IMPROVED ODS ALLOY FOR HEAT EXCHANGER TUBING

Cooperative Agreement # DE-FC26-05NT42238
Period of Performance: 02/28/05 – 02/27/07
DOE Project Officer: Richard B. Read
read@netl.doe.gov
Telephone: (412) 386-5721

Project Manager: Lawrence E. Brown
Edison Welding Institute
1250 Arthur E. Adams Drive
Columbus, Ohio 43221
larry_brown@ewi.org
Telephone: (614) 688-5080
Fax (614) 688-5001

ABSTRACT

The Department of Energy (DOE), National Energy Technology Center (NETL), has initiated a strategic plan for the development of advanced technologies needed to design and build fossil fuel plants with very high efficiency and environmental performance. These plants, referred to as "Vision 21" by DOE, will produce electricity, chemicals, fuels, or a combination of these products, and possibly secondary products such as steam/heat for industrial use.

Prime candidate materials being considered for a high temperature heat exchanger are oxide dispersion strengthened (ODS) alloys; however, there are some gaps in the data required to commit to the use of these alloys in a full-size plant. This project will develop an INCOLOY® alloy MA956 tube which will lead to the design and fabrication of a MA956 full-scale tube heat exchanger.

(Note: This project is a new start in FY05, thus this paper presents a brief overview description of the project. Also to be noted is that this project is the continuation of former project funded by DOE-NETL under Cooperative Agreement DE-FC26-00NT40970)

OBJECTIVE

The objective of this project is to develop an INCOLOY® alloy MA956 heat exchanger tube which will lead to the design and fabrication of a MA956 full-scale tube heat exchanger. The necessary steps required for the commercial production of such a tube are: (a) produce a MA956 tube with a significant increase in circumferential strength compared to currently available material; (b) develop the welding technology required to produce a cost-effective joint between an ODS tube and an ODS tube, and a joint between an ODS tube and a heat resistant alloy; (c) determine the critical strain the MA956 material can withstand during tube bending and not undergo recrystallization during

subsequent operation; (d) characterize the MA956 alloy in environments likely to be encountered on the inner diameter of the tube (working fluid side) and the outer diameter of the tube (fireside); (e) generate data to be used by heat exchanger designers and the ASME BPV Code; (f) analyze the data for the purpose of setting limits on the design of a MA956 heat exchanger.

The members of the team that will complete the project activities of research are: the Edison Welding Institute (EWI), Foster Wheeler Development Corporation (FWDC), Special Metals Corporation (SMC), and the University of California, San Diego (UCSD). Oak Ridge National Laboratory is also participating in aspects of the project; those activities are being funded via a previously approved Field Work Proposal (FWP FEAAA058) that was part of the original award made to SMC under 00NT40970.

The scope of work has been broken down into eight tasks. These tasks correspond to the primary activities associated with increasing the circumferential strength of MA956 tubing, flow forming of the MA956 tubing, joining of MA956 tubing, assembling property data for the alloy, and determining the implication of the property data on the design of an ODS heat exchanger. The project duration is estimated to be 24 months. A work breakdown structure and project team task activity is showed below in Figures 1 and 2 respectively.

