DEVELOPMENT OF ODS HEAT EXCHANGER TUBING

Quarterly Technical Progress Report

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ABSTRACT

Work continued on three major tasks of this project – increasing the circumferential strength of the MA956 tube, joining of the MA956 alloy, and determination of the high temperature corrosion limits of the MA956 alloy. With respect to increasing the circumferential strength of a MA956 tube, an additional 120 MA956 rods have been extruded (total of 180 rods) using 16:1 and 10:1 extrusion ratios and extrusion temperatures of 1000, 1075, 1150, and 1200°C. Also, approximately 40 cold work (0, 10, 20, 30, 40%) plus annealing treatments (1000, 1150, 1300°C) have been completed with sample microstructure presently being analyzed. Also, creep testing to determine the “stress threshold” curves for this alloy continues. Regarding joining of the alloy MA956, work continued on the friction welding, magnetic impulse welding, explosive welding, and transient liquid phase bonding, with joints produced using the friction, magnetic impulse and explosive welding techniques. And finally, fluid-side high temperature corrosion tests of the material have been initiated.

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INTRODUCTION

This research is seeking to develop a MA956 heat exchanger tube that will lead to the design and fabrication of a MA956 full-scale tube heat exchanger composed of the referenced alloy. The alloy MA956 is an oxide dispersion strengthened (ODS) material that possesses superior creep strength and corrosion resistance at very high temperatures (e.g. $T > 2000^{\circ}\text{F}$) compared to traditional wrought or cast alloys. However, the creep properties are unidirectional (typically stronger in the longitudinal direction compared to the transverse direction), fabrication of components made from this alloy is relatively difficult, and the corrosion limits of the alloy MA956 in coal-fired environments are not known. Thus, the technical tasks being executed in this Vision 21 project are:

Task 1: Project Management

Task 2: Improvement of Circumferential Creep Strength of MA956 Tubes

Task 3: Joining

Task 4: Bending of MA956 Tubes

Task 5: High Temperature Corrosion Limits of MA956

Task 6: Generation of Data for Designers

Task 7: Implication of ODS Properties on Heat Exchanger Design

Task 8: Reporting

The members of the team conducting this research are: Huntington Alloys (HA), Foster Wheeler Development Corporation (FWDC), Oak Ridge National Laboratory (ORNL), University of California, San Diego (UCSD), Michigan Technological University (MTU), and the Edison Welding Institute (EWI).

EXPERIMENTAL

Experimental work associated with the tasks identified in the previous section is discussed below.

Task 2: Improvement of Circumferential Creep Strength of MA956 Tubes

The following matrix of tests shown in Table 1 below is currently being performed at HA. All of the extrusions have been completed (180 total) and approximately 40 of the cold work + recrystallization treatments have been performed and the samples have been shipped to UCSD for microstructural analysis.

Table 1
Matrix of Extrusion + Cold Work + Recrystallization Parameters

Extrusion Temp ($^{\circ}\text{C}$)	Extrusion Ratio	Amount of Cold Work (%)	Recrystallization Temp ($^{\circ}\text{C}$)	Recrystallization Time (h)
1000	10:1	0	1000	0.5
1075	16:1	5	1150	1
1150	20:1	10	1300	6
1200		15		
		25		

Creep testing continues at ORNL for the purpose of determining the ‘threshold stress’ curves of the MA956 alloy. Results of this testing will be discussed in the next section.

Task 3: Joining

Friction Welding: A series of welds were made on the first lot of material received. Metallographic analysis and tensile tests were conducted on two different sets of welding parameters.

Transient Liquid Phase Bonding: Paste boriding work has resulted in the successful production of samples with uniform borided layers 3 to 5 microns thick. Work is currently underway to develop an improved method of cleaning the MA956 alloy surface after boriding. Also, tooling is being designed for bonding trials in the hot press.

Explosive Welding: Experimental setups for explosion welding of the MA956 alloy to the 601 alloy and the MA956 alloy to itself were prepared and weld trials performed.

Magnetic Impulse Welding: Joining trials using ½ inch diameter tubes have been performed.

