4th International Ingot Casting Rolling Forging (ICRF) Conference
21–23 June 2022, Pittsburgh, Pa., USA
DOI 10.33313/530/001

Manufacture of Large Superalloy Ingots and Extruded Pipes

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Keywords: Vacuum Induction Melting, Electroslag Remelting, Vacuum Arc Remelting, Extrusion, Pipe

INTRODUCTION

Projects to develop and demonstrate high-efficiency advanced energy systems that could operate continuously at 700°C and above have been underway for more than 20 years. The primary goal of these projects has been to reduce the quantity of carbon dioxide emissions per unit of delivered electric power. One such project is the US Department of Energy/Industry collaborative project known as the Advanced Ultra-Supercritical (AUSC) Steam Boiler initiative. This project was administered by the National Energy Technology Lab (NETL) with significant technical input from the Electric Power Research Institute (EPRI) and Oak Ridge National Lab (ORNL). The goal of this project was to develop technology to enable the development of a coal fired Rankine cycle steam power plant that would operate at 760°C[1-5]. The initial phase of the project included an analysis and definition of material requirements for critical components of the boiler and steam turbine, a broad survey of properties of applicable materials and a down select of materials for more extensive characterization. INCONEL® alloy 740H® was selected for further evaluation for boiler tubing and steam transfer piping. This alloy is a γ' strengthened nickel-base alloy that was developed specifically for the application[6]. Characterization of the alloy under this program by NETL, ORNL and various consortium members supported a data package that resulted in the first ASME Boiler & Pressure Vessel Code Case for an age-hardened nickel-base alloy for use in welded construction for service in the time dependent property temperature range[7]. The second phase of the AUSC project that has just been completed involved demonstration of the capability of the US manufacturing supply chain to produce full scale, or largest possible, critical boiler and turbine components. Special Metals was tasked with producing steam header and reheater pipes and a "wye" forging. This involved initially making the largest possible alloy 740H ingots and extruded pipes. The manufacture of the wye forging that was tasked to Scot Forge will be reported separately. This paper describes the ingot production and extrusion processes and acceptance test results. A more detailed presentation and analysis of material properties and formability will be presented later.

Materials of welded construction for coal-fired power plants have historically included ferritic and austenitic steels and occasionally solid solution strengthened nickel-base alloys. However, the relatively low strength of these materials under the temperature and pressure goals of the AUSC program result in excessive wall thickness and low steam transfer capacity. The case for higher strength materials was laid out at the start of the program[1]. For boiler tubing, creep strength of at least 100 MPa at 100,000 h, steam and coal ash corrosion resistance, fabricability and weldability were required. For steam transfer pipe, only steam corrosion is involved, but due the pipe wall thickness, weldability challenges are much greater. Based on evaluation of lab scale and then small-scale production, alloy 740H met the program requirements. An initial scale up for pipe production conducted in 2011, demonstrated a pipe 15" OD X 3.5" W with properties meeting ASME requirements[8,9]. A 21,000-pound, 30-inch diameter VIM/VAR ingot, the largest made to that time, was used for the project. The demonstration Phase 2 of the AUSC project required much larger ingots and pipes. While no major manufacturing issues were encountered in the initial scale-up, potential problems were anticipated for Phase 2. Given the likelihood of solidification segregation in ESR, it was determined that either VIM/VAR or VIM/ESR/VAR melting practices would be needed. At Special Metals the largest diameter VAR crucible is a nominal tapered 36" diameter. That defined the largest ingot size possible. The primary concerns were VAR arc instability causing solidification segregation and catastrophic electrode stress cracking. For extrusion the concerns were cracking, processing difficulties caused by the auto-aging nature of the alloy and insufficient force to pierce the ingot during the blocking operation.

Age-hardened nickel-base alloys were initially developed to support the manufacture of components for aircraft gas turbine engines. The size requirements were modest so the production of 20” diameter VAR ingots weighing approximately 8,000 lb became common practice. Production equipment at many companies was sized to produce and handle these ingots. Gradually, larger ingots were applied for non-critical uses such as forging dies and low temperature static parts. While it was known that certain alloys such as 706 were capable of much larger section size[10], ESR and VAR instability made routine production unreliable. This situation changed dramatically in the early 1990’s when GE and its’ ingot suppliers perfected large-ingot triple melt (VIM/ESR/VAR) technology to develop alloy 706 for large-frame gas turbine wheels and rotors weighing up to 15,000 pounds[11]. This process was enabled by a sound electrode that greatly improved VAR arc stability and reduced the likelihood of freckle segregation. As alloy 706 has very poor as-cast ductility and hence is sensitive to residual stress induced cracking, advances in thermal management during ingot processing were needed to prevent catastrophic electrode cracking. Measures such as hot stripping, hot transfer and electrode annealing were key to the success of this effort. The commercial implementation of this capability led to its application to other γ'' strengthened nickel alloys such as 625 and 718[12,13]. With this background, the present project sought to extend the technology to the more rapidly age hardened γ' strengthened alloy 740H and to large diameter extruded pipe.

