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Oxide Dispersion Strengthened Steel (14YWT) Tube Fabrication and Processing

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Introduction

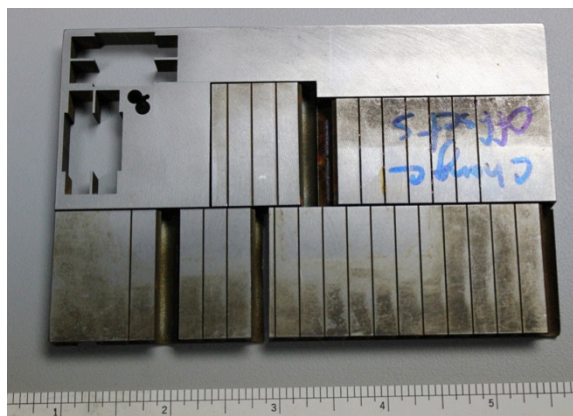
In order to support the Fuel Cycle Research and Development program funded by the US Department of Energy [1], irradiation testing of thin-walled tubes fabricated from Oxide Dispersion Strengthened (ODS) steels is required. Tubes will be irradiated in the BOR-60 reactor in Dimitrovgrad, Russia, for 10-20 dpa at 370°C and 410°C. This report summarizes efforts to process plate ODS material into tubing, and gives details of the 32 tubes submitted for irradiation testing.

Initial Material Processing Trials

14YWT material was supplied in plate form in two heats, PM2 and FRCD-NFA1, as shown in Figure 1, with the nominal compositions of Fe-14Cr-3W-0.4Ti-0.20Y-0.014O (wt. pct.).



(a)



(b)

Figure 1 – Images of plates (a) PM2 after removal of the initial 0.250-inch swaging trial sample, and (b) FRCD-NFA1 after electro-discharge machining (EDM) of 32 tubes.

Initial studies began with the PM2 plate. In order to ensure the material has sufficient ductility to perform room-temperature deformation processes, a sample piece was swaged. Swaging was chosen as the preferred method for deformation, as it is designed to reduce cylindrical sections. Example images of the swaging equipment and dies are shown in Figure 2.

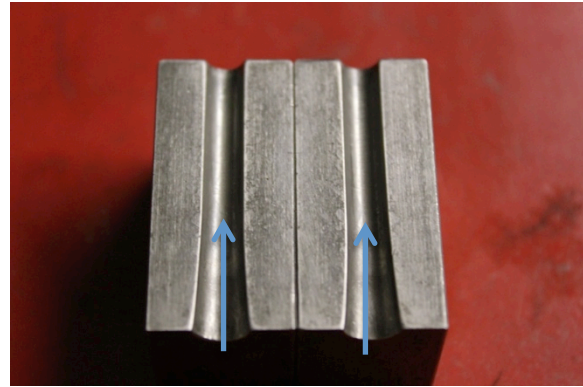
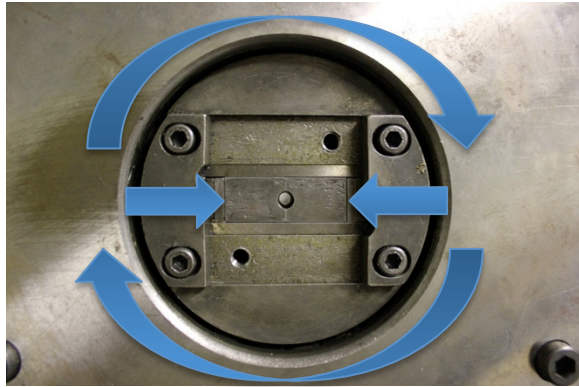
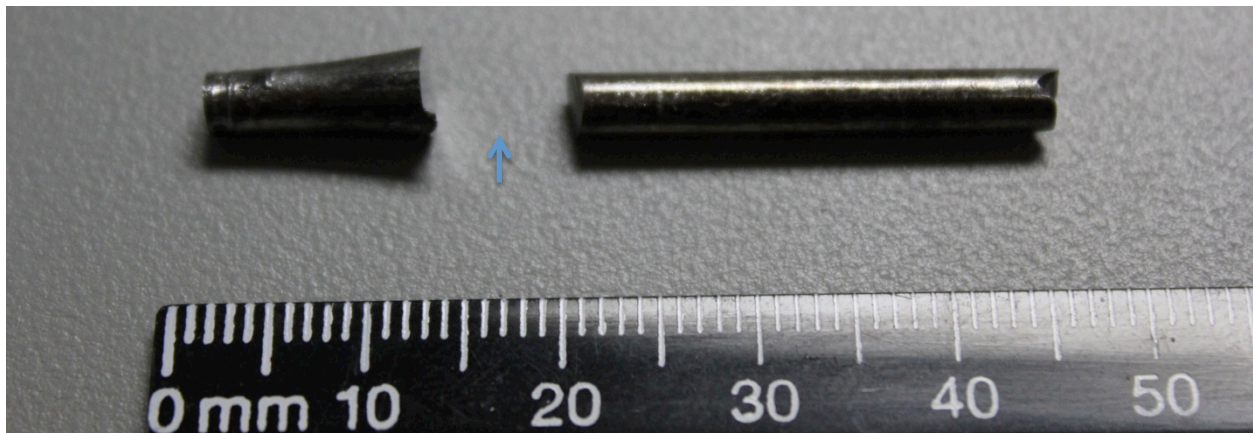
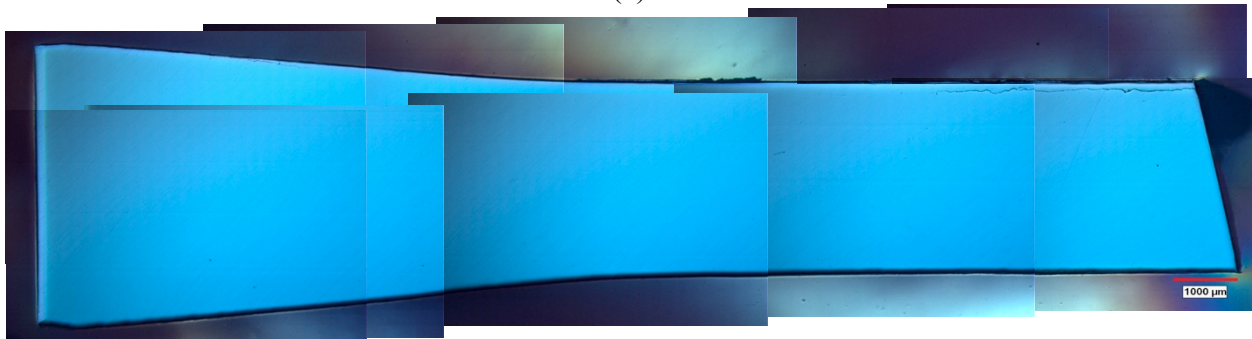


