Agile, Team-Based Response in Casting Furnace Placement and Technology Realization

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ABSTRACT

In 2018, a joint leadership team comprised of personnel from the U.S. National Nuclear Security Administration (NNSA), Lawrence Livermore National Laboratory (LLNL), and Y-12 National Security Complex (Y-12) recognized that a promising alloy casting technology, pioneered for the titanium industry and expanded to other metals in the 1990s, could be revisited for current alloy casting modernization efforts. In an effort to accelerate deployment of the technology, the LLNL / Y-12 team, with support from NNSA, has contracted with a commercial vendor, which already has experience with metal and alloy metal fabrications for Y-12. This expertise, as well as early involvement by Design Agency (DA)/Production Agency (PA) teams in the technology maturation work, is allowing a streamlined path to mature this promising technology from TRL 3 to TRL 6 over the course of approximately 3 years. Additionally, significant cost, time, and footprint savings are being realized by carrying out this earlier part of the technology maturation at a commercial location. In particular, the presence of a national laboratory liaison technology lead embedded at Y-12 and closely interacting with the commercial partner has proven highly advantageous. Benefits of this early engagement between technology developers and production/manufacturing leads to develop strategy and implementation plans, especially with an early focus on application and manufacturability, will be discussed.

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Context for an Agile, Team-Based Response

The United States Department of Energy, through its National Nuclear Security Administration (NNSA), funds technology development to improve various aspects of nuclear material performance and security. Some of this technology development involves large-footprint scale industrial equipment and requires the expertise of scientists and engineers spread across the United States. One such example is the piloting of a melting furnace that does not use vacuum or inert gas induction heating for creating relevant alloys, such as titanium-niobium and uranium-molybdenum, among others. One unique aspect of this area of technology development is the agile team approach taken to continue to advance technology in the face of obstacles. Specifically, early engagement between technology developers and production/manufacturing leads allows strategic development of implementation plans with a keen focus on application and manufacturability. In addition, any manufacturing technology plan must include realistic coordination of feedstock availability, wherein requests for feedstock material are issued by the technical leads, are approved by the administrative leads and material movement, tracking, and processing are executed by production leads. Broad communication among the three entities, and including a fourth entity via the production lead to its sub-contractor, facilitated the siting of the furnace equipment in a readily outfitted and accessible location. This cohesive, connected, and constant collaboration and dynamic approach to inputs and feedback to achieve a workable solution represents the agility necessary for responsive manufacturing.

Technology Background

Non-induction melting furnace (NIMF) of various types were being developed to support the titanium industry throughout the 1970's, 1980's, and 1990's. Industrial research in this area aimed to improve material utilization by increasing the amount of good scrap of various types of high value alloys that would be re-processed, even refined, without the requirement of an induction furnace.

In previous research, LLNL retrofitted an existing, on-site, qualified vacuum processing system as a NIMF. Funding was obtained to demonstrate the capability of producing alloyed ingots meeting Y-12 specifications and to design and construct a scrap feeder capable of recycling chopped Y-12 plate scrap of various alloys. A modeling effort was also initiated to better understand the relationships between input process parameters and final ingot structure. A study was undertaken at LLNL to characterize alloy ingots produced via this NIMF compared with alloy ingots prepared via more traditional induction furnace melting. Samples of both the ingot and feed material were analyzed for the alloying constituents and trace metallic elements, carbon, oxygen and nitrogen. This material was also inspected metallographically and via microprobe analysis. The procedures used to characterize the NIMF ingot closely followed the evaluations first devised by Y-12 for standard induction melting product. A process flow diagram for these procedures is shown in Figure 1. The characterization efforts were organized into sectioning, wet chemical analysis, interstitial analysis, microprobe analysis and metallography.