RESULTS AND DISCUSSION

1. Manufacturing Design for Ingots

The project had the primary objectives of making the largest possible pipe and wye fittings possible from alloy 740H. The pipe dimensions were constrained by extrusion press limits, but also by ingot size. Ingot size at the Special Metals Huntington facility is constrained by furnace crucible working height and hence charge weight and the maximum electrode pour height. Previous extrusions made from 30-inch diameter VIM/VAR ingot indicated that a 36-inch diameter ingot (Special Metals largest diameter VAR crucible) made from a full-pour 34-inch diameter electrode could yield approximately 25,000-pound ingot that would provide sufficient material for two trial extrusions. However, a wye fitting designed to accommodate the planned pipe sizes would require an even larger ingot. Based on the existing practice for alloy 706, it was decided to make a 39-inch electrode that would consume the maximum VIM melting volume. This electrode would be remelted in ESR to a 44-inch “ingode” which would subsequently be forged to approximately 34-inch diameter that would be suitable after conditioning for remelting in VAR. An additional size constraint is the maximum safe liquid height in the VAR crucible. Combing all for these factors into the plan it was judged that a 30,000-pound cropped, and ground ingot was possible. The pipe sizes were selected based on advice from OEM and Electric Utility members of the AUSC project team for the minimum viable dimensions of header and reheater pipes for an 800 MW facility. These sizes roughly corelated with previous estimates by Klingensmith for the maximum 740H pipe sizes that could be made on the Wyman-Gordon Houston press[8]. The wye fitting was based on a 30,000-pound starting ingot, expected forging envelope losses and accommodation of a 28-inch OD outlet.

Although conventional melting, refining, and casting procedures were to be used for the VIM consolidation melt, more detailed analysis was required to support selection of ESR and VAR remelting parameters. The ESR process was simulated using the MeltFlow-ESR™ software developed by Innovative Research, llc[14]. The development, validation and application of this model is reported by O’Connell et al[15]. The model predicts local solidification time, thermal profile (pool depth), fluid flow, slag skin thickness and a Raleigh model-based freckle criterion. A representation of the output is shown in Figure 1. By running a series of simulations, it was possible to design start-up, main step and hot top conditions. The VAR process was simulated using Solar, a software package developed by Universite de Lorraine, Nancy, France[16]. Additional detail about the use and results of these simulations will be presented at the Liquid Metals Casting and Processing Conference[17].

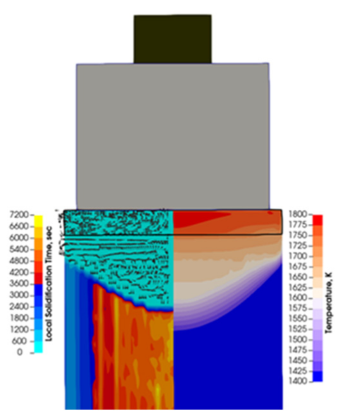

Figure 1. Representation of output for ESR simulation using MeltFlow-ESR

1.1 Vacuum Induction Melting

Conventional nickel-base superalloy charging, melting, and vacuum refining procedures were used for each of the three heats. A mixture of raw material and about 50% same or similar alloy scrap was used. All electrodes were poured to full height with weights of 37,180 and 37,453-pounds for the 34-inch electrodes and 47,686-pounds for the 39-inch electrode. The electrode composition for each of the alloys, based on a furnace dip sample taken after final additions, is shown in Table I along with the aim composition range. VIM melting was generally uneventful with no recorded process deviations. The electrodes were teemed through a multi-chamber tundish into pre-heated cast iron molds. Following a defined cooling period, the still hot electrodes were transferred to a mill furnace and subjected to a full solution anneal. A process deviation did occur during electrode annealing of HT9039JS when the electrode was inadvertently pulled from the furnace before it had fully cooled. This may have caused the VAR melt rate excursion that is discussed later. A photo of one as-cast electrode is shown in Figure 2a.

Table 1: Composition of alloy 740H heats, ladle and ingot.