Figure 2 – (a) Rotating mechanism of the Torrington 211 model 2-die swager used in swaging trials, with working dies in the center. As the mechanism rotates, the working dies are forced together intermittently to reduce the work piece. (b) Inside faces of working dies showing the gradual reduction in diameter as the piece is fed through the swager, with arrows showing the feed direction.



(a)



(b)

Figure 3 – (a) Piece from PM2 after initial swaging trial, and with metallographic sample removed. (b) Metallographic images of the swaged material, showing a small amount of cracking on only the highly-reduced section.

A 0.250-inch diameter x 1-inch long cylinder was removed from the PM2 plate with the long axis perpendicular to the rolling direction. This 0.250-inch diameter cylinder was successfully swaged at room temperature to a diameter of 0.150 inch in a single pass, which results in a 64% area reduction. Images of the as-swaged material are presented in Figure 3, with (a) a photograph with an arrow showing the location of the metallographic sample, and (b) a reconstructed optical metallographic image of a radial section of the as-swaged piece in (a). Note a small amount of sub-surface cracking on the top of the reduced section in Fig 2(b), which disappears as the amount of reduction decreases (toward the left of the image). Despite the cracking, these encouraging initial swaging trials indicate the material shows sufficient ductility, and is expected to be able to be deformed as long as controlled reduction increments are used.

Based on the promising initial swaging trial results, swaging trials for thin-walled tube making were initiated. These trials required (1) appropriate mandrel material to support the tubing during swaging without deforming, (2) swaging dies designed to give small amounts of reduction per pass, allowing annealing between passes to achieve the desired reduction, and (3) EDM fabricated tubes with wall thicknesses of greater than 0.010-inch.

Mandrel materials

In order to reduce the wall thickness of the as-EDM fabricated tubes, the material must be swaged to reduce wall thickness, or outside diameter (OD), without decreasing the inside diameter (ID) dimension. An example schematic of swaging over a mandrel is shown in Figure 4. Several materials were considered to use as mandrels, but the essential requirement is higher strength than the material to be deformed. Since the yield stress and hardness of the 14 YWT in the annealed condition are 1475 MPa and 45 HRC, respectively, rods of O1 tool steel were chosen to use as mandrel material. O1 tool steel has a yield stress and hardness of 2200 MPa and 60 HRC in the oil-quenched (hardened) condition. O1 tool steel drill rods were procured and swaged to size in the annealed condition. Swaging of hardened O1 tool steel rods was attempted, and, as expected, resulted in no diameter reduction.