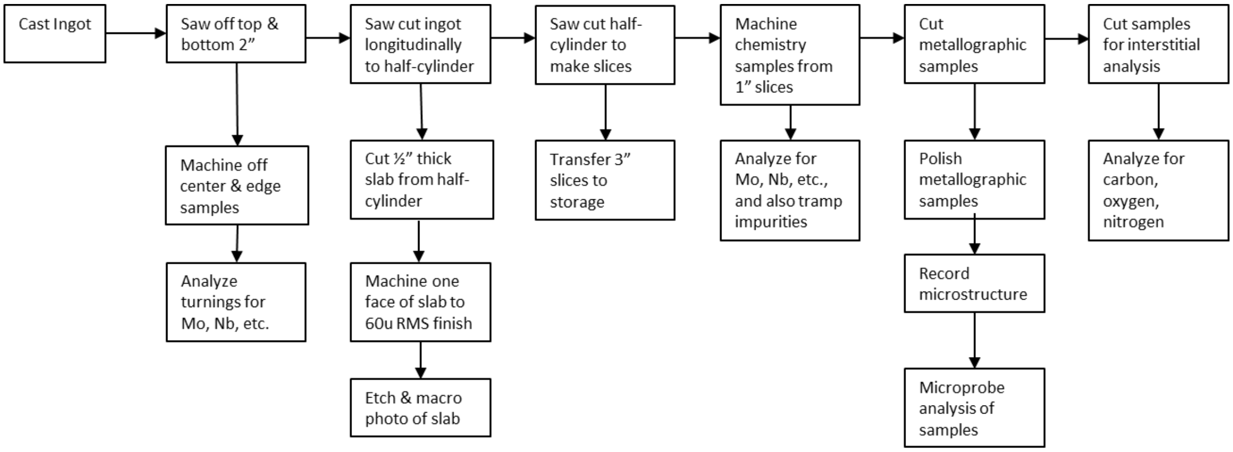


Figure 1. Flow of sampling and characterization of traditional induction and non-induction melting.

Chemical analysis of the ingot was performed to quantify percentage alloying metal and trace metallic impurities in order to compare the non-inductively melted ingots with induction melted ingots. Chip samples were dissolved in acid and analyzed for base metal percentage, alloying metal percentage and trace metallic impurities. Samples were also analyzed for carbon, oxygen, and nitrogen using standard combustion analysis equipment for solid samples. Previous Y-12 investigations on purification of Ti or U base metal by non-induction melting has shown substantial reductions in high vapor pressure metallic impurities after a single non-induction melt. Table 1 shows similar results for this current investigation. Chromium and manganese levels, the two high vapor pressure constituents measured, are preferentially lowered during electron beam processing. The more reactive metals (Ni and Zr) also appear to be somewhat lower in the ingot than in the feed, although it is not clear if this is due to their higher vapor pressures with respect to base metal, or to their reactivity with carbon in the melt to form insoluble metal carbides. Overall, tramp impurities are lowered by NIMF, resulting in a modest improvement in material purity. It is known that certain tramp impurities affect corrosion resistance in such alloy systems.

	Al	**Cr**	**Mn**	**Ni**	**Zr**
Specification	75			75	500
Feed	0	23	14	20	31
Bottom-edge	0	7	2	18	18
Bottom-center	0	7	4	14	16
Top-edge	0	15	8	15	22
Top-center	0	26	4	20	22

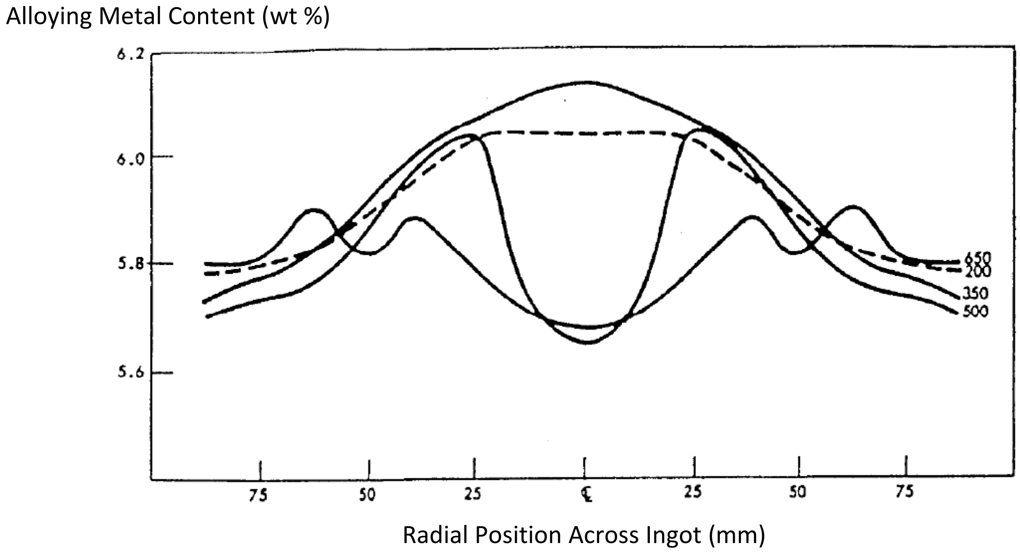
Table 1. Example of chemical composition of some tramp impurities in NIMF alloy recycled from traditional induction melted alloy feedstock.