	Header Pipe Heat No. HT9067JY (VIM/VAR)			Reheater Pipe Heat No. HT9039JY(VIM/VAR)			Wye Forging Heat No. HT9484JW (VIM/ESR/VAR)			Aim Composition Range	
Element	**Ladle**	**Head**	**Toe**	**Ladle**	**Head**	**Toe**	**Ladle**	**Head**	**Toe**	**Min**	**Max**
C	0.04	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.04	0.02	0.05
Mn	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.2	0.5
Fe	0.4	0.4	0.4	0.6	0.6	0.6	0.5	0.6	0.6		1.5
Si	0.15	0.15	0.15	0.15	0.14	0.15	0.16	0.15	0.14	0.1	0.25
S	0.0004	0.0003	0.0003	0.0012	0.0006	0.0007	0.0004	0.0001	0.0001		0.0015
Ni	49.4	49.4	49.4	49.3	49.3	49.3	49	49.2	49.0		Bal.
Co	20.0	20.1	20.0	20.0	20.1	20.0	20.0	19.8	20.1	18.0	22.0
Cr	24.5	24.6	24.6	24.5	24.5	24.5	24.7	24.6	24.8	23.5	25.5
Mo	0.48	0.48	0.48	0.49	0.48	0.49	0.49	0.61	0.49	0.35	1.0
Al	1.50	1.49	1.50	1.49	1.49	1.50	1.55	1.51	1.56	1.3	1.6
Ti	1.47	1.42	1.46	1.48	1.42	1.46	1.48	1.50	1.42	1.3	1.6
Nb	1.6	1.5	1.6	1.6	1.5	1.6	1.5	1.5	1.5	1.4	1.6
W	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		0.1
N	0.004	0.001	0.004	0.003	0.006	0.003	<0.001	0.005	0.005		0.015
Zr	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.03	0.01	0.03

1.2 Electroslag Remelting

This process step was applied only to heat HT9484JW that was to be used for the wye fitting. After annealing the electrode was lightly ground and a nickel alloy stub was welded to the toe. The electrode was then remelted, head down using a cold start with an oxyfluoride slag mixture. The remelting process lasted approximately 32 hours. The remelting profile consisted of the usual start-up, main step and hot top phases. The main step phase being done under melt-rate control. The resulting melt trace is shown in Figure 3. The operation went very smoothly and provided an almost perfect trace. The minor variations in melt rate result from fluctuations in the AC power supply and are not material related.

Following completion of the ESR process (power off) the ingode was cooled in the crucible to enable the slag to fully solidify. It was then stripped from the crucible and immediately transferred to a nearby stress relief furnace for equilibration. Figure 2b illustrates the extreme temperature gradient that exists along the length of the ingode after it is removed from the crucible. The stress field combined with poor as-solidified ductility is a common cause of catastrophic cracking of large superalloy ingots. Following the 24-hour equilibration treatment, the ingode was transported by truck with an insulated box from Burnaugh, KY to Huntington, WV (~27 miles). Figure 2c shown the ingode on the truck bed in the Huntington mill as the hot box was removed. The ingode at that point was uniformly hot.

Figure 2. a) As-cast VIM electrode, b) ESR Ingode after stripping, c) Equilibrated ingode delivered for forging.

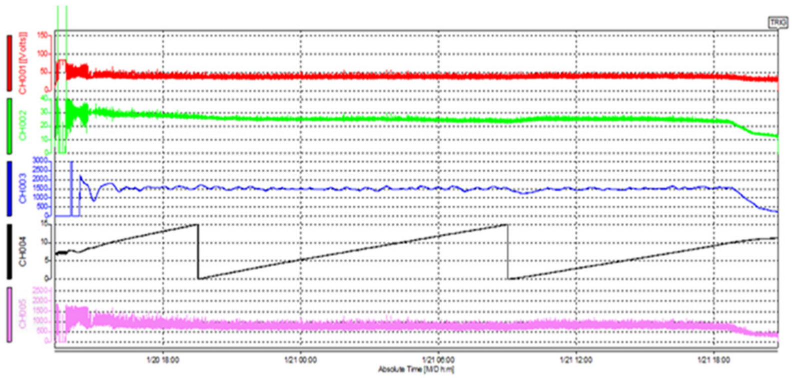

Figure 3. ESR remelt trace: Red = Volts, Green = Amps, Blue = Melt Rate, Black = Ram Travel, Purple = Power.

The next step in the manufacturing process for the triple melt ingot was draw forging of the nominal 44-inch diameter ingode to a diameter suitable for VAR on the Huntington 4500-ton Erie hydraulic forge press. The hot practiced ingode was charged into a mill furnace and soaked at 2100°F. The target forge diameter of 34-inch was accomplished in three steps with reheats. The first step in the forging process is shown in Figure 4a. Light surface cracking was seen on the first forging step. This superficial cracking is commonly seen in γ'-strengthened nickel-base alloys. It is due to the surface of the forging falling below the γ' solvus where ductility is reduced. The cracks did not propagate during the second and third forging step. The cracks which are visible on the end of the cooled ingode (Figure 4b) were removed with surface grinding. After grinding the head and toe of the ingode was cropped to square the ends and to remove any possibility of slag contamination.

