (the weld was in service near 560°C, i.e., 1040°F, for over 50,000 h). A — etched; B — etched in 2% nital

to 2¼ Cr-1 Mo steel tubes with Type 309 stainless steel filler metal and were in service near 560°C (1040°F) for 50,000 to 100,000 h. A comparison of the cracks in these micrographs with the cracks developed in the new test apparatus (Figs. 4-8) clearly demonstrates the similarity.

The two types of cracks observed in the test apparatus are also evident in the welds taken from the tubes. Again, there are the continuous cracks proceeding in from the external surface. For the tube welds, these generally contain a larger amount of oxide than was true for the specimens from the test apparatus. However, this is a reflection of the longer exposure time for the tubes.

There is also an indication that tortuous cracks proceed along 2¼ Cr-1 Mo steel grain boundaries further back from the fusion line. These cracks were generally observed within regions that appeared to be highly decarburized. This was true for both types of penetrations — Figs. 8 and 10. From the qualitative comparisons made in the present tests, all indications are that the cracks observed in specimens tested using the new test apparatus are similar to those that occur in an operating fossil-fired boiler.

We previously discussed a failure mechanism for dissimilar-metal welds (Ref. 8). Although that mechanism is not discussed in this paper, the observations on the failures generated in the new test apparatus appear to be compatible with the proposed mechanism. This is true for both types of penetrations that were observed.

It is now generally agreed that there are fundamental differences in appearance in the weld failures of tubes welded with the austenitic stainless steel and nickel-base filler metals (Ref. 6, 10). This difference results because of different microstructures developed in the 2¼ Cr-1 Mo steel near the weld interface in the two types of welds (Ref. 8). In particular, the "tortuous" grain boundary penetrations are not generally observed in welds made with nickel-base filler metals. As stated above, this type of penetration is apparently caused by the greater amount of decarburization caused by the stainless steel weld metal.

When these experiments were started, the primary objective was to determine if a simple test apparatus could be developed that would reproduce the failure behavior of dissimilar-metal welds in steam generators. Because it was known that fusion welds made with Type 309 stainless steel filler metal were more susceptible to failure than those made with nickel-base filler metals, Type 309 stainless steel welds were tested.

Of more interest to the utility industry in recent years are welds made with nickel-base filler metals. This is because most repair welds and dissimilar-metal welds in new steam generators are made with nickel-base filler metals. Offhand, we know of no reason why the test apparatus described in this paper will not give accelerated "typical" failures of welds made with nickel-base filler metals similar to those of failed tubes taken from steam generators. To determine if this is the case, tests are being undertaken on welds made with ERNiCr-3 filler metal.

The test apparatus and procedure that have been developed in this work should be ideal for comparative testing of improved dissimilar-metal welds that may be developed in a research and development program. In such a program, large numbers of welds could be loaded similarly and tested simultaneously. The improved welds could also be simultaneously compared with welds made with austenitic stainless steel and nickel-base filler metals, which could serve as reference welds. The simple test apparatus and procedure also has significant experimental and economical advantages over the tests presently in use (Ref. 6,10,11).

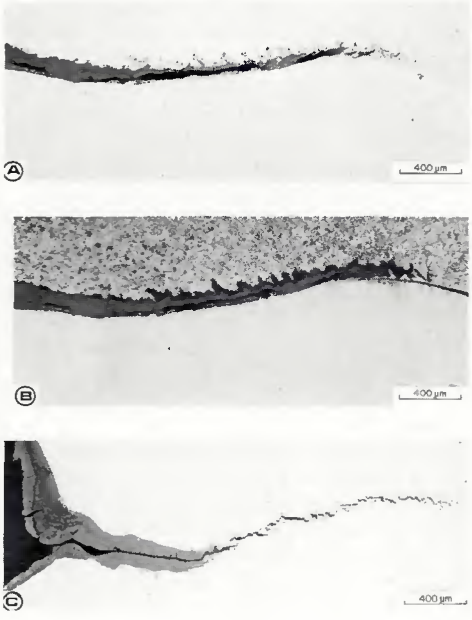

Fig. 11 — Examples of cracks in dissimilar-metal welds between an austenitic stainless steel tube and a 2¼ Cr-1 Mo steel tube with Type 309 stainless steel filler metal (the tubes were in service for over 50,000 h at approximately 560°C, i.e., 1040°F). A and B — same weld; C — weld after being etched with 2% nital

Conclusion

A simple test procedure has been developed to produce cracking in dissimilar-metal welds between austenitic stainless steels and low-alloy ferritic steels. This accelerated test procedure was shown to produce cracking similar to that observed on failed steam tubes taken from fossil-fired steam generators.

The test is a simple three-point-loading, bent-beam test that is made on sheet specimens (127 × 19.1 × 3.2 mm, i.e., 5 × 0.75 × 0.126 in.) that are machined from a dissimilar-metal weldment. To determine the applicability of the test procedure, specimens were taken from a plate weldment made between Type 316 stainless steel and 2¼ Cr-1 Mo steel using Type 309 stainless steel filler metal.

Specimens were loaded at three different stresses after various postweld heat treatments. The loaded test apparatus was heated to 593°C (1099°F) in a box furnace, held at temperature for 20-70 h, and then cooled to room temperature, after which the cycle was repeated.

After the specimens were given 64 thermal cycles and had been at 593°C (1099°F) for a total of ~2300 h, all of the specimens developed cracks on the side of the specimen that had the maximum tension stress imposed on it. Metallographic comparison with similar tube welds that failed after 50,000-100,000 h in a fossil-fired steam plant showed that the failure mode in the specimens tested using the new procedure are the same as those taken from operating steam generators.

Indications are that the proposed test procedure is a simple and economical method to test large numbers of specimens simultaneously, thus giving a procedure that should prove extremely useful in a program designed to develop "improved" dissimilar-metal welds.

Acknowledgment

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