Task 4: Bending of MA956 Tubes

Tubing has been delivered to FWDC for the bend tests.

Task 5: High Temperature Corrosion Limits of MA956

The exposure of samples of MA956 bar stock in air at 1300°C until failure, has been completed.

Task 6: Generation of Data for Designers

No experimental work has been accomplished on this task during this reporting period.

Task 7: Implication of ODS Properties on Heat Exchanger Design

No experimental work has been accomplished on this task during this reporting period.

RESULTS AND DISCUSSION

Task 2: Improvement of Circumferential Creep Strength of MA956 Tubes

Preliminary microstructural analysis of the 40 MA956 rods that have been extruded + cold worked + annealed has shown a variation in the grain structure as expected.

Results of the creep testing of specimens cut in the axial direction from the walls of a nominal 1 inch diameter MA956 tube (Heat # WBD0643) are shown in Table 2. The specimens were loaded at the initial value indicated in the table, and the load was increased by 1 ksi every 100 hours until failure. The ‘life’ values show the total exposure time and, in brackets, the time spent in the last load increment. It is important to note that the reason for performing this type of creep testing is that the excellent strength of this alloy at elevated temperature results in a relatively “flat” stress rupture curve. Thus

extremely long times can be required to cause rupture if the applied stress is below a “threshold” value where essentially no creep occurs. In order to determine the approximate value of this threshold stress for a given alloy at a particular temperature, creep tests are conducted where the sample is incrementally loaded at 100-hour intervals. Testing of further specimens is in progress at different temperatures to establish the ‘threshold stress’ curve for this alloy.

Table 2
Results of Stress Threshold Testing for the MA956 Alloy

Temp. (°C)	Load (ksi)	Life	El. (%)	LM parameter
900	7-14	860 (44)	0	45.7
950	5-14	1224 (51)	—	47.8
1000	3-8	590 (59.2)	2.4	49.4

Task 3: Joining

Friction welding: A series of welds were made on the first lot of tubing supplied to EWI and metallographic analysis and tensile tests were conducted on samples welded with two different sets of welding parameters (noted as #I2 and #I3). For tensile testing, a strip sample was taken from various points around the diameter of the tube (noted as A, B, and C). Mechanical property data for each of the welds tested are listed in Table 3. These results appear promising compared to the parent alloy properties shown in the table, however work is underway to determine cause of the variation in mechanical properties around the circumference of the joint.

Table 3
Mechanical Property Data for Two Inertia Welds

Sample Identification	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)
I2-A	99.0	85.8	4.4
I2-B	73.3	N/A	0.2
I2-C	97.1	93.3	2.2
I3-A	80.0	N/A	3.4
I3-B	99.4	80.1	7.7
I3-C	67.0	N/A	2.0
MA956*	93.5	80.2	10

* Typical properties of parent material

Transient Liquid Phase Bonding: Paste boriding work has resulted in successful production of samples having uniform borided layers 3 to 5 microns thick. Vacuum furnace annealing trials have also confirmed the need for keeping the borided layer as thin as possible in order to avoid excessive meltback (and runout) during subsequent recrystallization annealing. Work is now underway to develop improved ways of

cleaning the MA956 surface after boriding. Surfaces are currently being polished manually, but this approach is quite time-consuming and not likely to be suitable for bonding of full-scale tubes. Tooling is also being designed for bonding the MA956 rod in the hot press. Since the hot press is coming online somewhat more slowly than anticipated, interim bonding studies are being carried out using hot isostatic pressing (HIP). Six samples have now been prepared for HIP. These include three samples (recrystallized -- recrystallized, non-recrystallized -- recrystallized, non-recrystallized -- non-recrystallized) where both pieces in the bonding couple have been borided, as well as 3 bonding couples with only one borided piece. These last three coupons represent a potentially attractive process variant that would facilitate bonding of full-scale tubes.

