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Reviewed by:

PNNL Project Manager

[Signature on file]

Ronald P. Omberg
Abstract

The Nuclear Technology Research & Development program of the Office of Nuclear Energy has implemented a program to develop an advanced reactor cladding fabrication capability by using the extrusion and pilgering processes. Oxide-dispersion strengthened (ODS) steels are a promising class of advanced materials, but processes need to be developed to produce tubing for these advanced alloys. The Pacific Northwest National Laboratory (PNNL) has converted its rolling mill into a lab-scale pilger mill, which required designing pilger tooling and rolls that contained multiple pilgering grooves and designing a servo-driven feed mechanism. Upon assembling and checking out the system, initial pilgering runs were completed. This report will provide verification of the design and performance of the lab-scale pilger mill.
## Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>14YWT</td>
<td>steel cladding material that has been used in liquid metal reactors</td>
</tr>
<tr>
<td>CCW</td>
<td>counter clockwise</td>
</tr>
<tr>
<td>CW</td>
<td>clockwise</td>
</tr>
<tr>
<td>HRC</td>
<td>Rockwell hardness scale C</td>
</tr>
<tr>
<td>NTRD</td>
<td>Nuclear Technology Research &amp; Development</td>
</tr>
<tr>
<td>ODS</td>
<td>Oxide-Dispersion Strengthened</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>ROA</td>
<td>reduction of area</td>
</tr>
<tr>
<td>SW</td>
<td>SolidWorks</td>
</tr>
</tbody>
</table>
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1. EXECUTIVE SUMMARY

Pilgering is a promising technique for fabricating advanced alloys such as oxide-dispersion strengthened (ODS) cladding (MA956 and 14YWT) suitable for producing tubing for reactor use. This project is using the lab-scale pilger mill located at the Pacific Northwest National Laboratory (PNNL).

2. BACKGROUND OF DEVELOPMENT OF PILGERING PROCESSES

PNNL has been focused on the development of pilgering processes for the external cladding layer of nano-ferritic materials such as 14YWT. This report will summarize the verification and development that have occurred for the advanced reactor cladding tube pilgering processes.

Figure 2.1 shows the commercial scale pilgering process which has been widely used to make thin-wall tubing and nuclear fuel cladding (Strehlau 2006.)

Figure 2.1. Commercial Scale Pilgering

Pilgering has many advantages compared to the drawing process. Pilgering can produce high levels of cold deformation in hard-to-process ODS, as well as produce advantageous textures in the material. The pilgering process allows for higher reductions of area (ROA) in a single pass than the cold draw process. This higher ROA potential is a result of the compressive nature of pilgering. The groove design on a pilger die can optimize the percent ROA as the pilger die grooves are not round and therefore compresses the tube incrementally. This “out of roundness” controls many aspects of a tube, such as outside diameter size, surface finish, and mechanical properties. The feed rate can be used to alter the measured yield strengths in the as-pilgered condition and be used to control the mechanical properties such as surface roughness by manipulating the contact stress. Many pilger processes allow for various mandrels to be used, such as straight taper, curved, or cylindrical.

3. PNNL LAB-SCALE PILGER MILL

PNNL has modified a rolling mill to perform lab-scale pilgering. Figure 3.1 shows the PNNL setup. Commercial pilgering is a large-scale operation, therefore PNNL’s lab-scale pilger mill
allows for the greater flexibility that is needed with research and development. The PNNL design has rolls with multiple pilger grooves which allows for different reduction ratios to be obtained without requiring tooling changes. The PNNL design also is servo motor-driven versus mechanically driven. This allows for incremental changes to the degree of die rotation as well as the tube feed rate and die rotation synchronization.

Figure 3.1. Modifications to the PNNL Rolling Mill for Lab-scale Pilgering
4. PILGERING DESIGN METHODOLOGY

The conversion of the rolling mill to a pilger mill consisted of removing the mechanical linkages that connected the gear motors to the roll dies. The pilger mill system was designed to use indexable servo motors that are connected to the large drive rolls directly. This design allows for more flexibility in the degree and speed of die rotation.

