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Utilization of Additive Manufacturing to support the Manufacturing Innovation Ecosystem

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Abstract

Additive Manufacturing (AM), commonly known as 3D printing, has been widely adopted across various sectors, including research and development, education, workforce training, and service-oriented activities. Numerous publications and institutional reports have highlighted the successes achieved through these initiatives, often measured by tangible indicators such as the number of intellectual property filings, patents, and textbooks or instructional materials produced.

Despite this growing body of work, a notable gap remains in the literature regarding the direct impact of AM on rural economic development, workforce advancement, and job readiness. This paper addresses that gap by presenting a series of week-long bootcamps designed to integrate AM into traditional manufacturing training programs. The study illustrates how AM technologies can enhance hands-on learning experiences, strengthen technical competencies, and support regional workforce development in rural settings.

1. Introduction

AM is a transformative technology in modern manufacturing ecosystems, reshaping how contemporary products are designed, manufactured, and reverse-engineered, beyond its well-documented role in research [1]. High-impact industrial innovations have been increasingly integrated into engineering education, modern technician training, and community-based maker spaces to enhance experimental learning and technical skill development in the 21st century. Educational institutions and workforce development centers have used AM to support project-based learning, rapid prototyping, and interdisciplinary collaboration. This innovative alignment with training outcomes, with Industry 4.0 [2], and smart manufacturing innovations [3]. This broader effort has produced measurable outputs, including curriculum modernization, instructional resources, and increased student engagement, reinforcing AM's value as both a technological and workforce development tool.

1.1 Overview of AM in Modern Manufacturing

The manufacturing term commonly known as 3D printing in the research and innovation field has become a cornerstone of contemporary manufacturing [4], enabling layer-by-layer fabrication of complex geometries that are difficult or impossible to achieve with conventional subtractive or formative manufacturing processes. Manufacturing supports rapid prototyping [5], low-volume production, mass customization, and reverse engineering in tooling development across sectors such as biomedical, automotive, aerospace, and high-end consumer products [6]. Its seamless integration with digital design tools, simulation, and data-driven workflows has positioned AM as a key player in smart manufacturing and Industry 4.0, prompting researchers and industries to reduce lead times, optimize material use, and accelerate innovation while maintaining flexibility in the production system [7].

Figure 1 clearly illustrates an integrated AM workflow that connects the design optimization process, selection, simulation, advanced manufacturing, and mechanical inspection and testing in a continuous, closed, iterative loop [8]. The process begins with bottom-up or top-down design optimization in computer-aided design, followed by the careful selection of AM process parameters, including layer thickness, layer resolution, support structures, nozzle temperature, and printing speed, as shown in Figure 1. The selection of materials is guided by simulation as needed. Advanced manufacturing also involves high-performance materials, such as carbon fiber and carbon nanotube-infused filaments [9], that improve the mechanical properties and longevity of AM parts. The final stage primarily focuses on the mechanical inspection and testing of printed components under load and various environmental conditions. This test involves tensile, fatigue, compression, and creep testing. Together, these four interconnected stages highlight a closed-loop framework for improving part performance from the design stage, enhancing reliability, and improving manufacturability in modern AM applications.

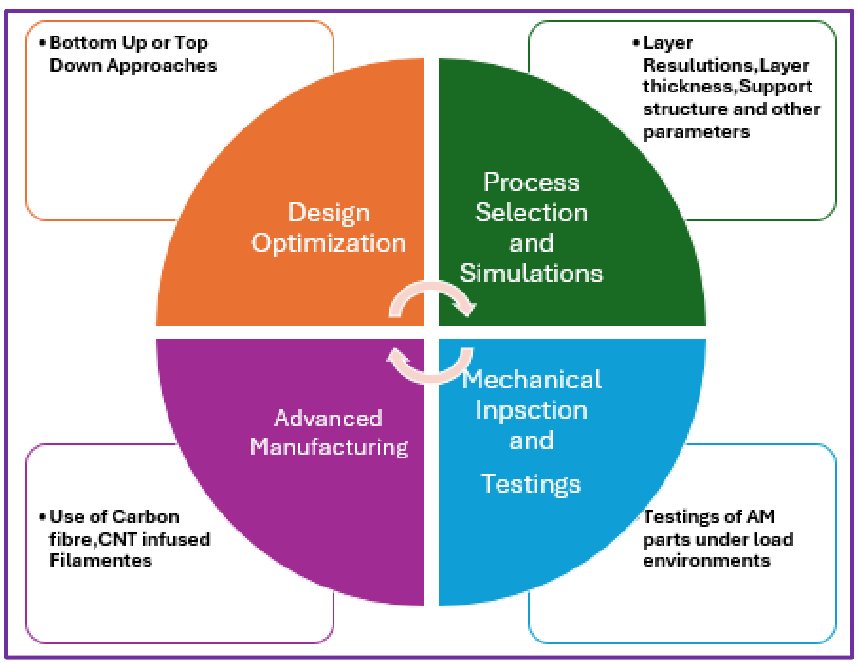

Figure 1: Overview of AM in Modern Manufacturing

AM also plays a crucial role in education, workforce training, and the innovation ecosystem by providing an accessible hands-on platform for developing design, manufacturing, and modern problem-solving skills [10]. This integration into classrooms, training programs, and maker support enables experimental learning, rapid innovation, and collaborations among academia, industry, and communities, helping to prepare a skilled workforce aligned with modern manufacturing needs [11].

