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A Tiered Approach to Addressing the Need for a Skilled METAL Manufacturing Workforce: Hands-On and On-line Education and Training

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A Tiered Approach to Addressing the Need for a Skilled METAL Manufacturing Workforce: Hands-On and On-line Education and Training

1 Introduction

The U.S. is facing a critical shortage of skilled personnel in the metal casting and forging industries. The Department of Defense (DOD) has prioritized this shortage as a national security threat due to the shrinking supply chain for critical weapon system components. It is anticipated that by 2028, the defense industrial base will require a minimum of 122,000 additional personnel for roles such as skilled technicians, engineers, and metallurgists [1].

According to industry statistics from the American Foundry Society, the United States had 1,750 foundries in 2020, a significant decline from the 3,200 foundries in the United States in 1991. The U.S. metalcasting industry provides approximately 160,000 jobs in the United States which has also declined significantly with the decline in the number of foundries [2]. However, in a 2022 industry survey by the American Foundry Society, labor shortages and lack of skilled workers were noted as challenges faced by the industry. Data from the forging industry shows similar trends where the workforce population is decreasing, and the average age of the workforce is increasing.

In terms of economic impact, the metal casting industry accounted for $41 billion in total output in 2006 which dropped to $23.3 billion in 2022. Similarly, metal forging saw a decline from $32.7 billion in 2006 to $25.8 billion in 2022. Although the growth outlook in these industries is favorable with projections indicating moderate output increases over the next decade, the increase is lower than the projected national growth in output [3]. Due to the importance of manufacturing to the U.S. economy, job market, and national defense, federal initiatives such as the METAL program (i.e., Metallurgical Engineering Trades, Apprenticeships, and Learning) aim to address workforce shortages [4].

The paper is organized as follows. In the program background, the administrative structure of the METAL program including the collaborative nature of the development effort will be described. Then, the level one core curriculum is detailed with a focus on both the self-paced, online training and the in-person, hands-on training (i.e., boot camps). Next, the early results of participant surveys are presented. The paper will conclude with a discussion of future METAL curriculum, data collection, and expansion plans.

2 Program Background

The METAL program was launched by The Institute for Advanced Composites Manufacturing Innovation (IACMI), also referred to as The Composites Institute, in December of 2023 in collaboration with the Pennsylvania State University (Penn State) and the University of Tennessee Knoxville (UTK). Headquartered in Knoxville, TN, IACMI was established in 2015 as the fifth Manufacturing USA Institute with the goal of hastening the development and adoption of manufacturing technologies for advanced polymer composites to support the automotive, aerospace, and power generation industries. Financial support and technical guidance for the METAL program are provided by the DOD's Industrial Base Analysis and Sustainment (IBAS) program with the mission "to improve the readiness and competitiveness of the U.S. industrial base by establishing high priority domestic capabilities for new supply chains needed for national security and mitigating exposure to global supply chain risks"[5].

Development of the METAL program is a cross-disciplinary, collaborative effort with partner organizations spanning industry, academia, and government. As of December 2024, the primary partners include IACMI, the DOD, Penn State, UTK, Jobs for the Future (JFF), and the Foundry Education Foundation (FEF). The primary responsibilities for each partner organization are shown in Table 1. Since its launch, the METAL program has rapidly deployed to offer workforce training activities including apprenticeship development, K-12 outreach workshops, online trainings, and in-person training sessions (i.e., bootcamps). The K-12 outreach workshops are targeted at inspiring young students to pursue further learning and potential careers in METAL. The Level 1, Level 2, and Level 3 curriculum is targeted to a broad audience from young adults through "gray" adults with increasing level number corresponding to more job/ industry specific trainings and the study of more advanced technologies and research topics. The overall targeted audience for the METAL program is said to be "K to Gray."

Table 1. Primary contributions to the METAL program by partner organizations.

Organization	Contribution
IACMI	program management / technical guidance
DOD	financial support / technical guidance
Penn State	curriculum development
UTK	curriculum development
JFF	apprenticeship development
FEF	program propagation / curriculum advising

Leveraging the organizational structure of IACMI's America's Cutting Edge (ACE) workforce development program [6], the METAL program aims to create a nationwide workforce development network to provide free training in the fields of metallurgical engineering, metal casting, and forging. The training is delivered in two pedagogical modalities: (1) online, asynchronous, and (2) in-person, hands-on. The curriculum will be delivered in multiple levels, or "tiers." This paper will detail the development of the so-called level one (core) curriculum which covers a broad range of topics and is intended to build foundational knowledge for an unexperienced audience. Additional METAL training levels, still in development, will provide deep dives into industry-relevant and advanced topics.