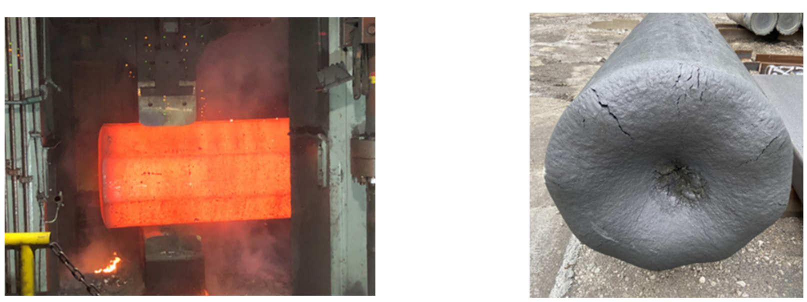

Figure 4. a) Forging 44-inch diameter ingode, b) Ingode after forging.

1.3 Vacuum Arc Remelting

For VAR of nickel-base alloys, it is essential that the surface of the electrode be clean and free of oxide. All three electrodes were spiral ground to an approximate diameter of 33-inch. Nickel alloy stubs were welded to the electrode head so that it is remelted toe down onto 740H starter plates. Based on the results of the VAR process simulation, VAR melting parameters were selected to provide optimum conditions for segregation-free solidification.

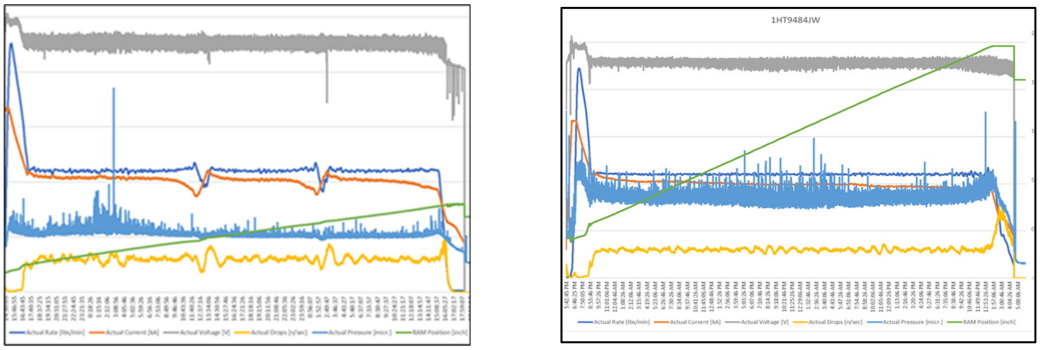

Figure 5. VAR remelt trace. a) HT9039JY, b) HT9484JW. Gray = volts, Green = ram travel, Dark Blue = melt rate, Red = amps, Light Blue = pressure, Yellow = drop shorts.

The VAR traces for HT9039JY (double melt process) and HT9484JW (triple melt process) are shown in Figure 5a-b. The trace for HT9039JY shows two melt rate excursions (MRE, dips in the dark blue line) that were probably caused by residual stress cracks in the interior of the electrode. While the disturbance is prominent on the melt trace, there was no external evidence of this MRE and it apparently had no effect on the pipes that were made from this ingot. The second double melt ingot HT9067JY showed a much more stable melt trace with no indication of an MRE. That was also true of the triple melt ingot HT9484JW shown in Figure 5b. After completion of the VAR process the ingots were stripped from the crucible and then allowed to cool for 48-hours in an insulated cooling can. Figure 6a shows on of the ingots in the shop after the can was removed. The ingots were subsequently homogenized for 48-hours at 2200° and slow cooled to minimize residual stress. The final steps included grinding, liquid penetrant testing and cropping head and toe. The final ingot weights were HT9039JY: 28,732-pounds, HT9067JY: 26,110-pounds and HT9484JW: 30,250-pounds. The latter ingot was actually larger, but it required an additional crop to accommodate the L/D limit requested by the forger. This ingot is shown in Figure 6b.

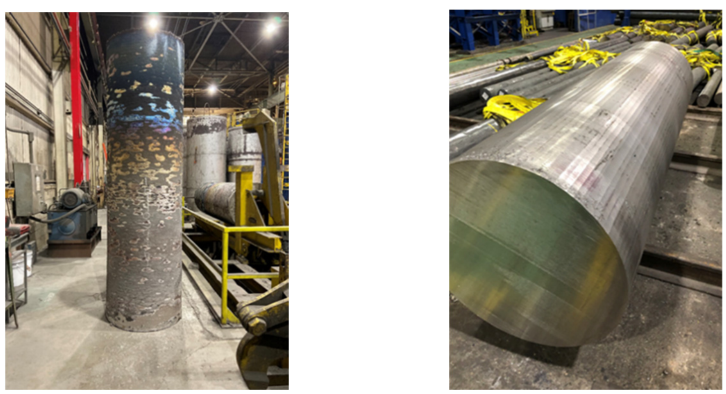

Figure 6. a) VAR ingot after stripping, b) Homogenized, ground and cut ingot.