Figure 1. Project Work Breakdown Schedule

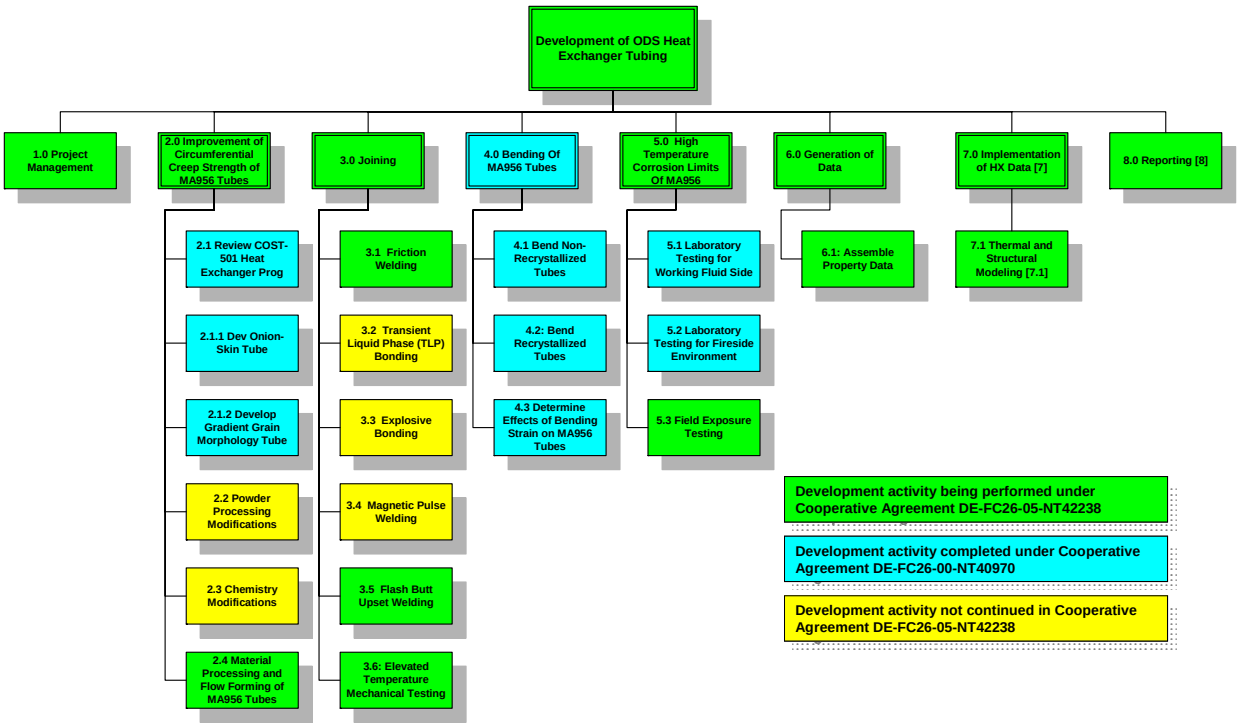
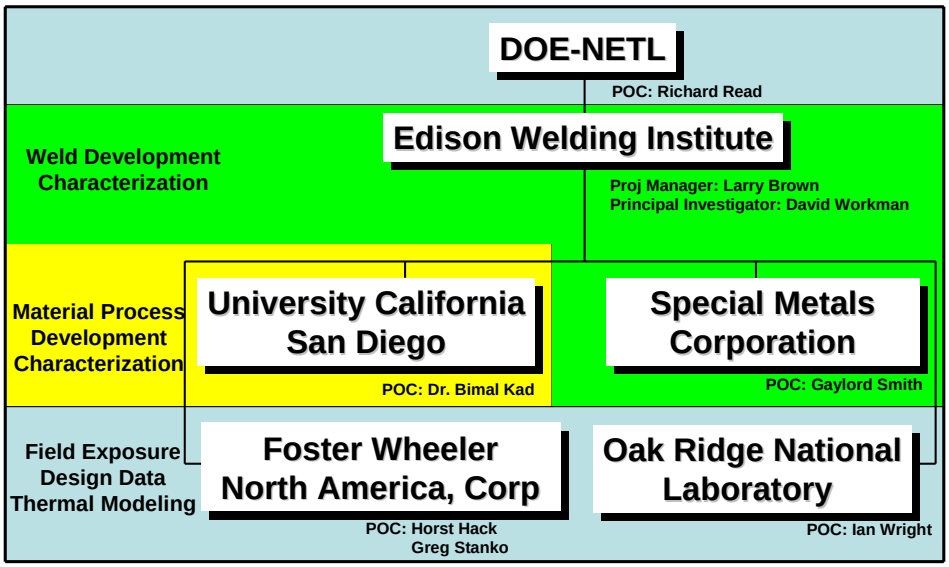


Figure 2. Project Team & Task Activity



DEVELOPMENT APPROACH

Material Processing And Flow Forming Of Ma956 Tubes

Ambient Temperature Flow Forming and Flow Spinning

- Flow Forming of un-recrystallized MA956 tubes
- Ring rolling (forging) for optimum circumferential alignment

This task seeks to effect ambient temperature MA956 material flow in an orbital/circumferential direction via flow forming techniques. For the purposes of mandrel flow forming it is expected the tube ID is essentially concentric with the out of roundness not to exceed ± 0.005". A tentative test matrix is proposed in Table 1 for the purpose of flow-forming tubes with the aid of an outside vendor. Tubes measuring 8-12" lengths, 2-1/2" diameter, with ¼" wall thickness tubes will be used in each trial.

