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Prepared by
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
managed by
Lockheed Martin Energy Research
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CRADA Final Report
for
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Abstract

In 1993, a Cooperative Research and Development Agreement (CRADA) was undertaken between Oak Ridge National Laboratory and ABB Combustion Engineering to examine advanced alloys for fossil power systems. Specifically, the use of advanced austenitic stainless steels for superheater/reheater construction in supercritical boilers was of examined. The strength of cold-worked austenitic stainless steels was reviewed and compared to the strength and ductility of advanced austenitic stainless steels. The advanced stainless steels were found to retain their strength to very long times at temperatures where cold-worked standard grades of austenitic stainless steels became weak. Further, the steels exhibited better long-time stability than the stabilized 300 series stainless steels in either the annealed or cold worked conditions. Type 304H mill-annealed tubing was provided to ORNL for testing of base metal and butt welds. The tubing was found to fall within range of expected strength for 304H stainless steel. The composite 304/308 stainless steel was found to be stronger than typical for the weldment. Boiler tubing was removed from a commercial boiler for replacement by newer steels, but restraints imposed by the boiler owners did not permit the installation of the advanced steels, so a standard 321 stainless steel was used as a replacement. The T91 removed from the boiler was characterized.

Goals

The CRADA had five goals: (1) to produce commercial grade tubing; (2) to demonstrate superior performance of the tubing; (3) to establish the acceptable limits of cold work; (4) to show that components could be fabricated; and (5) to determine the cost of commercialization of steel tubing. To achieve the goals, four phases of work were identified. Progress on the four phases is identified below.

Benefits

Many commercial pulverized power plants in the United States have accumulated service lives well-beyond the original expectations. Cyclic operation, changes in coal chemistry, and extended service life demands have produced concerns about the integrity of the high-temperature components such as superheaters and reheaters. The repair or replacement of a superheater is a costly and highly competitive undertaking, so the boiler manufacturing industry is examining alternative materials and fabrication procedures to minimize costs. Many of the critical superheaters operate with steam temperatures of 932 to 566°C (950 to 1050°F) and tubing materials include both ferritic and austenitic steels. Advanced ferritic steels, such as T91, are difficult to weld and require expensive post-weld heat treatment after welding. The ferritic steels have excellent physical properties but their "over-temperature" strength capabilities are limited. Unstabilized grades of stainless steels, such as 304H and 316H, are more expensive but ease of fabrication and good "over-temperature" strength capability continues to make these steels attractive. The higher temperature capability and corrosion resistance of the stabilized grades of austenitic stainless steels such as 321H, 347H, and 310HCbN, makes these steels most desirable, but a tendency for cracking in severely worked tube bends places restrictions on the amount of cold work that can be tolerated. Research at the Oak Ridge National Laboratory has produced new austenitic stainless steels that are under-stabilized yet possess very-high strength in either the annealed or cold worked condition. The purpose of this CRADA was to evaluate the potential of these steels for use in boilers operating under conventional steam temperatures and pressures and to explore their use in the extension of steam conditions to higher temperatures and pressures.

Accomplishments

Phase 1 of the work involved the production of prototype tubing. Type 304 stainless steel was selected as the reference material and a modified 316 stainless steel, identified here as the HT-UPS steel was selected as the developmental new material. The target composition of the HT-UPS was chosen to be 0.08% C; 0.1% Si, 2% Mn, 16% Ni; 14% Cr, 0.3% Ti, 0.1% Nb, 0.5% V, 2.2% Mo, 0.007% B; 0.01% max S; and 0.04% max P. Processing parameters were selected by ABB-Combustion Engineering to be electric-furnace argon-oxygen deoxidation (AOD) melting, centrifugal casting, and cold pilgering with a final bright anneal of 1200°C (2200°F) followed by 2% cold work.

The tubing producer selected by ABB-Combustion Engineering went out of business about the time the CRADA was being negotiated. The remaining austenitic tubing producers in the U. S. were production facilities and did not have the capability to produce small lots of experimental tubing. To provide an interim material for the other phases of the CRADA, tubing produced by a different fabrication route was selected. In this case a vacuum induction melted (VIM), electroslag remelted (ESR), ingot was pierced, hot-extruded, and cold finished. The tubing was provided to ABB-Combustion Engineering for cold bending. Two tubes of type 304H stainless steel were cold bent by ABB-Combustion Engineering and provided to ORNL. These bent tubes are shown in Fig. 1. The tests on the tubing specified by ABB-Combustion Engineering included tensile, stress-rupture, and tube burst. Specimens from butt welds were also of interest.