The following four figures depict the modifications that were done to the rolling mill to create the PNNL lab-scale pilger mill. Figure 4.1 shows the PNNL roll modification for pilger grooves. The roll modifications utilize six grooves, with six different ROA.

![Figure 4.1. Roll Modification with Pilger Groove Locations](image-url)
The feed rate, rotation, and groove design all impact the resulting ROA. Consequently, it is possible for some of the grooves to be used for more than one of the reduction passes. For example, ROAs in the high 30s and low 40s may use the same groove, whereas the 11% ROA and the 77% ROA are drastically different than other ROAs, requiring their own groove designs.

Table 4.1. 14YWT Optional Reduction Schedules and Resulting ROA

<table>
<thead>
<tr>
<th>Option</th>
<th>Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>2</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>65%</td>
</tr>
<tr>
<td>3</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>64%</td>
</tr>
<tr>
<td>4</td>
<td>77%</td>
</tr>
</tbody>
</table>

The flexibility inherent with this six groove design permits multiple passes to be conducted without die changes. Furthermore, synchronization of the servo-die-feed rotation can be programmed with software without the need for mechanical linkage modifications. Figure 4.2 illustrates the complexity of the groove radius that changes incrementally with the change in tube dimensions. The radii create the “out-of-round” die grooves. The subtle widening of the entry radius allows for an optimum level of work without compromising the tube integrity. The ROAs that drive these groove changes have been initially selected as shown in Table 4.1.
Figure 4.2. Groove vs Tube Radius Incremented with ROA

Figure 4.3 shows the mill modification for the tube feed mechanism. The tube feed mechanism utilized a cylindrical mandrel to control the tube Inside Diameter (ID). Figure 4.4 shows the feed mechanism chuck design for the mandrel/tube. The feed mechanism was designed to move laterally so as to line up with each pilger groove (grooves A-C). The feed mechanism motor is a
servo motor like that of the roll drives. This allows for a common program to synchronize the roll-feed rotation. Furthermore, grooves 1A-1C utilize 180 degrees of each roll and grooves 2A-2C utilizes the opposing 180 degrees.

Figure 4.4. Feed Mechanism Chuck Design for Tube
5. PROCUREMENT AND FABRICATION OF THE ROLLS

The procurement and fabrication of the two rolling mill rolls used similar processes with several differences for each roll. The machining/precision grinding of the two rolling mill rolls were physically similar but had differing pilgering roll orientations for the precision cold working of the difficult to process nuclear cladding materials. The grooves had one-quarter symmetry in the plan view but had continual reduction in area in the rotation direction of the roll. They were also oriented differently in each roll, with a total of six (6) different groove segments located on three (3) groove locations across the length of the rolls.

The two rolls were manufactured from A-6 steel, heat treated to HRC 58 through-hardness. The two rolls had identical groove geometries and overall dimensions but were machined and finished in different clockwise orientations. The manufacturing of the rolls required multi-axis computer numerical control (CNC) machining, including rotational positioning of the work piece, and stress-free precision grinding was required for final dimensional finish. The overall finish requirement for the rolls were for precision grinding of all surfaces to 8 or better root mean square (RMS) in the final heat-treated condition. This high level of surface finish required pre-machining of the groove profile followed by immediate heat treatment and final precision grinding of all groove dimensions to a finish of 8 RMS or better. This high level of surface finish was required for the development of the desired metallurgical texture and for release and rotation of the tube on the feeding mandrel.