Table 1. Flow-Forming Test Matrix for Un-Recrystallized MA956 Tubes

Material Condition	% Reduction/Pass	Wall Thickness Reductions
MA956, un-recrystallized	5%	60%, 70%, 80%
MA956, un-recrystallized	10%	60%, 70%, 80%
MA956, un-recrystallized	20%	60%, 70%, 80%

The material formability will be evaluated via the extent of wall thickness reduction (i.e., 60-80%) possible. The variable of % reduction/pass evaluates the forming rates effect on the overall process. Material hardening characteristics will be evaluated using hardness measurements. This is expected to guide the need for intermediate annealing steps to soften the worked tube. All annealing treatments will be performed in the 600-800°C temperature range to prevent any incidental recrystallization at this metalworking stage

Recrystallization and Microstructure Evaluation

- Recrystallization annealing: static and gradient
- Material texture evaluation before and after recrystallization
- Microstructure characterization and evaluation (Optical and TEM)

This task activity involves the methodical characterization of the flow-formed tubes produced in activity mentioned above. Processed tubes will be cut into segments for evaluating the recrystallization kinetics and the optimum conditions for developing a large processed grain structure. A tentative recrystallization schedule is listed in Table 2.

Table 2. Static Recrystallization of Flow-Formed MA956 Tubes

Flow-Formed Condition	Temperature	Hold Time
Initial, 60%, 70%, 80%	1200°C in Air	1 hr, 3 hrs, 6 hrs
Initial, 60%, 70%, 80%	1250°C in Air	1 hr, 3 hrs, 6 hrs
Initial, 60%, 70%, 80%	1300°C in Air	1 hr, 3 hrs, 6 hrs

The recrystallization time-temperature conditions are suggested following initial work in this program on cold worked MA956 rods. It is expected that this matrix will yield the best combination of flow forming and consequent thermal treatments to develop the coarse grain aligned structure critical for hoop creep applications. In addition, where needed, gradient recrystallization treatments will be conducted in the 1200-1300°C temperature range employing a high-intensity traversing heating source as a means of improving the control of the secondary recrystallization process. Samples will be cut from the processed tubes (see Table 1, 2) in the longitudinal and transverse orientations and examined via optical and transmission electron microscopy (TEM) methods.

Creep Performance Evaluation: Stress Rupture and Threshold Tests

Running concurrently with the above two tasks, this activity will evaluate the ultimate success of each task for its improved high temperature stress-rupture and creep performance. This applies to both the metal forming, as well as, the recrystallization. In recognizing the through-thickness

gradient nature of the flow forming process, creep test specimens are to be constructed from the entire section thickness. Creep tests are proposed for flattened strip specimens (longitudinal (**L**) and transverse (**T**) orientations) to be conducted in accordance with the ASTM E139-00 testing standard. A tentative test matrix is proposed in Table 3.

Table 3. Stress-Rupture and Creep Testing of Flow-Formed MA956 Tubes

Recrystallization	Orientation	Test Temperatures
1200°C, Time (1-3-6 hrs)	**L, T**	800, 900, 1000°C
1250°C, Time (1-3-6 hrs)	**L, T**	800, 900, 1000°C
1300°C, Time (1-3-6 hrs)	**L, T**	800, 900, 1000°C