Limited testing short of a full ingot cut-up is possible for these large ingots. The customary head and toe macro-etch slices were taken for each ingot. The slices were etched in 3:2:1 solution of H_2O, HCl and H_2O_2. The slices are taken to reveal cracks and structural features such as white spot, tree ring, center segregation, inclusions and freckle. ASTM A604 standards were used for the acceptance criterion. No rejectable indications were found. Figure 7a-b shows photos of the slices for HT9484JW.

A strip was cut across the ingot center for chemical analysis. The acceptance test was taken from the mid radius. These results are contained in Table 1. Very little change was noted from the ladle chemistry. Additional chemistry samples were taken at the ingot head. Any center segregation tendency would be revealed by this test. The results for HT9039JY are shown Figure 8a-b for niobium and titanium respectively. The differences recorded are considered insignificant and somewhat surprising for such a large ingot.

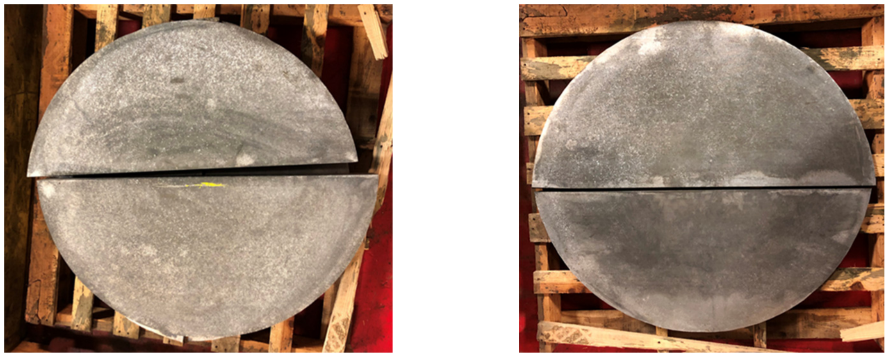

Figure 7. Macro-etch slices for heat HT9484JW, a) Head, b) Toe

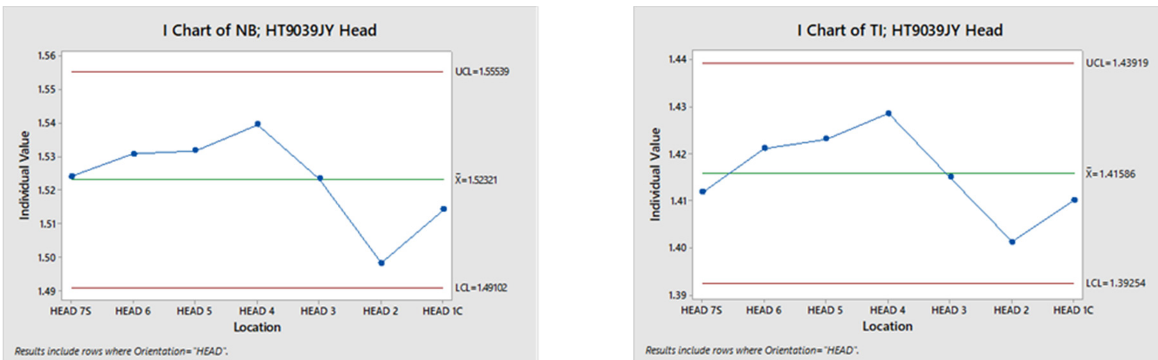

Figure 8. Composition traces at ingot head, a) Niobium, b) Titanium.

2. Manufacturing Design for Pipes

The pipe extrusions were performed on the 35-KT press at the Wyman-Gordon plant in Houston, TX. This is the largest press of its type in the United States. This press has extruded much of the heavy-wall alloy steel pipe used for coal-fired power plants. It had previously been used to produce the prototype 15-inch OD by 3.5-inch wall alloy 740H pipe[8]. While this pipe was much smaller than those needed for a full-scale power plant, the project demonstrated that the alloy had sufficient ductility to withstand the process and that it had properties after heat treatment in heavy section that met the ASME code case requirements. The goal of the present project was to demonstrate the capability of making pipes of a size to be used in a full-size Advanced Ultra-supercritical power plant. The primary concern for processing was that the piercing and extrusion forces would exceed the press safe limits resulting either in stalling or excessive surface chilling resulting in cracking. A general view of the two Wyman-Gordon presses is shown in Figure 9. The 14-KT press in the foreground is used for blocking and piercing; while the 35-KT press in the background is used for extrusion.

Figure 9. Wyman-Gordon Presses, Left: 35KT extrusion press; Right: 14KT blocking and piercing press.

The extrusion process used by Wyman-Gordon is somewhat unique in that the pipe is extruded vertically upward rather than horizontally. A schematic of the process is presented in Figure 10a-c. In the first step an ingot or billet is blocked by expanding it against a die. In some cases, multiple blocking operations are required to input sufficient strain to break up the cast structure.