Fig. 1. Cold bent 304H stainless steel tubes.

Phase 2 of the work involved an assessment of the technology by ABB-Combustion Engineering to determine if the cost and properties of the advanced austenitic steels were economical for the end application. While the assessment was being undertaken, new ferritic boiler tubing alloys were approved for construction under the rules of ASME Section I, so the assessment by ABB-Combustion Engineering required consideration of these new alloys in addition to standard 300 series stainless steels. It was found that one new ferritic alloy, namely T23, possessed fabrication and pricing characteristics that made it very competitive for many of the steam conditions in which 300H stainless steels were being used. Hence, final assessment of the potential of the advanced stainless steels required that the new ferritic steels be included into the testing and evaluation phases of the research.

Phase 3 of the work involved the collection and analysis of data regarding the properties of the cold worked austenitic stainless steel tubing relative to annealed tubing. References 1 to 7 list some of the open-literature papers and reports that were reviewed. Also, unpublished and proprietary data were reviewed. Generally, it was found that cold working enhanced the short-time high-temperature strength of both unstabilized (304H and 316H) and stabilized (321H, 347H, and 310HCbN) grades of stainless steels. With increasing time and temperature, the all grades, when tested in the cold worked condition, lost strength relative to annealed condition. The loss in strength increased with increasing cold work. A correlation developed by the Japanese and shown in Fig. 2 was found to be helpful in understanding results. The chart plots the ratio of the creep strength at 650°C (1202°F) against the Nickel equivalent (Ni-eq) and shows that composition as well as cold work influences the loss in strength of cold worked tubing. The compositions of the reference 304H stainless steel and the advanced HT-UPS steels are indicated in the chart. Clearly, the HT-UPS steels, with a Ni-eq in excess of 30, are expected to tolerate cold working better than standard 304H stainless steel.

Fig. 2. The effect of composition and cold work on the 100,000 h strength ratio of cold-worked and annealed stainless steel at 650°C

Tensile and stress-rupture tests were performed on the 304H stainless steel tubing supplied by ABB-Combustion Engineering. Samples were taken in the longitudinal direction. Threaded-end bars had 28.6-mm (1.125-in.) length and 3.17-mm (0.125-in.) cross sections. The yield strength data are shown in Fig. 3, where they may be compared to typical strengths for annealed 304H stainless steel and the HT-UPS stainless steels.

Fig. 3. Comparison of the yield strength of 304H stainless steel tubing to annealed 304H stainless steel and HT-UPS stainless steel in three conditions.

Stress-rupture tests were performed in the temperature range of 593 to 760°C (1100 to 1400°F). Testing times ranged from 40 to 5000 h. Creep curves for tests at 704°C (1300°F) are shown in Fig. 4. Here, it may be seen that the specimens spent most of their lives in tertiary creep but possessed creep elongations in excess of 30%. The stress-rupture data were compared to the database for 304H stainless steel on the basis of the Larson Miller parameter, and these results are shown in Fig. 5. The 304H tubing supplied was found to be substantially stronger than the heats of 304H stainless steel included in the historic database.

Stress-rupture testing was also performed on butt-welded tubes. Here ER 308 stainless steel stainless wire was used and welds were made by the gas tungsten-arc process. Threaded-end bar specimens were machined to include the weld, heat-affected-zone (HAZ) and some of the base metal in the 38.1-mm (1.5-in.) reduced test section. Specimen diameters were 5.72 mm (0.225 in.). To cover a broad range of stresses, temperatures were varied from 593 to 982°C (1100 to 1800°F). Most failures occurred in the weld metal, but above 760°C (1400°F) base metals failures were encountered. The base metal tubing data are compared to the weldment data in Fig. 6.

Fig. 4. Creep curves for specimens from 304H stainless steel tubing at 704°C (1300°F) showing extended tertiary creep and excellent creep ductilities.