Explosive Welding: Parametric calculations for the explosion welding of a 0.375 in. thick MA956 plate, with an estimated room temperature yield strength of 80 ksi, indicated the potential for successful welding of the 4 in. x 6 in. plate samples would be marginal. Therefore, an initial setup for an MA956-to-601 weld trial was disassembled and the MA956 plate was milled down to 0.25-in. thickness to match the thickness of the 601 plate. The setup was then shot (explosion welded) with the MA956 plate accelerated down onto the stationary 601 plate. Ultrasonic inspection of the sample indicated a non-bond at the start-up of the joint 1-1.5 in. long with the remaining 4.5-5 in. of the joint being bonded. This preliminary examination indicates a successful weld between the material couple. This plate will be examined metallographically for the purpose of studying the morphology of the bondline. If the bondline is determined to be satisfactory, shear testing of the joint will be performed.

The setup for explosion welding the first sample of MA956-to-MA956 was also prepared and welded during this quarter. Initially, the cladding or accelerated plate was milled down to 0.25-in. thickness, the same as had been done for the MA956-to-601 weld trial. The base or stationary MA956 plate, however, was not reduced in thickness, as its thickness does not effect the explosion welding collision conditions. The explosion welding parameters used to weld this sample were the same as those used on the MA956-to-601 weld trial with a minor change in the setup to reduce the amount of non-bond experienced on the initial sample shot. Following this explosion welding trial, preliminary ultrasonic inspection revealed the sample to be completely bonded over the entire 4 in. x 6 in. surface area. The sample is now in the process of being sectioned for metallographic examination of the explosion weld interface and a second set of samples of each combination (MA956-to-MA956 and MA956-to-601) is now in the process of being prepared for shooting. The parameters utilized on these shots will be based on the results of the examination of the initial two samples.

Magnetic Impulse Welding: Joining trials using ½ inch diameter tubes has shown this process to be feasible to join the MA956 alloy, however higher impact velocities may be needed and thus a new concentrator is being built for this purpose.

Task 4: Bending of MA956 Tubes

Tubing has been delivered to FWDC for the bend tests.

Task 5: High Temperature Corrosion Limits of MA956

Laboratory Testing for Working Fluid Side: The exposure of samples of MA956 bar stock in air at 1300°C until failure has been completed. The total mass change data are shown in Figure 1, and the observed and predicted lifetimes as a function of specimen thickness are shown in Figure 2. The lifetime calculations were based on a two-stage oxidation model developed using data for the MA956HT alloy, but using the oxidation rates (parabolic and linear stages) and transition oxide thickness measured for the MA956 alloy. The fit of the model appears to be good, except for the thinnest specimen. The only difference from the fit used for the MA956HT alloy was a change in the factor that qualifies the rate exponent in the 'linear' oxidation phase (f_{n3}) from 0.06 to 0.03 (see Fig. 2). Obviously, the oxidation lifetime of the MA956 alloy at 1300°C in air is significantly lower than that of the MA956HT alloy. The important difference between the two alloys appears to be that the rate of oxidation (in Stage 2 and Stage 3) is higher for the MA956 alloy. Since both alloys form the same oxide, the reason for this difference is not obvious. The oxidation rate of alumina-forming alloys can be significantly affected by doping with reactive elements such as Y, but the Y levels of the MA956 and MA956HT alloys are essentially the same (0.40 and 0.38 weight percent, respectively). Specimens will be prepared for examination of the structure and compositions of the alloy-oxide interface and the oxide grain boundaries by TEM. Further specimens are being exposed at 1250°C in air to determine lifetimes.

Laboratory Testing for Fireside Environment: The search for a typical Vision 21 gas environment continues.

Field Exposure Testing: A trip was made to one of the host utilities to survey the location for the corrosion probes and determine what equipment and modifications will be required.

CONCLUSIONS

No technical conclusions are available at this time. Work continued under Tasks 2, 3, 4, and 5.

REFERENCES

None.

Figure 1. Total mass gain data for the MA956 alloy at 1300°C, 100 cycles in air.

Figure 2. Comparison of oxidation lifetimes of the MA956 and MA956HT alloys at 1300°C in air as a function of specimen thickness. The data points indicate observed lifetimes. The solid line is the fit of a two-stage model developed from data on the MA956HT alloy.