Selected samples were examined via electron microprobe techniques for alloying metal variations on a micro scale. This NIMF ingot produced from 100% recycled scrap appears to be comparable to the standard induction melted product in all areas studied. Gross segregation (top-to-bottom) is comparable. Macro-segregation (banding) of the NIMF material appears to be slightly less distinct than in the induction melted material. Banding is a result of solidification dynamics for furnace melting alloy systems and indicates areas of high and low alloying metal within the ingot on a macro scale. The liquid pool at steady state in this NIMF, as judged from the band profiles, is only about 33% as deep as a pool depth of for the typical induction furnace melting product. Non-induction melt processing gives the ability to independently vary rate and power input to promote shallow or deep pools as desired for a particular metal. In the current studies, a shallow pool is desired to minimize banding.

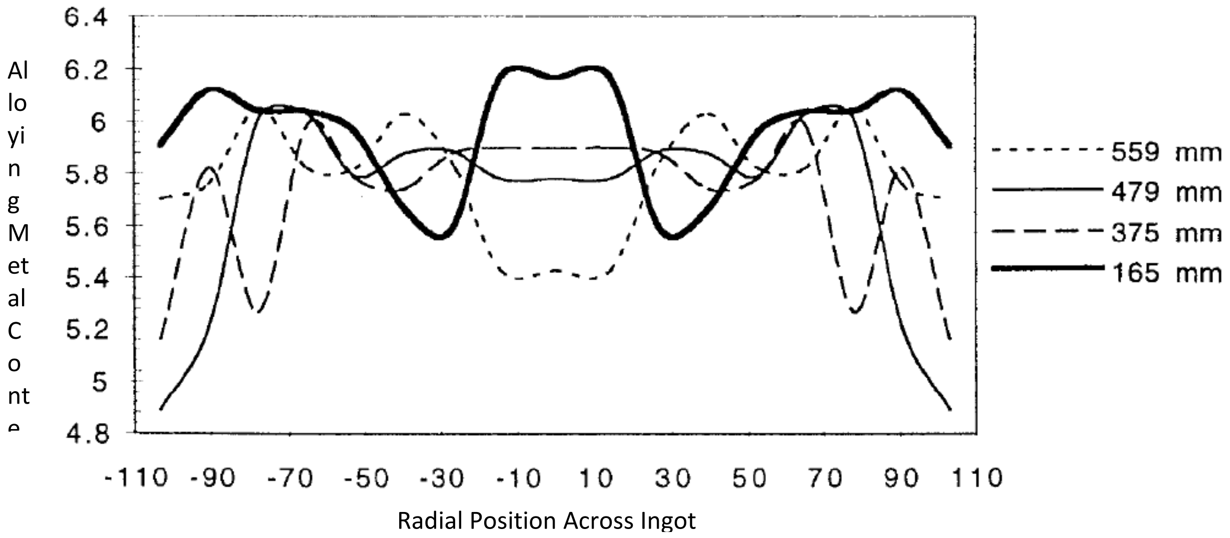
A full sized ingot produced under typical operating conditions was selected for characterization. Raw material for producing this ingot was 100% scrap alloy that met compositional requirements. The LLNL system utilized a vibratory feeder to continuously feed this chopped scrap to the NIMF. A light dross forms over the liquid metal in the melt region, presumably from base metal oxides, and possibly from silicon oxides from the sand used to grit blast during material preparation, but appears to dissipate in the downstream region of the melt, resulting in a clean, oxide free metal stream being poured to the crucible. The mechanism for this dross removal appears to be that the high energy of the melt breaks down the base metal oxides and silicon oxides into higher vapor pressure sub-oxides, which are then volatilized. A picture of the melt in the NIMF recently installed at the subcontractor's facility in Oak Ridge, TN, USA, is shown in Figure 2.