Fig. 5. Comparison of the rupture strength for 304H stainless steel tubing to literature data on the basis of the Larson Miller parameter.

Fig. 6. Comparison of rupture strength of 304H/308 stainless steel butt welds to 304H stainless steel on the basis of the Larson Miller parameter.

Fig. 7. Pressurized tube specimen of 304H stainless steel

In preparation for the testing of the advanced stainless steel tubing, a multiaxial stress testing facility at ORNL was refurbished and recommissioned. Tubular specimens were machined from tubing, as shown in Fig. 7, and a pressurized tube test was begun at 704°C (1300°F) and 95.5 MPa (13.86 ksi). The tube was expected to rupture in 1700 h, assuming maximum principal stress failure, or 18000 h, assuming von Mises failure criterion. The test is still in progress at 5000 h.

The HT-UPS stainless steels were tested in a variety of conditions, ranging from annealed to heavily cold worked (8, 9, 10). Yield strengths ranged from under 200 MPa (29 ksi) to 735 MPa (107 ksi). Ultimate strengths ranged from 490 to 840 MPa (71 to 122 ksi). Testing temperatures of the HT-UPS stainless steels were in the range of 600 to 800°C (1112 to 1472°F) and times ranged to 60,000 h at 700°C (1292°F). The effect of cold work on the shape of the creep curve for tubing is shown in Fig. 8. Typical of austenitic stainless steels, the cold work reduced the creep rate at 170 MPa (24.7 ksi) and 700°C (1292°F). Another comparison is shown in Fig. 9, which plots stress versus the Larson Miller parameter for the rupture of 304H stainless steel and the HT-UPS stainless steels in the annealed and the worked conditions. The HT-UPS stainless steels are about three times stronger than the 304H stainless steel.

Fig. 8. Effect of cold work on the creep curve of HT-UPS stainless steel tubing at 170 MPa (24.7 ksi) and 700°C (1292°F)

Fig. 9. Stress versus the Larson Miller parameter for 304H stainless steel and the HT-UPS stainless steels.

Phase 4 of the work involved the installation of tubing into a boiler for field testing. The Tennessee Valley Kingston Unit 5 was selected, since this boiler was expected to be down for maintenance at a time when the advanced tubing was expected to be ready for installation. However, during the period of the CRADA some failures were experienced in several high-temperature components which were attributed to cold work in austenitic alloys containing MC formers. Action was initiated through the ASME Code Sect. I to limit the allowable cold work in such alloys to 5%. Since the candidate HT-UPS stainless steels contained MC-forming elements and were intended to be used at cold work levels exceeding 5%, it did not appear that approval to insert the tubing in Unit 5 would be obtained. During the shutdown, T91 tubing was removed and replaced by 321H stainless steel. A metallurgical examination of the T91 and dissimilar metal welds to the 321H stainless steel was undertaken (11). Further work on the introduction of cold-worked stabilized stainless steel tubing was deferred pending the resolution of the Code issues. The advantages in using the HT-UPS stainless steels and similar stainless steels were presented to the American Boilers Manufacturing Association (12) but it became clear that most boiler manufacturers preferred to work with readily available ferritic steels that could be cold-bent without the need for reannealing and welded without the need for post-weld heat treatment.

References

1. D. D'Angelo, et al., "Creep of Cold Deformed AISI 347 Stainless Steel," pp. 127 to 133 in Proceedings of the Fifth Conference on Creep of Materials, ASM International, Materials Park, Ohio, 1992.
2. L. Bernard, E. Campo, and S. Quaranta, "Creep Behavior of AISI 304 and 316 Stainless Steels and Influence of Cold Working," pp. 88 to 93 in Mechanical Behavior and Nuclear Application of Stainless Steel at Elevated Temperatures, The Metals Society, London, UK, 1982.
3. M. Gold, W. E. Leyda, and R. H. Zeisloft, "The Effect of Varying Degrees of Cold Work on Stress-Rupture Properties of Type 304 Stainless Steel," Trans. ASME J. Pressure Vessel Technol., Vol. 97, pp. 305-312 (October 1975).
4. B. Mitchell, "High-Temperature Materials for Electrical Power Generation," pp. 547 to 560 in High-Temperature Properties of Steels, Iron and Steel Institute, London, UK, 1966.
5. R. A. Moen and D. R. Duncan, Cold Work Effects: A Compilation of Data for Types 304 and 316 Stainless Steel, HEDL-TI-76005, Hanford Engineering Development Laboratory (March 1976).
6. R. A. Moen and G. V. Smith, "A Consideration on Limits of Cold Working in Nuclear Construction" J. Eng. Mater. Technol., Vol. 97, pp. 162 (Apr. 1975).
7. V. K. Sikka, et al., "Residual Cold Work and Its Influence on Types 304 and 316 Stainless Steel," Nuclear Technology, Vol. 31, pp. 96-114 (Oct. 1976).
8. R.W. Swindeman, P. J. Maziasz, E. Bolling, and J. F. King, Evaluation of Advanced Austenitic Alloys Relative to Alloy Design Criteria for Steam Service: Part 1-Lean Stainless Steels, ORNL-6629/P1, Oak Ridge National Laboratory, Oak Ridge, TN (May 1990).