PNNL provided the manufacturer a machining language SolidWorks (SW) data file that contained complete dimensions, geometries, and models for the rolls, along with the release section for each groove and the required tolerances and surface finish requirements. The machining language file also contained the specific geometry of the grooves and dimensional tolerances of the overall roll geometry that allowed it to fit into the existing PNNL rolling mill. All radii needed to be smoothly blended in the final heat-treated rolls. Although the basic roll design is identical, the two rolls were identified as the upper (U) roll and the lower (L) roll for identification during subsequent machining of the pilgering grooves. The two rolls were required to meet final dimensional, hardness, and surface finish requirements after the pilgering grooves were machined and the rolls were heat treated.

Figure 4.1 shows the upper and lower roll with the locations of the pilgering grooves. Each roll had six (6) different pilgering grooves machined into the basic roll form at three (3) specified locations. As described above, the pilger grooves were quarter symmetrical in the plan view and taper continuously from the initial datum point to the release pocket. The upper (U) roll when viewed end-on from the square roll drive boss will need to rotate in the clockwise (CW) direction over a work rotation of approximately 180 degrees. The lower (L) roll will need to rotate in a counter clockwise (CCW) direction and the grooves in each roll will be indexed to the exact starting point of the pilger groove large area end. Because of the different rotation direction of the U and L rolls, the pilger grooves needed to be machine into the rolls with opposite orientation. For the upper roll, the pilger groove started from the starting datum (large area end start of the groove) and was tapered in a CCW direction. For the lower roll, the pilger groove started at the datum mark and tapered in a CW direction. This orientation requirement applied to all six pilgering groove profiles at the three groove locations. The six pilger grooves were
identified for the upper and lower rolls as follows, and were etched or scribed along with a datum line locating the start of the pilger groove (large area):

Upper Roll (U) U1A, U1B (Groove location 1); U2A, U2B (Groove Loc. 2); U3A, U3B (Groove Loc. 3)

Lower Roll (L) L1A, L1B (Groove Loc. 1); L2A, L2B (Groove Loc. 2); L3A, L3B (Groove Loc. 3)

A second datum line was indicated in the SW groove geometry file that corresponded to the maximum reduction section of the groove. PNNL provided the SW model of the dimensional profile of all six grooves that included the location of the grooves. Again, grooves on the upper roll tapered from large to smaller in the CCW direction, while grooves on the lower roll taper large to small in the CW direction.

Figure 5.1. Close up of As-Received Pilger Roll
Figures 5.1 shows a close up of one of the rolls, with the different groove segments located on three (3) groove locations across the length of the rolls. Figure 5.2 show the as-received pilger rolls.

Figure 5.2. As-Received Pilger Rolls
6. INSTALLATION AND PROGRAMMING OF TUBE PILGER ROLLS

The mill and the control system logic are designed to operate in multiple configurations including tube pilgering. Tube pilgering will use the infeed actuator plus a rotating servo-drive wrist to both infeed and twist the tube. In later applications the outfeed actuator may also be used to tension the tube for improved straightness and reduced roll separation force. This variable configuration requires quick disconnects for the electrical connections to the infeed, outfeed, and rotating wrist. It also requires that the mill controls recognize these components are present or missing and work accordingly.

Tube Pilgering: Control System Functionality, Input Data, and Output Data

During tube pilgering, the control system coordinates the motion of the two tube pilgering rolls plus the motor-driven infeed, the actuator and the mandrel rotational stepper motor. The user input data defines the specific pilgering process. The controller records output data during pilgering to evaluate the process loads.

The controller functionality consists of:

1) Control Electronics: The controller must a) coordinate the motion for all motors, b) provide a user interface to program and control the system, and c) collect data during operation. PNNL staff will develop the control system programming to meet the project needs.

2) Working Roll Position: Encoders are mounted on the two working rolls to control and record the position of the roll shafts. The position of the drive motor shafts can also be recorded and the recording used to monitor the clash between the drive rolls and the working rolls.

3) Roll Drive Motors: The two roll drive motors will be electronically synchronized using an automation controller’s electronic gearing function. The motors work through a 40:1 ratio gearbox to provide the high torque and low speed that is required. The rolls will start at an indexed position, rotate to a specified angle (i.e., between approximately 120 to 240 degrees), and reverse back to the home position for each cycle. Hundreds of cycles will be required to process a specimen. One roll drive motor will be the master motor, and the other roll drive motor will be electronically geared to it.