The second step is vertical piercing. The alloy is back extruded along the shaft of the piercing ram. Following a reheat and if necessary, surface conditioning, the alloy is forward extruded into a pipe. The emerging pipe is gripped by a crane fixture to facilitate transfer and laydown.

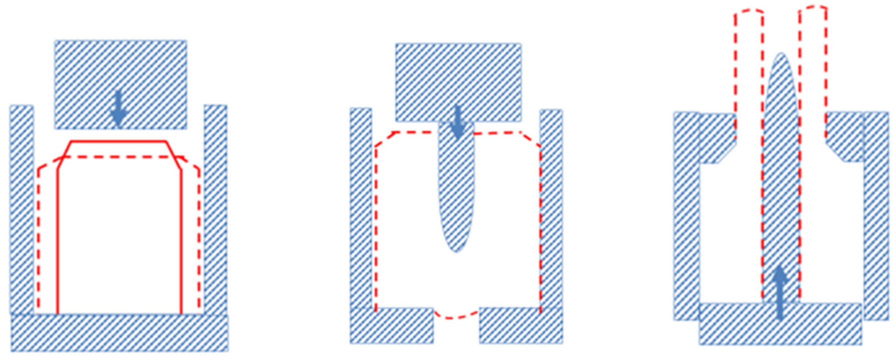

Figure 10. Schematic of Wyman-Gordon pipe process, a) Blocking, b) Piercing, c) Extrusion.

In planning for this demonstration project it was recognized that, due to the high flow stress of alloy 740H, it would not be possible to extrude the largest pipe sizes currently used for coal-fired power plants. The target sizes were based on advice from the AUSC project team and a spreadsheet of projected possible sized generated from the previous alloy 740H pipe extrusions. Two specific configurations were defined: 1) a heavy-wall pipe that would represent a size needed for a high pressure steam header pipe, and 2) a larger diameter thin-wall pipe that would represent the steam reheater. The former was expected to approach the extrusion press load limit. The latter, representing a much more difficult extrusion, would challenge the piercing press load limit and also pose greater challenges for cracking and dimensional control. The final design goals were 1) 22 ± 0.20 inch OD, 3.7 + 0.74/-0 inch minwall; and 2) 28 ± 0.20, 1.5 + 0.30/-0 inch minwall. Both pipes ordered per Special Metals PS-112 Rev 0, which required mill solution anneal plus sonic and hydrostatic testing and supply of nose and tail test rings to Special Metals for acceptance and other mechanical property testing. These first of a kind extrusions were performed on a best effort basis and commercial specifications may vary based on the experience gained in this project. One significant departure from previous 740H extrusions was to employ a mild steel can designed to reduce surface thermal gradient. It was also decided to cut the ingots in half so that two extrusions could be made. While this compromised the goal of making the largest possible pipe, it allowed for a backup and procedure modification if a problem occurred on the first extrusion.

2.1 Pipe Extrusion

The four extrusions were performed iteratively over a period of a year. Modifications and adjustments were made on the fly to overcome problems experienced. The details of individual extrusions will be included in the final contract report to be published by OSTI. All four extrusions were ultimately successful as discussed below, however, surface cracking and dimensional issues, primarily on the thin wall pipes, were experienced. While all of the ingots were canned as shown in Figure 11a, the can became detached on the second header pipe and it was extruded bare. Wyman's proprietary lubricant Camlube plus a glass frit coating were used on all extrusions. The nominal process steps included initial charging into a black furnace, slow ramp and intermediate temperature hold with a final soak at 2150°F. After blocking and piercing the billet were set out for air cooling and inspection and in the case of one pipe of each diameter machined to remove cracking. The billets were then reheated and extruded at 2150 or 2175°F. A photo of one of the header pipes air cooling on the runout table is shown in Figure 11b. The residual steel can was then removed, and the pipes were solution annealed per ASME Code Case 2702 at 2025°F ± 25°F for 4.4-hours (header) or 2.25-hours (reheater) and water quenched. After annealing the pipes were straightened, cut and ground to size. Residual cracks were removed by spot grinding. As expected, the larger diameter thin wall pipes were more difficult to clean up on the OD. The ID surface was ground while the OD surface was ground and polished. Following this the pipes were checked for dimensions, ultrasonic inspected and hydrotested. Photos of two of the finished pipes are shown in Figure 12a-b.


Figure 11. a) Billet ready for blocking, b) As-extruded pipe.

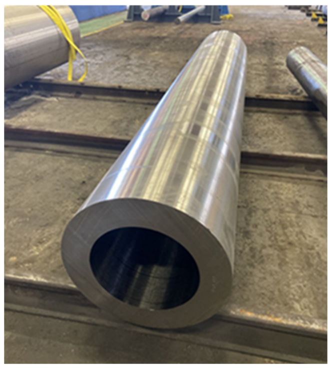


Figure 12. a) 22-inch OD x 4-inch W header pipe, b) 28-inch x 2-inch W reheater pipe.