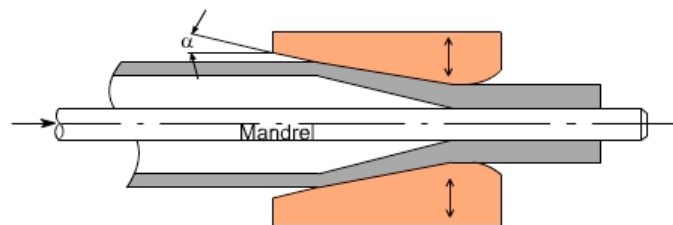


Figure 4 – Schematic of swaging process over a mandrel. In this case, the ID and OD are reduced, which results in an increase in wall thickness. For thin-walled tube manufacturing described here, the initial tube has the same ID as the mandrel diameter, and only the OD of the tube is reduced (which also results in lengthening of the tube). Image from [2].

Swaging dies

Since initial swaging trials suggested that minimizing reduction per pass would reduce the risk of sub-surface fracture, a set of seven dies were designed to produce tubing with a final OD of

0.180-inch, and reduction increments limited to approximately 10% per pass from an initial OD of 0.220-inch. Images of the dies are shown in Figure 5, along with the dimensions for each reduction.



(a)

0.2200 to 0.2110	(5.59 to 5.36 mm)
0.2110 to 0.2035	(5.36 to 5.17 mm)
0.2035 to 0.1970	(5.17 to 5.00 mm)
0.1970 to 0.1915	(5.00 to 4.86 mm)
0.1915 to 0.1870	(4.86 to 4.75 mm)
0.1870 to 0.1830	(4.75 to 4.65 mm)
0.1830 to 0.1800	(4.65 to 4.57 mm)

(b)

Figure 5 – (a) Set of seven swaging dies designed for thin-walled tube fabrication. (b) Dimensions for each die, resulting in seven reductions of approximately 10% from 0.220-inch to 0.180-inch.

EDM-fabricated tubes

Three tubes were removed from plate PM2 via electro-discharge machining (EDM) with dimensions of 1.25 inches in length (approximate, full width of the plate), 0.160-inch inside diameter (ID), and 0.190-inch outside diameter (OD), as shown in Figure 6. All three tubes were annealed for one hour at 1100°C in a vacuum furnace.



Figure 6 – Tubes EDM fabricated from plate PM2 with dimensions of 1-inch in length, 0.190-inch OD, and 0.160-inch ID.

Three separate swaging trials were attempted on the three tubes: (1) Swaging to final size (0.190 to 0.180 inch OD) in one pass on an annealed O1 tool steel mandrel, (2) swaging to final size in one pass on a hardened O1 tool steel mandrel, and (3) swaging in one 10% pass (0.190 to 0.187 inch OD) on a hardened O1 tool steel mandrel. These trials were designed to test whether (1) hardening of the mandrel material is necessary, (2) larger reductions (33%) are possible, and (3) smaller reductions (10%) are possible. Results of swaging trials showed that swaging reductions of approximately 10% on a hardened O1 tool steel mandrel are possible for the

14YWT material tested here. Figure 7 shows the results of the swaging trials, which support the need for hardened mandrels and limiting reductions to 10% per pass. In order to meet reactor insertion dates, manufacture of tubes for irradiation studies via swaging was halted in order to produce tubes to final size by EDM fabrication. Future work to optimize the swaging process will be performed, which will include swaging material from 0.220-inch OD diameter tubes to 0.180-inch diameter tubes using the seven-step die set and full annealing between each deformation step. These initial results suggest that this processing path has a high probability of success.



Figure 7 – Tubes resulting from swaging trials. (a) Tube swaged on annealed O1 tool steel mandrel, showing resulting cracking. (b) Tube swaged 33% on hardened O1 tool steel mandrel, also showing significant cracking. (c) Tube swaged 10% on hardened O1 tool steel mandrel, showing no cracking.

Tubes Manufactured for Reactor Testing

Reactor testing required 32 total tubes. Of these, 24 were specified to have dimensions of 1.22 inch in length and 0.138 and 0.180 inch in ID and OD, respectively. The other 8 were specified to have dimensions of 1.05 inch in length and 0.158 and 0.180 inch in ID and OD, respectively. In addition, each tube was to be marked with a laser-engraved timing mark and identification

numbers. ID numbers were to be L101-L104 and L201-L204 for the 8 shorter tubes, and L105-L116 and L205-L216 for the 24 longer tubes.

These tubes were manufactured directly from the FRCD-NFA1 plate by EDM fabrication. For each of the tubes, the long axis is parallel to the rolling direction, which is perpendicular to the extrusion direction (see Figure 1). Each tube was then polished on the OD surface to remove the recast layer from EDM processing. These tubes were then laser-engraved with the appropriate timing mark and identification number, as shown in Figure 8.