3 METAL Level One (Core)

METAL trainings are intended to cover a wide range of industry relevant topics in metalworking beginning with basic, foundational knowledge and progressing through advanced university-level research topics. The training curriculum is colloquially referred to as "tiered" or "stackable" reflecting that each subsequent level builds upon knowledge gained in prior levels. Specifically, each level (i.e., tier) is designed specifically for a target audience. As an example, the METAL level one curriculum, detailed in this paper, is often referred to as the "core" curriculum and provides foundational knowledge in the fields of metallurgy, mechanical testing, metal casting, forging, and post processing of near net shape parts. Due to the wide breadth of topics in the level one curriculum, it lacks depth in each individual topic and is intended primarily for those participants with little or no experience in these fields of study. Level one "core" training is provided at no cost to participants and is offered as two primary components: (1) online, self-paced sessions and (2) in-person, hands-on trainings (i.e., bootcamps).

3.1 Online Curriculum

The METAL online curriculum is hosted on the Canvas Learning Management System (LMS) and consists of thirteen modules covering the following topics:

- introduction to metal casting
- metal casting processes
- metallurgy and heat treatment
- nonferrous metals and alloys
- cast irons
- steels
- introduction to casting design and modelling
- additive manufacturing techniques for casting
- introduction to forging and rolling processes
- melting processes
- introduction to post processing
- introduction to mechanical properties and testing
- careers in metal

The Canvas modules include video presentations followed by quizzes to reinforce learning objectives as well as self-paced, computer-aided drafting (CAD) and computer-aided manufacturing (CAM) software tutorials. Training modules must be completed sequentially with subsequent modules becoming available after the participant achieves a satisfactory score on the prior module's quiz.

3.2 In-Person Curriculum

The online training modules ***must*** be completed as background work prior to attending the in-person boot camp. After completing the online training modules, interested students can sign up for an in-person boot camp. The bootcamp consists of a four-day (8:00 am – 5:00 pm) in-person training where participants complete the following activities:

- Casting solidification and flow modeling simulated in a guided lab, allowing participants to apply their knowledge gained from the online modules to the physical castings they would be pouring in the following days at the boot camp.
- Participants actively cleaned, inspected, and set the pre-made 3d printed sand molds of the castings they had previously simulated in the boot camp.
- Participants hand-packed Green Sand molds of a step cone, fluidity spiral, and trinket castings using the in-lab facilities.
- Participant volunteers participated in the casting of aluminum and a copper-based alloy by pouring the molten metal into the hand-packed green sand, lost foam pattern, and cleaned 3d printed sand molds previously mentioned.
- Participants played a hands-on role in the post-processing of the castings, including the breakdown of the molds and the subsequent removal of sand from details in the casting, properly supervised use of the band saw by qualified participants to remove the gating, and the sanding down of riser connections.
- The importance of austenitizing and tempering was demonstrated to participants, through allowing them to compare the hardness they measured (measured in lab facilities) of water-quenched and air-quenched steel samples, as well as the subsequent change in hardness due to the tempering of samples after quenching.
- Participants were able to explore the changes in mechanical properties and dimensions of wrought materials due to the cold rolling of samples. Participants fed the samples through rollers, and measured the change in length, thickness, and hardness in the samples.

The four-day METAL level one bootcamp training features self-paced training in the use of casting design software (i.e., solidification and flow modeling) where the participants' learning is supplemented by instructor guidance and oversight. During this training, participants simulate the solidification process for two components that are later manufactured during the training by sand casting using 3D printed sand molds; see Figure 1. The METAL medallion, shown in Figure 2 and Figure 3, is cast from a silicon brass casting alloy (i.e., UNS 87400) and is subsequently machined to improve the surface finish and achieve the necessary dimensional accuracy.

Figure 1. A METAL level one bootcamp participant pouring A356 (i.e., an aluminium casting alloy) into a 3D printed sand mold.

Figure 2. METAL medallion sand cast during the METAL level one bootcamp (left). Post process machining of the METAL medallion on a three-axis vertical machining center (right).