The creep and stress-ruptures test will be conducted in a combination format: 1) initially incremental 1ksi loading will be applied after each 100 hour exposure till failure, following which 2) constant threshold stress loads will applied to record long term exposure exceeding 1000 hours. For example a transverse test is commenced at 2ksi stress initially – and the stress incremented following each 100 hours of exposure till the specimen fails at a value of '**n**' ksi. This test will then be followed by a constant stress test at '**n-1**' ksi to achieve a 1000 hour exposure at otherwise similar test conditions. If the sample fails before the 1000 hours exposure, the stress will be reduced to '**n-2**' ksi and the test repeated until we can reproducibly obtain the 1000 hour threshold exposure. Given the high stress sensitivity of the material, it is expected that this iterative testing method will provide a quick but robust evaluation of the threshold performance stresses for the longitudinal (**L**) and transverse (**T**) orientations. As-processed and crept microstructures will be evaluated by optical, scanning (SEM) and transmission electron microscopy (TEM) techniques.

Joining Development

A joining study is being conducted to determine and understand the best method to join an ODS tube to an ODS tube and the best method to join an ODS tube to a heat resistant alloy (e.g., the 214 or 617 alloy). Emphasis are being placed upon solid-state joining process procedures to produce a cost-effective weldment for joining the ODS tubing.

Weld development will be performed as follows:

- Material Couples
  - MA 956/MA 956 (with and without recrystallization treatment)
  - MA 956/ heat resistant alloy (MA 956 recrystallization treatment prior to welding)

- Joining Processes
  - Friction Welding
  - Friction Stir Welding
  - Flash Butt Upset Welding
- Limited Characterization for Process Screening
  - Mechanical Testing
  - Metallographic Examination

Initial development has been performed with friction welding. The process is described in Figure 3 with a representative microstructure show

Figure 3. Description of friction weld process

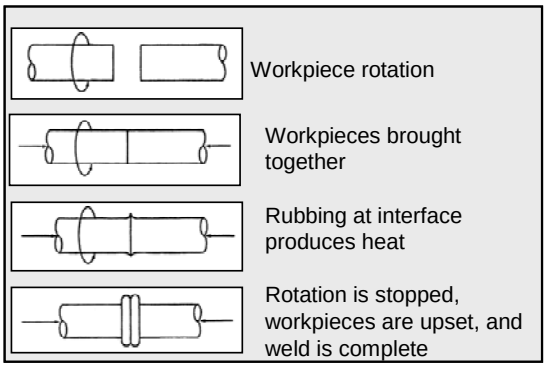
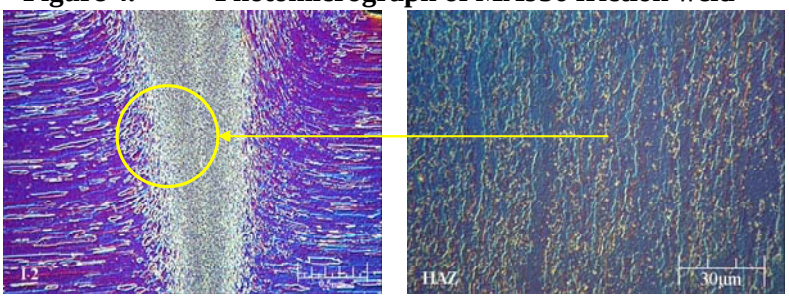


Figure 4. Photomicrograph of MA956 friction weld



Field Exposure, Analysis and Modeling

The effect of fireside corrosion on MA956 in an actual coal-fired boiler at 2000°F and 2200°F will be studied using air-cooled probes. Air-cooled probes will be fabricated with three temperature zones, for testing at 1900-2000°F, 2000-2100°F and 2100-2200°F. Testing to be performed as follows:

- Install air-cooled probes in one coal-fired boiler.
- Maintain air-cooled probes for 12,000 hours at coal-fired boiler.
- Conduct post-test analysis of samples (optical, SEM), in order to evaluate morphology, and determine corrosion rates.

Assemble Property Data

Data generated in the above tasks will be added to that available from the ORNL program, and supplied to designers.

Thermal and Structural Modeling

This work will reveal design considerations, accounting for the axial and hoop stresses of MA956 heat exchanger tubes subjected to multi-axial loading. The result will be a set of design guidelines to be followed by the heat exchanger designer. These guidelines will allow designers to more readily incorporate the MA956 tubes in various designs, and accelerate commercialization of this technology.