Figure 2.   NIMF Containing Melt Material

Uniformity in alloying metal throughout the base metal profile of an alloyed ingot is important to its further processibility and material performance. The radial distribution of the alloying metal throughout the base metal in alloyed ingots produced via traditional induction melting is shown in Figure 3a and from NIMF in Figure 3b. From these curves, it can be seen that in both cases, the alloying metal tends to be higher in the center of the ingot near the bottom of the ingot whereas toward the top of the ingot, the situation reverses and alloying metal is lower in the center. For this particular set of casting conditions, NIMF appears to produce a product comparable in trend to the material prepared with traditional induction melting.



a) Typical radial distribution of alloying metal across an ingot produced via traditional induction melting furnace



b) Typical radial distribution of alloying metal across an ingot produced via non-induction melting

Figure 3. Radial distributions of alloying metal across ingots produced via traditional induction melting (a), and non-induction melting (b).

Technology Transition for Current Applications

The studies at LLNL described above demonstrated the viability of the single-step NIMF process to produce alloys from both virgin (alloying) and scrap (recycling) material. Ingots that were produced met or exceeded specifications for elemental impurity content and alloying metal homogeneity, and the studies concluded that ingots produced by NIMF could be comparable to those produced by the traditional induction furnace melting process.

In FY 2019, LLNL initiated preliminary proof-of-concept and bench-scale studies to establish an NIMF process that could be transferred to Y-12 as the technology levels are successfully advanced. To support this effort, LLNL and Y-12 contracted with an experienced industrial partner to design and build an NIMF system capable of meeting throughput and safety requirements. A commercial vendor utilized their on-site equipment with the goal of developing process parameters, optimizing equipment, and customizing support features for feedstock delivery and production of test castings. LLNL has completed studies using commercial vendor equipment to evaluate alloying, and recycling. Briefly, recycling efforts focused on the configuration of scrap materials as feedstock and the development of an appropriate feedstock delivery system. Different scrap forms and feeder systems were evaluated, and lessons learned were incorporated into the design of a prototype NIMF system. Alloying efforts used composite rods comprised of titanium cores and machined niobium metal tubes with welded end caps. The feedstock configuration was demonstrated successfully, and an alloy ingot was cast. Single and multiple bar feeding systems of the tube feedstock were also successfully demonstrated.

During development of the NIMF by the experienced commercial subcontractor, it was determined the equipment would need to be sited elsewhere than LLNL due to schedule and cost concerns. A team of upper level management from NNSA, LLNL, and Y-12 convened and determined that a suitable relocation of the NIMF equipment could be achieved. A commercial operation already processing the alloy of current interest was identified and Y-12 took action, with technical input from LLNL and administrative mission guidance from NNSA. This agile formation of a multi-institutional team and assertive utilization of subcontractors allows the development of the NIMF technology to proceed on schedule and at lower cost. While the new NIMF equipment was developed and underwent a successful Factory Acceptance Test, the commercial entity that would receive the equipment and continue development of the technology under LLNL and Y-12’s supervision began site preparations. Weekly communications between LLNL and Y-12 complemented bi-weekly communications with NNSA. In addition, subject matter experts (SME) on technology implementation and maturation across the nuclear complex in the U.S. conferred quarterly to receive progress updates on the technology’s maturation and give input to inform planning, scheduling, and performance documents and expectations. Figure 4 shows a partial contingent of the blended team, with NNSA, LLNL, and Y-12 contributors present, as well as subcontractors from the subcontracted developer entity.

Figure 4. Partial contingent of the team at the experienced commercial development subcontractor's location (left, pre-COVID) and at the siting subcontractor's facility (right, during COVID).

Management of Technology Maturation: Agility through Collaboration

A Technology Realization Team (TRT) is comprised of members from LLNL, Y-12, Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), and Oak Ridge National Laboratory (ORNL), as well as NNSA representatives and ad hoc SME. The TRT is co-led by LLNL and Y-12, advised by LANL as a second DA, and NNSA sponsored. A Federal Program Manager from each organization interfaces with the TRT, and NNSA provides oversight and guidance. TRT leads have been provided by the two DAs, LLNL and LANL. The PA, Y-12, has provided the overall TRT lead, a Y-12 technical lead, a project manager, a project engineer, a subcontract technical representative, and TRT support. An on-site LLNL detailee is stationed at Y-12.