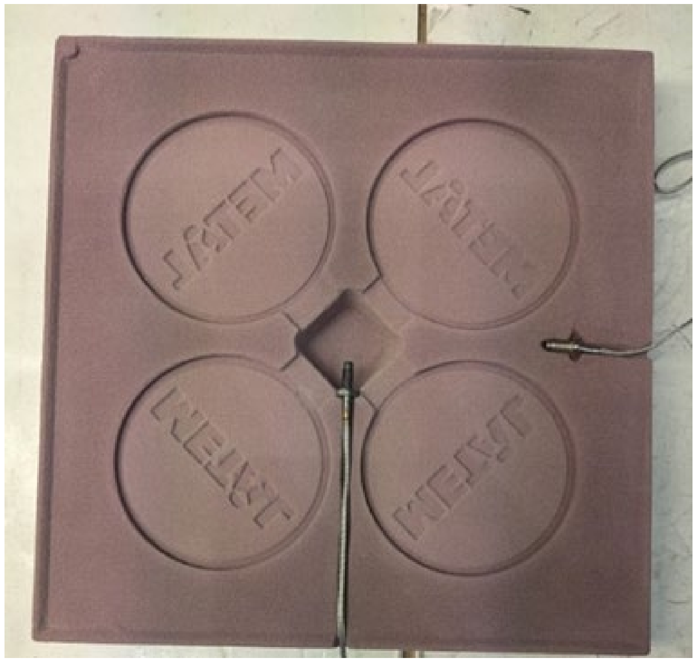

Figure 3. An instrumented sand mold, manufactured by 3D binder jet sand printing, used to cast the METAL medallion.

Bootcamp participants are introduced to expendable molds (i.e., green sand and 3D printed sand molds) and permanent molds (i.e., cast iron or steel molds). The effects of pour temperature and alloy chemical composition on the fluidity of molten aluminum (i.e., A356) are observed using fluidity spirals; see Figure 4. Additionally, bootcamp participants produce stein mugs by lost foam casting and air engine bases for the ACE program by sand casting; see Figure 5.

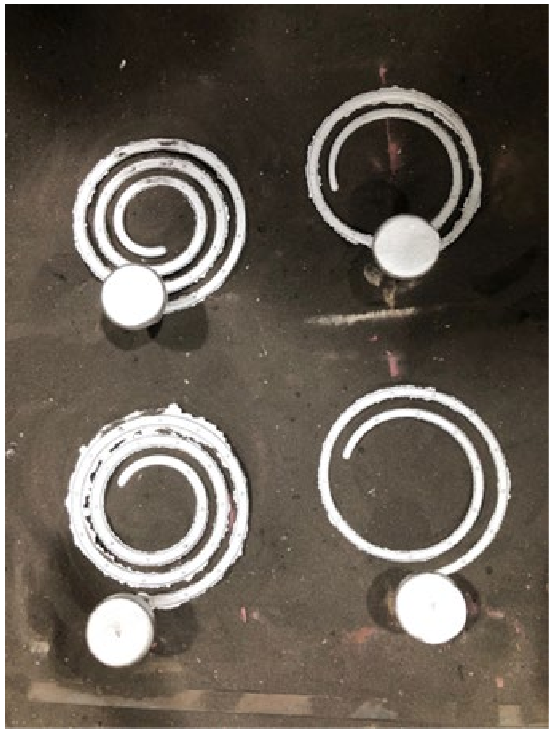

Figure 4. Fluidity spirals produced by pouring A356 aluminum into 3D printed sand molds using different pour temperatures and alloy chemical compositions.