2.2 Pipe Testing and Properties

The pipe dimensions as reported on the Wyman-Gordon product certificate of performance are shown in Table II. Pipe length was specified as "product of extrusion" which accounted for the uncertainty that the entire extruded pipe would clean up when the min-wall criterion was applied. Additional losses are accounted for by test rings and UST standards so the billet length was not maximized. Consequently the product yield data shown in Table III underestimate the actual pipe length capability. The 22-inch diameter header pipe was well within the ordered dimensional tolerance although the wall was left on the heavy side to minimize ID grinding. The 28-inch reheater pipes had more excentricity, especially the second pipe for which the blocker was not machined. This combined with more OD and ID cracking meant that while the pipes met the min-wall criterion, they were undersize on the OD in places. Measured straightness and ovality met Wyman-Gordon internal standards for all pipes. Based on these results it is concluded that the current process is capable for pipe wall down to about 2-inches, but additional process improvement is needed to meet the original goal of 1.5-inches.

All pipes received ultrasonic examination per ASTM E213 using a 740H reference standard with 5% ID and OD notches. The pipes received a helical scan using a pulse echo technique with the search unit in fixed position. Water was the couplant. There were no rejection level indications. The pipes were also hydrotested to a pressure of 1000-psi with no failed tests.

Table II. Pipe dimensions.

	Max/	Head 1"		Head 2'	Center	Tail 2'	Tail 1"		Ovality, %		Eccentricity, %		Length,	Wgt,	Straight
Pipe	Min	OD	Wall	Wall	OD	Wall	Wall	OD	Head	Tail	Head	Tail	ft	lb	ness
Header 1	Max	21.98	3.97	3.93	21.98	3.96	3.93	22.02	0.49	0.42	2.7	1.7	11.15	8585	0.20
	Min	21.87	3.75	3.80	21.92	3.81	3.80	21.92							
Header 2	Max	21.94	3.91	3.92	21.94	3.96	3.93	21.93	0.06	0.11	0.9	1.2	10.38	8065	0.18
	Min	21.92	3.85	3.86	21.92	3.84	3.83	21.90							
Reheater 1	Max	27.54	1.78	1.84	27.67	1.76	1.75	27.63	0.17	0.5	6.3	2.2	16.7	8455	0.18
	Min	27.49	1.57	1.58	27.54	1.68	1.68	27.54							
Reheater 2	Max	28.03	1.98	1.92	28.01	1.95	2.01	28.01	1.34	0.38	8.7	7.7	14.5	7740	0.18
	Min	27.74	1.66	1.66	27.9	1.78	1.72	27.9							
Order Requirements: SMC PS-112;															
Header: OD = 22.00 ± 0.20; W = 3.70 + 0.74, - 0.00															
Reheater: OD = 28.00 ± 0.20; W = 1.50 + 0.30, - 0.00															

Table III: Product yield summary

Heat No.	Pipe	Billet Wt, lbs	Pipe Weight, lbs	Yield, %
HT9067JY-11	Header 1	12,900	8,585	66.6
HT9067JY-12	Header 2	13,140	8,065	61.3
HT9039JY-11	Reheater 1	14,366	8,455	58.9
HT9039JY-12	Reheater 2	14,366	7,740	53.9

All the pipes were delivered to Special Metals in the solution annealed condition. Test rings (5.5-inches long) were aged in electrical resistance heated box furnace by a commercial heat treater. The aging treatment for all test rings was 4-hours at 1472°F followed by air cooling. Mechanical property testing was designed primarily to ensure acceptance to ASME Code Case 2702 requirements and to verify product uniformity. Much more extensive testing including creep-rupture and fatigue has been proposed for a future DOE program. Creep-rupture testing of other 740H pipes extruded on the Wyman-Gordon 35KT press showed rupture life consistent with the consolidated data used to establish the ASME code case design stress allowables.

Based on previous observations that alloy 740H significantly auto-ages in heavy section components on cooling from solution treatment, through wall hardness testing was conducted on each quadrant of the first header and reheater pipes. Representative data for the header pipe taken before and after the age hardening treatment are shown in Figures 13a-b. There was no significant difference in these profiles around the pipe circumference or end to end. It can be seen in Figure 13a that below a surface layer of about ¼-inch, there has been substantial auto-aging. The full age hardening treatment produced a uniform hardness across the pipe wall. This high hardness of the solution annealed pipe needs to be considered when planning bending, straightening, or cutting operations.