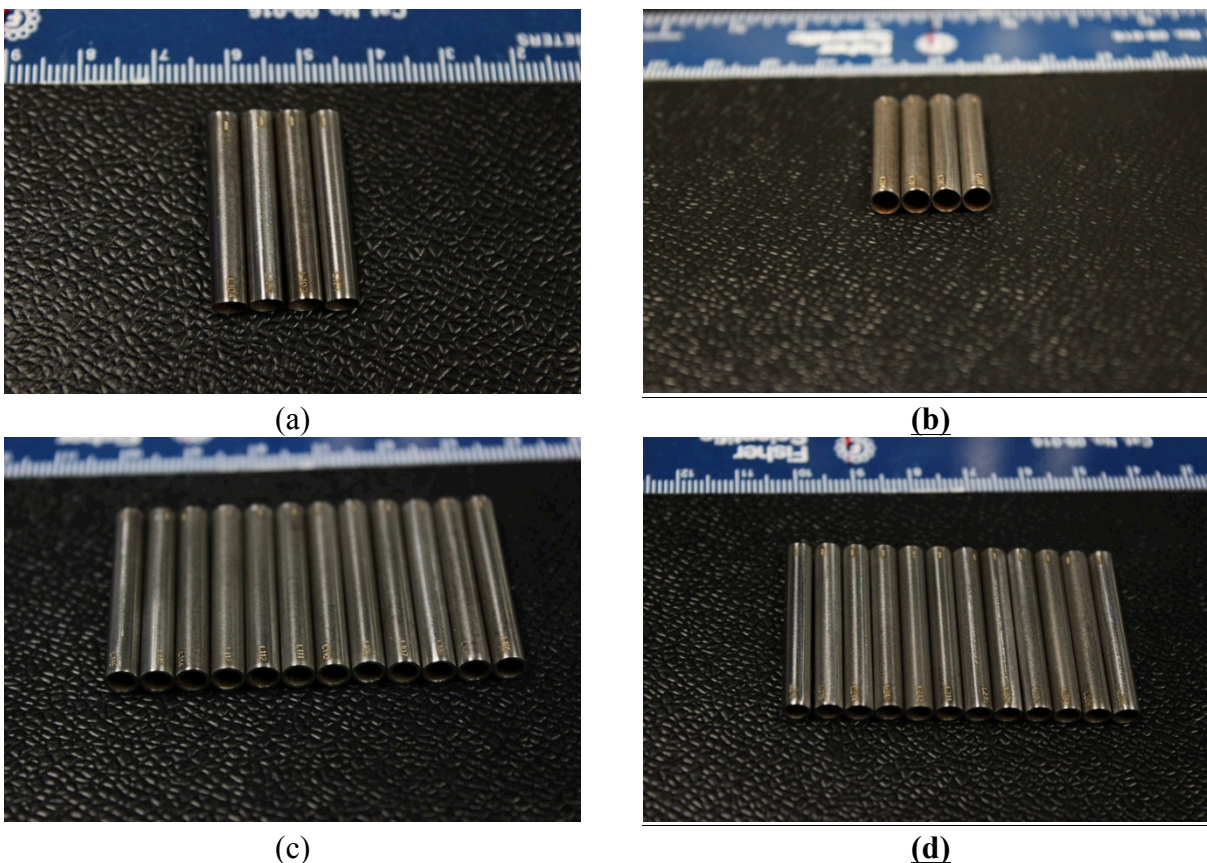


Figure 8 – Tubes submitted for irradiation testing. (a) Tubes L101-L104. (b) Tubes L201-L204. (c) Tubes L105-L116. (d) Tubes L205-L216.

Summary

- The 14YWT material in tube form was shown to have sufficient ductility at room temperature to swage in reductions of approximately 10% wall thickness.
- Hardened tool steel (O1) has sufficient strength to use as mandrel material during swaging of 14YWT material at room temperature.
- Swaging dies were designed and manufactured to process the 14YWT material from thick-walled EDM fabricated tubing (0.220 inch OD, 0.160 inch ID) to thin-walled tubing (0.180 inch OD, 0.160 inch ID).
- EDM fabrication has the precision to manufacture thin-walled tubing directly from as-rolled plate suitable for reactor testing. Laser marking of these materials was also successful.

ACKNOWLEDGEMENTS

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2. Image from <http://www.nptel.iitm.ac.in/courses/Webcourse-contents/IIT-ROORKEE/MANUFACTURING-PROCESSES/Metal%20Forming%20&%20Powder%20metallurgy/lecture3/lecture3.htm>, accessed on 6-15-13.