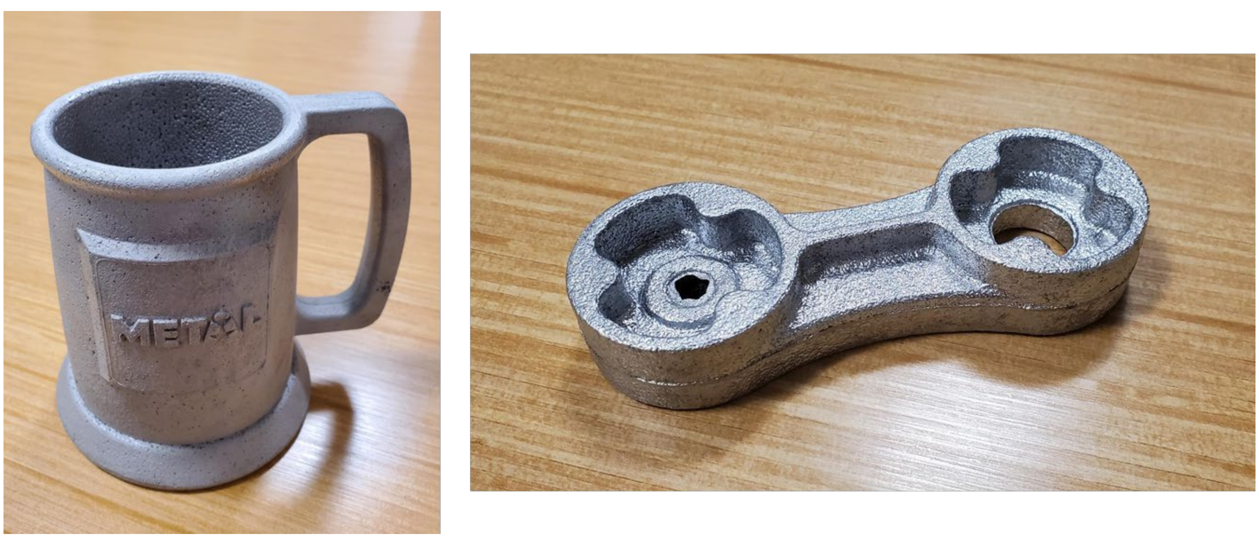

Figure 5. A356 aluminum stein mug produced by lost foam casting (left). A356 aluminum ACE air engine base produced by sand casting (right).

Cast and forged workpieces often undergo significant post processing to: (1) remove excess and unwanted material, (2) achieve the required geometric accuracy and surface finish, (3) alter the mechanical properties of the material, (4) increase corrosion resistance, and (5) clean or prepare the surface for further processing. Participants are introduced to three post processing techniques:

- sanding and/or grinding to remove unwanted material from the castings' parting lines
- bead blasting to clean the surface and improve the aesthetic appeal of the METAL medallion
- computer numerical control (CNC) milling of the METAL medallion to create a reflective surface finish and achieve the appropriate thickness for the wooden base

Participants are introduced to CNC milling through instructor-guided CAD/CAM software training and on-machine demonstrations. The CAD/CAM software activity includes fixture design and toolpath generation to perform a facing operation on the silicon brass METAL medallion. A CAD model of the METAL medallion machining setup with visible toolpaths is shown in Figure 6.

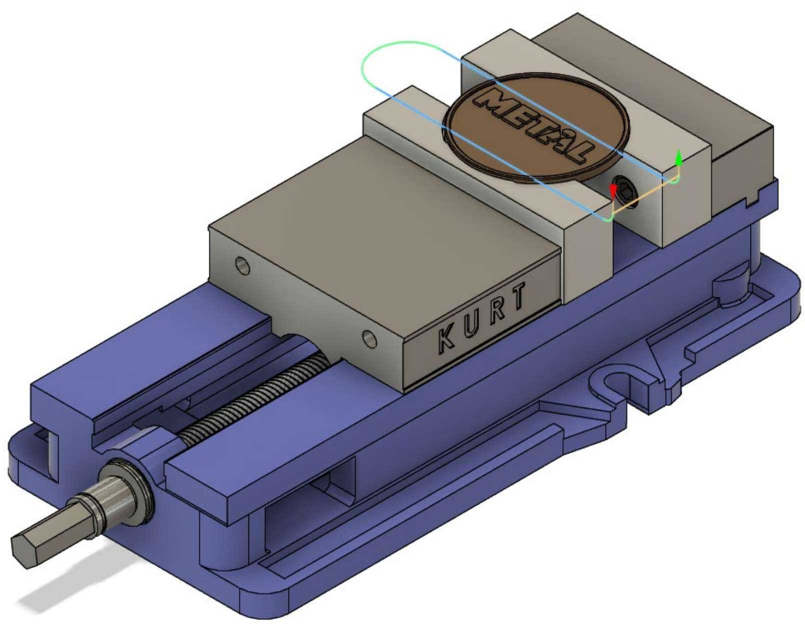

Figure 6. CAD model of the machining setup for the METAL medallion with visible toolpaths.

Other METAL level one in-person training activities include mechanical testing (i.e., tension and hardness testing), heat treatment of steel alloys (i.e., AISI 1060 and/or 1045), forging, and rolling. The topics for each day of the four-day schedule are summarized. These activities include both classroom and laboratory sessions. The detailed daily itinerary can be found in Appendix A.