4) Infeed Motor Actuator: The infeed actuator controls the position of the tube and mandrel between the rolls during the pilgering operation. The relationship of infeed position and roll rotation is specified in an input file provided by the user. The tube also in-feeds a specified increment between forward and backward passes of the rolls. A load cell monitors the axial force applied as the tube passes through the rolls. Back tension on the infeed and forward tension on the outfeed are used in rolling processes to reduce the roll separation force. Control can be based on the load applied as the specimen feeds through the roll, or a position that is synchronized to the roll motors, or a combination of both. This will be an option implemented through the control system programming. Manual control of the infeed will be included to position the tube in the mill prior to starting the pilgering process.

5) Interlocks are defined and programmed into the control system to ensure safety of the equipment and operators. Interlocks include monitoring roll motion, roll separation force, and torque limits to ensure they remain below maximum specified values. The motors are
electronically geared together so that if the master motor stops, all other motors will also stop. The machine interlocks are defined as input to the controller. Knee activated emergency stop bars are located on the infeed and outfeed sides of the mill. An emergency stop function is also programmed into the touchscreen control panel as well.

**Input Data:** The following input data define the tube pilgering process:

1) Equipment limit loads: Motor/gearbox limit torque, linear actuator limit force, and others.
2) Each pilger pass is defined by a series of die rotations vs. linear feed positions. The linear feed position is based on the length of groove per degree of die rotation. The linear feed position is adjusted with a factor from 0.5-1.5 to incrementally adjust the amount of linear force per degree of die.
3) Linear feed increment between pilger passes. This, along with the roll rotation vs. linear infeed, define the total reduction achieved by pilging.
4) Pilger cycles per minute. Note each cycle is comprised of a forward and a backward pass. The linear infeed is incremented at the end of each forward pass and again at the end of each backward pass. Therefore, 30 cycles per minute is 60 pilger passes per minute.

**Output Data Recording:** The pilger mill is designed to be capable of 60 pilger passes per minute, and each pass is defined by at least 40 data pairs of roll rotation versus linear infeed position. Therefore, the minimum data acquisition rate is 50 times per second (50 Hz), or every 20 milliseconds. The following data will be recorded during the pilger pass for post investigation of the forming process:

1) Roll separation force at each of four mill stand pillars
2) Torque (motor current) at each of two roll drive motors
3) Infeed position
4) Outfeed position
5) Tube feed actuator rotation in degrees
6) Die rotation angle at each of two working rolls
7) Infeed force
8) Outfeed force
9) At least four additional data ports to allow expansion of the control algorithm or collection of additional process data.

The pilger process will work in the following sequence:

1. Dies begin positioned at the end of the 0° pocket
2. The tube moves a specified distance with the pocket as the die rotates
3. The dies rotate to the 30° groove engagement point to start the reduction with the synchronized linear feed
4. The dies rotate synchronized with the feed motion (pulling the tube away from the dies) until the tube reduction finishes
5. The dies continue to rotate synchronized with the feed motion through the sizing zone
6. The dies continue to rotate to the end of the 180° pocket with synchronized feed and tube rotation
7. Cycle is repeated.
Run menus are designed to provide the operator with controls to monitor and command the system through each operation. Each tube pilgering run menu (Figure 6.1) will contain the necessary controls and data required to safely operate the tube pilgering process in that mode.

Figure 6.1. Menu for Tube Pilgering Run
7. DESIGN AND FABRICATION OF STAINLESS STEEL SPECIMENS

Multiple four foot sections of 304 SST tube with the dimensions shown in Table 7.1 were procured. This enabled the use of stainless steel specimens to test out the installation and programming completed to control the pilger mill. The purchased stainless steel tube was drilled out with the desired lengths to acquire the desired IDs. Figure 7.1 shows the stainless steel tube with the pilger mandrel inserted prior to pilgering.