The overall structure of the management and responsibilities for technology maturation, implementation, and qualification are shown in Figure 5. Briefly, certification/qualification plans are provided to Y-12 jointly by LLNL and LANL, Y-12 and LLNL provide test ingots for certification and qualification, LLNL provides technology transfer to Y-12, and Y-12 supports LLNL technology maturation and certification/qualification activities to ensure proper technology transfer. LLNL holds primary responsibility for development and maturation of the NIMF technology for creating relevant alloys, such as titanium-niobium and uranium-molybdenum, among others. This includes research, prototype development, and technology transfer to Y-12. Y-12 is responsible for demonstrating prototype operation and advancing the equipment through operational readiness and production.

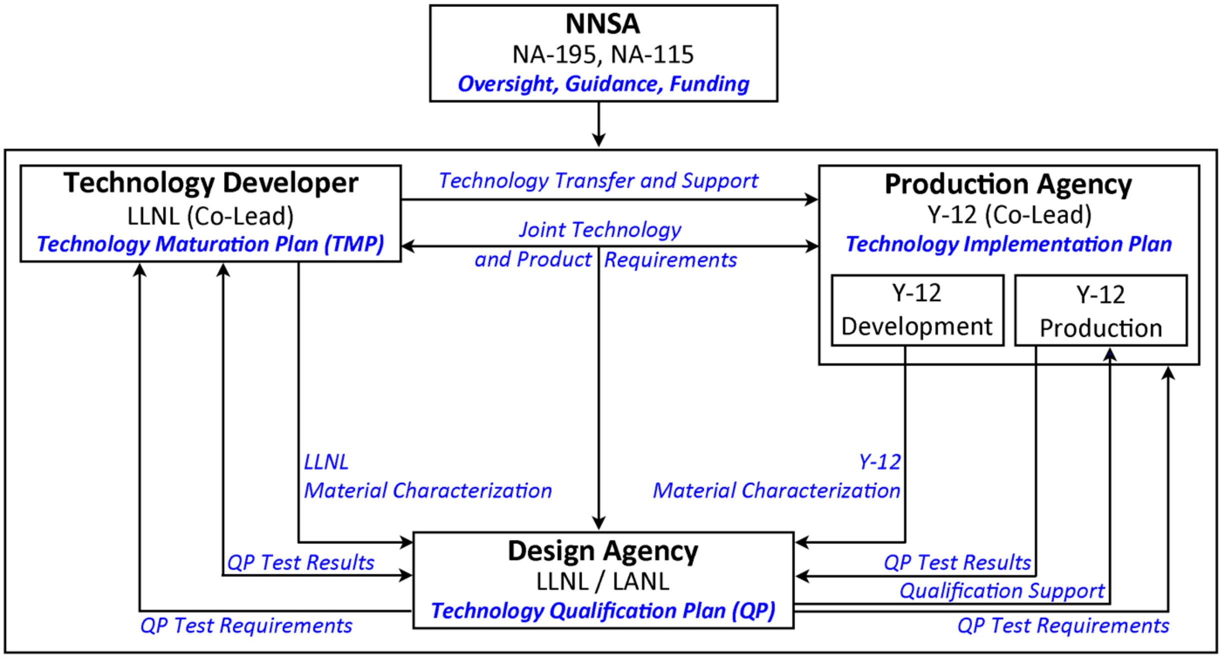


Figure 5. Overview of management and responsibilities for technology maturation, implementation, and qualification.

Current Efforts in Technology Maturation

Site acceptance testing after installation of the equipment was completed recently, and training by the commercial vendor, including test melting executed by the subcontracting company employees is underway. The LLNL detailee co-located with the NIMF equipment allows seamless guidance and collaborative technical data evaluation and processing and experimental production design between LLNL, Y-12 engineers, and the subcontractor in executing this alloy melting. An ingot produced at the site during SAT is shown in Figure 6. Information flows in a near-constant stream to the funding and mission-defining administrators at the NNSA. More immediate interactions between the LLNL SME detailee and the Y-12 technical lead engineer based on experimental outputs, as they relate to realistic implementation in a production setting, are facilitated by the daily collaboration at the subcontractor site where the NIMF equipment is being utilized. Early outcomes of beginning to mature a promising technology via a multi-entity team with maximum on-going communication demonstrate the advantage of agility in alloy manufacturing.

Figure 6. Ti-Nb Ingot Produced in NIMF Furnace Placed Based on Agile Effort