At the conclusion of the four-day, in-person bootcamp, each participant is awarded a Credly badge (i.e., digital credential) and a certificate of achievement. They also keep the following manufactured parts: (1) ACE air engine base, (2) METAL medallion and base, and (3) METAL stein mug; see Figure 7.

Figure 7. Manufactured parts and certificate of achievement that each bootcamp participant keeps at the end of the training

3.3 K-12 Outreach

To spread awareness of the METAL program and spark an interest in manufacturing and STEM as viable career paths, K-12 outreach events have been developed. Research has shown that youth in the age window of 6 to 14 years of age is a critical time to foster personal growth and interest in furthering education in specific areas that could also lead to career interests and choices [7]. These outreach efforts consist of metal casting demonstrations and explanations of the importance of manufacturing to the U.S. economy as well as national security. Participants learn the basic principles of sand casting being taught through hands-on metal casting activities using a low melting temperature tin alloy. They are given step-by-step instructions on the process of building a sand mold and are then guided through the hands-on activity with instructor supervision; see Figure 8 and Figure 9. Each participant produces a cast tin part of their choosing (i.e., starfish, baseball, or smiley face); Figure 10.

During the summer of 2024, Penn State Behrend (in Erie, PA) hosted seven K-12 outreach workshops as part of the College for Kids summer enrichment program that provides age-appropriate classes for children and young teenagers from six to fourteen years of age [8]. The workshops were 3 hours in duration and the ratio of student participants to instructors was 2:1. Out of the 102 student participants, 82 (80%) were in the six to eight age range, 20 (20%) were in the ten to fourteen age range, 38 (37%) were females, and 64 (63%) were males.

Figure 8. Sand molds produced by student participants during a K-12 outreach event.

Figure 9. K-12 outreach participants prepare and clean 3D printed sand molds.

Figure 10. Student participants in a METAL K-12 activity proudly display their cast tin parts.

3.4 Participant Demographics

Since its introduction at the Defense Manufacturing Conference (DMC) in Nashville, TN on December 11, 2023, METAL has expanded to include apprenticeship development, online training, in-person bootcamps, and K-12 outreach workshops.

The online curriculum was launched in March 2024 and as of January 2025 there have been 230 participants from 23 states. The demographics of the online participants are as follows:

- 43 (18.7%) females, 187 (81.3%) males
- 176 (76.5%) students, 54 (23.5%) industry employed

Of the online participants, 18.7% are females which is comparable to the nationwide averages in the metal casting and forging industries of 16.9% and 22.1%, respectively [3, 9]. The largest participant group, students, were composed of 14 from high schools, 10 from two-year community colleges, and 152 from four-year colleges and universities. Completion of all online training modules earns each participant a certificate of completion and a Credly badge (i.e., digital credential [10]) awarded by IACMI. Among the 230 participants, 65 (28.3%) have completed the online training modules.

As of January 2025, three in-person training sessions have been completed at Penn State University. Each in-person training session is four days and approximately 32 totals hours (8:00am – 5:00pm). The completed in-person training includes:

- March 4-8, 2024 (pilot bootcamp), 22 total participants
- August 19-22, 2024, 15 total participants

- January 4-8, 2025, 14 total participants

At the conclusion of each in-person training the participants are surveyed for feedback on the program. Of the 39 participants completing the level 1 bootcamp exit survey, 25 were students, 7 were educators, 7 were from industry, and 4 were veterans. The gender breakdown was 31 males and 8 females (20.5%).

4 Pedagogical Philosophy

A significant amount of thought, research, and planning went into determining how the METAL program would be delivered. The delivery methods for the METAL program (online and in person bootcamps) were put together using the result of highly effective engineering education research. Specifically, the METAL program utilizes the "I-C-D-M Methodology" (Interact, Cultivate, Deliver, Motivate) which was developed over a five-year time span specifically to improve undergraduate engineering student motivation, satisfaction, and performance. There were five main phases of this work. The Interact component of this approach calls for providing detailed feedback, being approachable to students/ participants, stressing the significance of the course material daily, and relating the training content to participant interests. The Cultivate component of this approach calls for providing real world connections/ examples, connecting skills being learned to future careers, relating all training activities, and encouraging active engagement by all participants being trained. The Deliver component of this approach involves using interactive presentations, creating problem-solving activities, and promoting collaboration within work groups. The Motivate component of this approach involves reminding trainers to incorporate the I-C-D method and to always be aware of the importance of paying attention to the participants while looking for ways to decrease anxiety, improve participant self-recognition, improve cognitive recognition, and improve intrinsic value all in an effort to improve participant self-motivation.