Table 7.1. Table of Dimensions

<table>
<thead>
<tr>
<th></th>
<th>Desired Dimensions based on Measurements</th>
<th>Dimensions Ordered</th>
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<tbody>
<tr>
<td>Outside Diameter (OD)</td>
<td>0.379 – 0.367</td>
<td>0.375</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>0.0773 – 0.0797</td>
<td>0.083</td>
</tr>
<tr>
<td>Inside Diameter (ID)</td>
<td>0.224 – 0.208</td>
<td>0.209</td>
</tr>
<tr>
<td>Drill bit sizes:</td>
<td>0.221 – 0.228</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.1. SST Tube with Pilger Mandrel Inserted
8. VERIFICATION OF TUBE PILGERING DEVELOPMENT PROCESS

Figure 8.1. Incremental Pilgering with Lubrication – SS Tube Exiting

Figure 8.1 shows the incremental steps as the pilgered SS-304 tube exited on the initial reduction pass. The pilgering utilized “nickel never seize” as lubricant on both the mandrel and the exterior of the SS-304 tube.

Figure 8.2. Pilgering Run 1 / Comparison of SS-304 Tubes Pre- and Post Pilgering

Figure 8.2 shows the result of the pilgering run 1 pre- and post pilgering. The tube next to the ruler is prior to pilgering. The tube at the top of the picture is post pilgering, with two reduction steps (utilizing groves 0.379 and 0.360). This pilgered tube is not to final dimensions.
Figure 8.3. Pilgering Runs 1 & 2 / SS-304 Tubes Pre- and Post Pilgering

Figure 8.3 shows the result of pilgering runs 1 and 2 for the multi-grove pilger process. The SS-304 tube at the top of the picture is prior to pilgering. The tube in the middle is post pilgering, with two reduction steps (utilizing groves 0.379 and 0.360). The tube above the ruler is post pilgering, with two reduction steps (utilizing groves 0.379 and 0.340) with the mandrel still in the pilgered tube. These pilgered tubes are not to final dimensions.

Figure 8.4. Pilgering Runs 1 & 2 / SS-304 Tubes Pre and Post Pilgering Design Verification

Figure 8.4 shows the results of the pilgering runs 1 and 2 which verified the design of the rolls, and the installation and control software for the multi-grove pilger process. The SS-304 tube shown at the top of both pictures is prior to pilgering. The one in the middle is post pilgering, with two reduction steps (utilizing groves 0.379 and 0.360). The tube above the mandrel and the ruler is post pilgering, with two reduction steps (utilizing groves 0.379 and 0.340). The mandrel itself is removed and positioned above the ruler. These pilgered tubes are not to final dimensions. Table 8.1 shows the tube dimensions, both pre- and post pilgering.
<table>
<thead>
<tr>
<th></th>
<th>Outside Diameter (OD)</th>
<th>Inside Diameter (ID)</th>
<th>Wall Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial SS Tube</td>
<td>0.375</td>
<td>0.199</td>
<td>0.088</td>
</tr>
<tr>
<td>1st Pilger Run</td>
<td>0.328</td>
<td>0.19</td>
<td>0.069</td>
</tr>
<tr>
<td>2nd Pilger Run</td>
<td>0.306</td>
<td>0.19</td>
<td>0.058</td>
</tr>
</tbody>
</table>
9. RESULTS, STATUS & PATH FORWARD OF ROLLING MILL-BASED PILGERING

![Development Process for Multi-Step Rolling Mill-Based Pilgering Diagram]

Legend: 
- **Completed**
- **To Be Done**

Figure 9.1. Development Process for Multi-Step Rolling Mill-Based Pilgering
10. BIBLIOGRAPHY

https://www.thefabricator.com/article/tubepipeproduction/introducing-cold-pilger-mill-technology