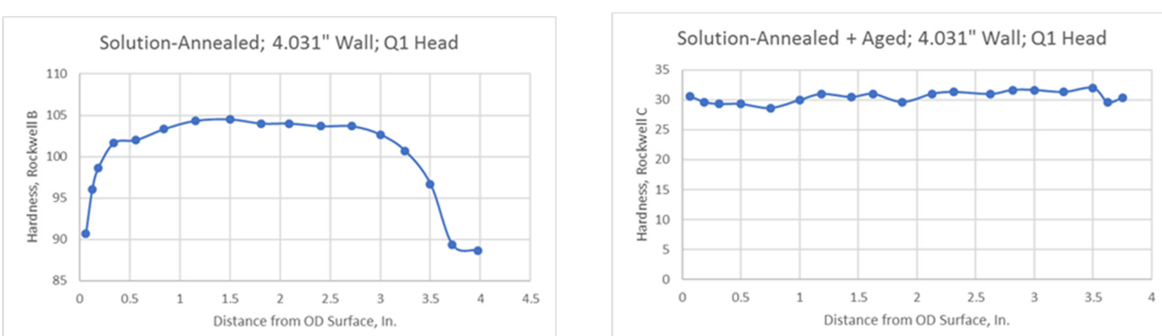

Figure 13. Hardness traverse through wall of header pipe: a) Solution annealed, b) aged.

Room temperature mechanical property data for each pipe are reported in Table IV along with data from other large 740H pipes previously extruded at Wyman-Gordon. The data match reasonably well despite the variations in pipe size, methods of heat treatment and the fact that the product of five VIM master heats are represented. All are well in excess of the required yield and tensile strength and ductility. The availability of the thick wall pipe provided the opportunity to measure directional properties. This data is presented in Table V. As expected, circumferential and through-wall ductility and impact toughness were lower, but still adequate. Longitudinally oriented carbide stringers are presumed to cause the reduction in ductility.

Table IV: Summary of room temperature mechanical properties

Pipe Size (OD/W)	Project	Aged	0.2% YS (ksi)	UTS (ksi)	Elong. (%)	RA (%)	CVN (ft. lb.)‡	GS (ASTM)
22" OD x 3.7" W	A-USC	Ring*	106.4	164	38.6	41.2	95.5	2
22" OD x 3.7" W	A-USC	Ring**	109.6	164.1	34.7	34.5	55.9	4
28" OD x 1.5" W	A-USC	Ring*	117.9	173.4	34	41.3	51.2	4
28" OD x 1.5" W	A-USC	Ring**	107.3	161.3	34	34	46	NA
12.8" OD x 0.9" W	Project 1	Ring	114.0	163.0	31.8	NA	NA	5
12.2" OD x 1.85" W	Project 2	Pipe	109.8	162.1	34.8	36.6	NA	2.5-4
14.9" OD x 3.5" W	SMC IR&D	Pipe	105.2	157.3	31.9	33.4	41	0-2
ASME 2702 min			90	150	20			
* First pipe, ** Second pipe							‡ Set of three	

Table V: Directional tensile and impact properties determined for header pipe 1.

Orientation	Location	0.2% YS (ksi)	UTS (ksi)	Elong. (%)	RA (%)	CVN (ft. lb.)*
Longitudinal	Toe	106.4	164.0	38.6	41.2	95.5
Longitudinal	Toe	108.2	165.0	38.7	40.9	
Longitudinal	Toe	112.2	166.1	37.8	40.8	
Circumferential	Toe	105.5	156.5	30.2	26.5	38.0
Circumferential	Head	109.1	160.7	27.5	22.7	
Through Wall	Toe	100.0	155.1	24.4	22.1	34.3
Through Wall	Head	102.7	154.2	21.9	20.7	36.2
* Average of 3 tests						

CONCLUSIONS

1. Two VIM/VAR 740H ingots exceeding the target weight of 25,000-pounds after conditioning and cropping met requirements for composition uniformity, cracking and freedom from solidification segregation.
2. One VIM/ESR/VAR ingot weighing more than 30,000-pounds after conditioning and cropping was produced. This ingot also met expectations and represents the largest size that Special Metals is currently able to manufacture.
3. Two heavy wall header and two thinner wall reheater pipes were produced by extrusion at Wyman-Gordon. These pipes had mechanical properties that exceeded ASME Code Case minimum values, and all met NDT requirements. The header pipe was also dimensionally acceptable. While the reheater pipes did not meet all dimensional requirements, it is believed that process adjustments are possible that will mitigate these dimensional issues. However, a wall thickness of about 1.5-inches is likely the minimum practical for an extruded pipe of 740H.

ACKNOWLEDGEMENT

This work was sponsored by the US Department of Energy, Office of Fossil Energy, award DE-FE0025064 administered by the National Energy Technology Lab. The authors acknowledge the critical role of Thomas Armstrong of Wyman-Gordon in engineering the extrusions and the patient guidance and encouragement of Vito Cedro III, NETL (Project Manager), Robert Purgert, Energy Industries of Ohio, (Principal Investigator) and Horst Hack, EPRI, (Technical Manager).

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