Previous research has demonstrated that implementation of the I-C-D-M methodology in a course or training should lead to increased student satisfaction, motivation, and performance. This was the reason for adoption of this methodology when designing online and in-person training content delivery. [11-12]. As mentioned, the I-C-D-M approach to delivering the training had special emphasis on manufacturing. Going a step further, one of the METAL team members worked on a body of engineering education research that specifically looked at identifying ways to improve student interest in launching a career in Manufacturing. This body of work included work on optimizing summer internship and co-op experiences for companies in the METAL industry [13-15].

5 Participant Feedback

To date, 39 of the 51 participants completing the METAL LEVEL 1 BOOT CAMP have provided feedback on their experience. On a scale from 1 (not satisfied) to 5 (very satisfied), the participant responses average 4.56 when asked about their satisfaction with the course content. On a scale from 1 (not organized) to 5 (very organized), the participant responses average 3.72

when asked about the organization and structure of the bootcamp. On a scale from 1 (not responsive) to 5 (very responsive), the participant responses average 4.92 when asked about how responsive and supportive the program staff and administration were during the bootcamp. On a scale from 1 (slow) to 5 (fast), the participant responses average 3.54 when asked about the overall pace of the bootcamp. On a scale from 1 (easy) to 5 (difficult), the participant responses average 2.54 when asked about the difficulty of the bootcamp.

100% of the respondents (39 out of 39) noted that "YES" they would recommend the bootcamp to a colleague or friend. Some quotes from METAL boot camp participants are as follows:

"Everyone was happy to answer my questions and willing to help me with projects I brought up to try outside of class." – Undergraduate student

"Best staff ever, zero complaints, all praise." – Full Time Manufacturing R& D Staff Member

'Hands-on activities were great." – University Professor/ Manufacturing Director

"Lots of hands-on activities and it was very nice how they were spread out through each day and not just all at once." – Undergraduate student

"I thought the instructors and instructions did a great job making the objective of the activity clear." – Undergraduate student

"Excellent training. Felt there was a great balance of classroom and hands-on activity." – Senior manager for economic and workforce development

"Excellent labs." – Manufacturing Laboratory technician and military veteran

6 Discussion and Future Work

This paper details the collaborative workforce development program known as METAL which is supported by the Department of Defense. It is a nationwide initiative to modernize the workforce in the fields of metallurgy, metal casting, forging, and post processing. The online, in-person, and K-12 curriculum of METAL level one was summarized in the previous section along with data on participant demographics and their feedback about the program. In this first year of the program launch, three in-person boot camps have been conducted with over 50 people participating and multiple K-12 outreach events have been carried out reaching hundreds of youth during a critical period in their development. Multiple in-person boot camps across an ever-growing list of participating universities are in the process of being scheduled and made available to interested potential participants. Thus far this program has been well received by both students and industry professionals and is actively in the process of expanding both its reach to the student population and the depth of topics covered, to best deliver the skills, knowledge, and content needed to address the knowledge and skills gaps that have been identified in critical metal manufacturing supply chains.

When fully developed it is anticipated that the METAL program will consist of three levels of training. The tentative level 2 curriculum, shown in Figure 11, will be developed in coordination with industry stakeholders with a strong focus on satisfying the immediate need for upskilling of the current workforce along with providing hours of training towards apprenticeship development. The tentative level 3 curriculum, shown in Figure 12, will be developed with the intent of modernizing current industry practices through training in university-level research topics that have progressed to a Technology Readiness Level (TRL) sufficient for implementation. The level two and three curriculum is also expected to expand college program offerings leading to specialized minors and certificates in advanced metalworking topics.