9. R. W. Swindeman, G. M. Goodwin, and P. J. Maziasz, Procurement and Screening Test Data for Advanced Austenitic Alloys for 650°C Steam Service: (Part 1-14Cr-16Ni Steels and 20Cr-30Ni-Fe Alloys), ORNL/TM-10206/P1, Oak Ridge National Laboratory, Oak Ridge, TN (April 1987).

10. R. W. Swindeman, G. M. Goodwin, P. J. Maziasz, and E. Bolling, Procurement and Screening Test Data for Advanced Austenitic Alloys for 650°C Steam Service: (Part 2, Final Report), ORNL/TM-10206/P2, Oak Ridge National Laboratory, Oak Ridge, TN (August 1988).

11. R. W. Swindeman, V. K. Sikka, P. J. Maziasz, and D. A. Canonico, "Evaluation of T91 after 130,000 Hours in Service," paper submitted to ASME Pressure Vessels and Piping Conference, San Diego, CA July 26-30, 1998.

12. R. W. Swindeman, "Code Approved Austenitic Materials and Advanced Alloys for Code Construction," paper presented at the Meeting of the American Boiler Manufacturing Association, Jupiter Beach, FL, April 18, 1997.

Inventions

The HT-UPS stainless steels involved in the research of the CRADA were covered by a prior invention disclosures. No new patents or potentially patentable discoveries were made.

Commercialization Possibilities

The high cost of new boiler construction and the uncertainty in the power industry regarding the effects that deregulation will have on the economics of electric power generation by the combustion of pulverized coal have made it difficult to promote advanced technologies that improve boiler performance. Several new ferritic and austenitic steel tubing materials are now code-approved, and a better understanding of the economics in the use of the new steels is needed before the high costs associated with the codification of the HT-UPS stainless steels can be justified.

Plans for Future Collaboration

Two areas for collaboration in research are being explored. One area concerns further studies of the embrittlement of the cold-worked MC-forming austenitic stainless steel tubing. Here, it is known that uniaxially-stressed specimens from cold-worked superheater tubes do not show the same sensitivity to cold work as the pressurized tubes. Additional testing of tubes in the multiaxial stress testing facility prepared for the CRADA work will be of benefit. Tubes supplied by ABB-Combustion Engineering will be evaluated at several levels of cold work and results will be compared to predictions from existing degradation models. A second area concerns Type IV cracking that occurs in weldments of advanced ferritic steel tubing. This type of cracking was observed in the T91 removed from service. Further evaluation of degradation of these advanced ferritic steel is needed to assure that they will be suitable replacements both as tubing and piping in high-temperature steam service. Tubing supplied by ABB Combustion will be evaluated and compared to expectations.

Conclusions

The HT-UPS stainless steels have significantly improved strength properties over type 304H stainless steel and are tolerate cold working for long times at temperatures to 700°C (1292°F). Commercialization of the HT-UPS steels is not practical at this time, since most interest by the boiler industry is for replacement tubing under service conditions that can be met by standard grades of 304H or the newly available Code alloys suce as 310HCbN stainless steel, T91, T92, and T23 ferritic steels. The long-time stability and embrittlement of the new Code alloys are issues that need to be addressed, and some of the technology developed for evaluating the HT-UPS stainless steels could be brought to bear on the resolution of these issues.

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