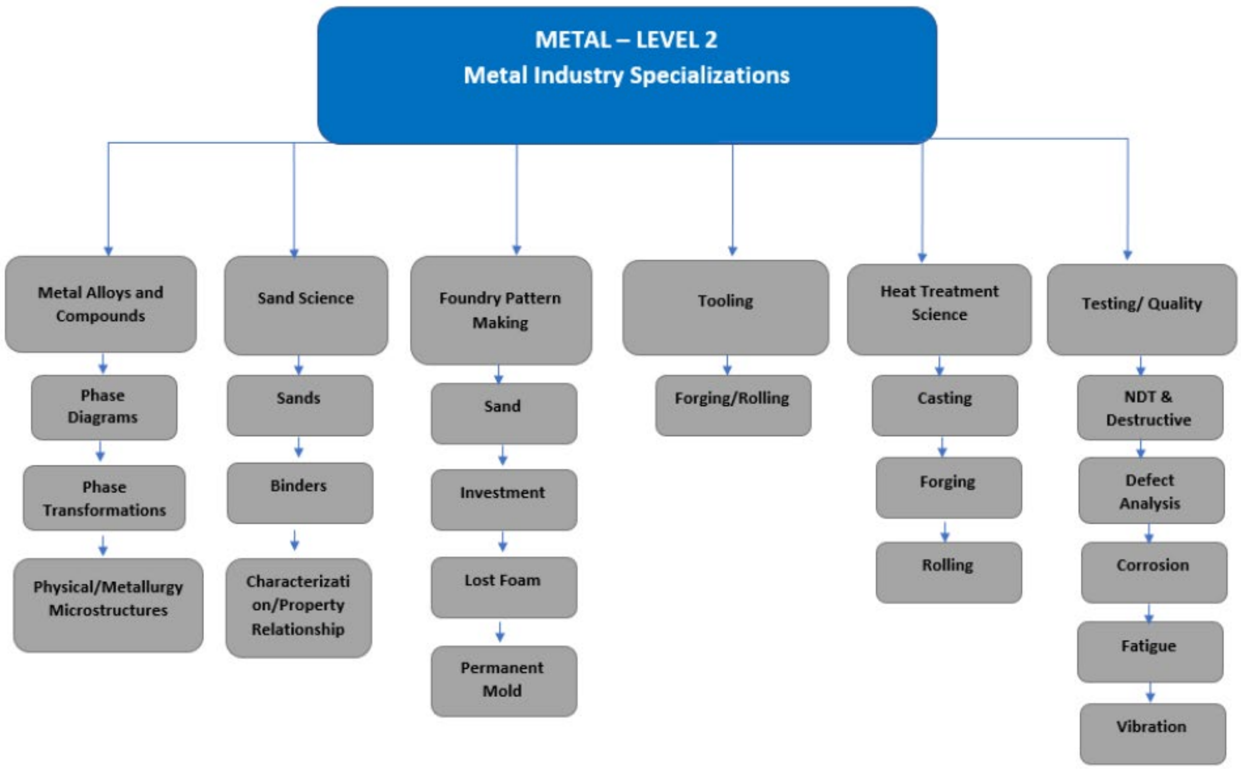

Figure 11. Proposed METAL level two curriculum.

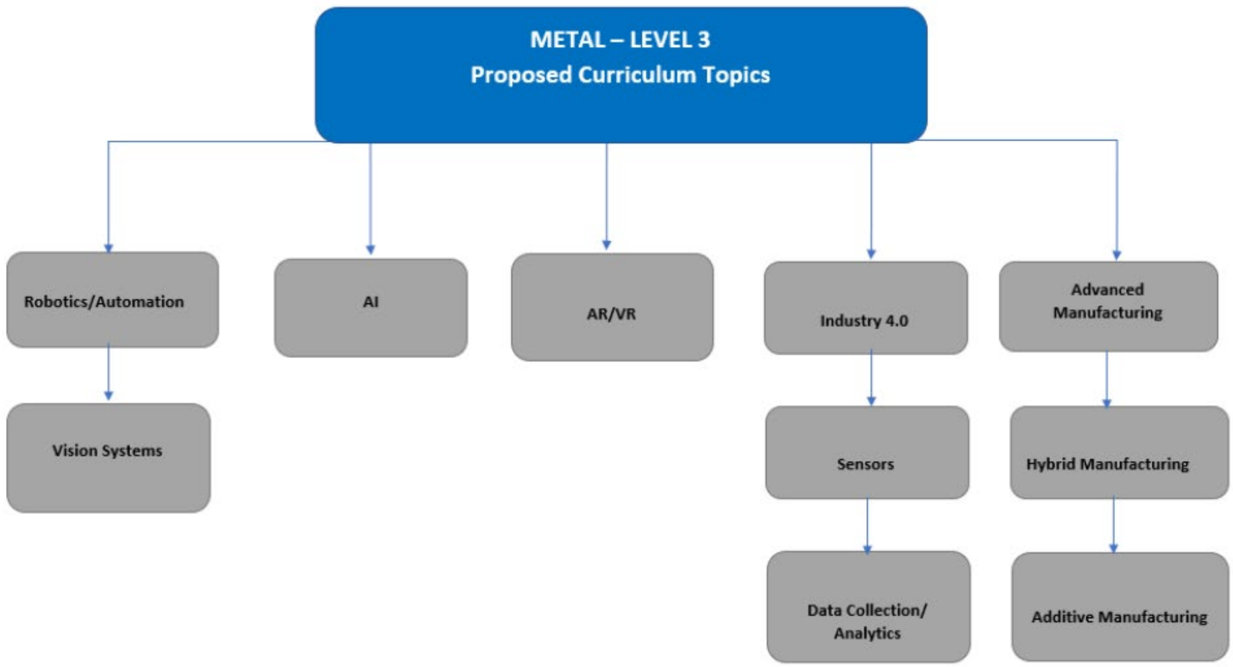

Figure 12. Proposed METAL level three curriculum.

It is well understood that additional data will need to continue to be collected to address the effectiveness of the program in achieving its goals. In addition to the data being collected, pre and post online and in person training to assess and measure knowledge retention and skill acquisition data will need to be collected. As the number of participants continues to grow and an increasing amount of data is collected, data should be analyzed to look for significant differences in participant subgroups (gender, etc.) along with skill levels. The authors have also identified future job placement and careers as data that must be captured to evaluate the effectiveness of the METAL program in accomplishing its core goals.

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8 Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of the U.S. Navy, U.S. Air Force, U.S. Army, the U.S. Department of Defense, or the U.S. Government.

9 Appendix - A

1. Monday – safety training, casting design, solidification modeling, introduction to machining, CAD/CAM exercise, pour aluminum castings (i.e., stein, fluidity spirals, ACE air engine base), begin heat treatment/metallurgy activities.
2. Tuesday – mold preparation, pour silicon brass METAL medallions, shakeout poured molds, begin post processing of castings (i.e., saw cutting, grinding, bead blasting), heat treat/quench/temper AISI 1045 and/or 1060 steel samples.
3. Wednesday – tensile testing, hardness testing, rolling and forging experiments, post process machining of METAL medallion.
4. Thursday – complete post processing of all cast components, cast iron alloying calculations, machining cost review, finalize all data collection/analysis.

Each day includes multiple learning topics and lab activities. The Monday agenda is included. The agendas for Tuesday through Thursday are similar.

8:00 am – Classroom session

- Welcome
- What is the METAL program?
- Introduce instructors
- Identify teams for the week – 6 to 8 participants per group
- Participants introduce themselves (name, affiliation, experience)
- Review participant outline for the week (goals for each day)
- Provide instructions for Internet access, confirm access to part files
- Safety reminders
- Closed toe shoes and safety glasses should be worn at all times in the machining laboratory
- Long hair/loose clothing should be tied back/tucked in
- Machined parts and cutting tools can be sharp; handle with care
- Foundry safety
- Compressed air warning
- Safety walk of the lab and foundry
- Safety training signature form (CANVAS)
- Leather boot casting video (CANVAS)
- Sneaker casting video (CANVAS)

- Distribute binders
- IACMI photo release form (CANVAS)

10:00 am – Group sessions

- Group A-A1 Casting design (Solidification modeling and flow modeling)
- Group B-A5 CAD/CAM, Fusion 360

12:00 pm – Lunch (provided)

1:00 pm – Foundry and lab

- Group A-A2, A4 Mold making, aluminum casting, post processing
- Group B-A3 Heat treatment/metallurgy – steels (forge vs. roll vs. cast), heat treatment, rolling, and mechanical property testing activities
- Mold preparation – vacuum printed molds
- Make stein molds
- Pour aluminum heat – fluidity spiral, step cone, steins, air engine base

2:15 pm – Foundry and lab

- Group A – Heat treatment/metallurgy – steels (forge vs. roll vs. cast), heat treatment, rolling, and mechanical property testing activities
- Group B – Mold making, aluminum casting, post processing
- Mold preparation – vacuum printed molds

4:30 pm – Classroom

- Recap and data review
- Preview Tuesday

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