1.2 Manufacturing Challenges in Rural and Regional Contexts

Rural and regional manufacturing ecosystems face a critical technical challenge: limited access to advanced manufacturing infrastructure, highly specialized equipment, and high-performance materials. Small and medium-sized enterprises in these areas often rely on legacy manufacturing processes, limit capital investment, and reduce exposure to advanced digital manufacturing tools such as modern simulations, automation, and data-driven process controls [12]. These limitations significantly limit process optimization, slow technological adoption, and reduce regional manufacturers' ability to meet the increasingly complex design certification and quality requirements of modern supply chains.

In addition to constant infrastructure-related workforce challenges, which widely impact manufacturing competitiveness in rural settings. Regional manufacturers frequently face skill gaps in CAD/CAM, AM, metrology, and advanced material processing, compounded by limited access to specialized training and continuing education [13]. These geographic isolations further reduce collaboration with research institutions and technology hubs, reducing opportunities for knowledge transfer and innovation. As a result, rural manufacturers face difficulties in scaling up production, maintaining quality consistency, and adapting to emerging manufacturing technologies, reinforcing the need for targeted technology-enabled workforce development strategies [14].

1.3 Integrated Methodology (AM, Lost PLA Casting, Polymer Forging Dies)

The proposed integrated methodology explored in this research paper combines AM with Lost PLA (Polylactic Acid) casting and the development of polymer-based forging dies to create a unified design for the physical manufacturing workflow. In this approach, high-fidelity solid models are first developed using Computer-Aided Design (CAD) tools and then directly translated into 3D-printed PLA patterns via material extrusion. These printed parts or patterns enable precise control over geometry, internal features, configurations, and surface characteristics that are very difficult to achieve using traditional pattern-making methods [15]. The patterns are assembled into clusters with optimized gating systems and embedded within sand molds. During metal pouring, the PLA pattern thermally decomposes and evacuates the mold cavity, enabling near-net shape metal casting with very low tooling complexity, reduced lead times, and improved design flexibility. AM-enabled Lost PLA casting approach supports rapid iteration, customization, and systematic process optimization for both ferrous and nonferrous alloys [16], as shown in Figure 2.

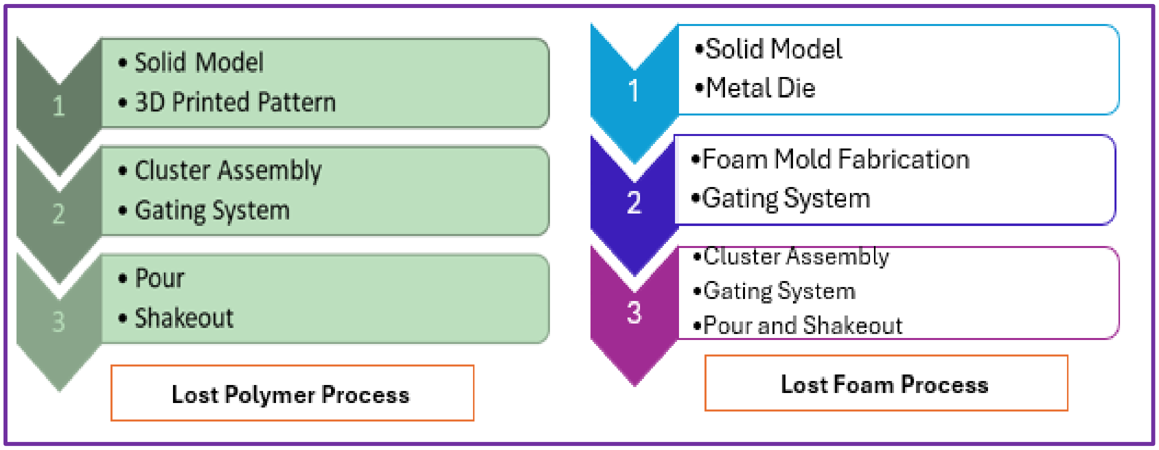

Figure 2: Overview of the Integrated methodology of Lost PLA and Lost Foam casting

Building on the cast components and expertise, the methodology is further extended to the development of polymer forging dies, thereby improving the high-strength, thermally stable polymer composites fabricated by AM. These AM dies are designed based on the requirements of forging load, environmental conditions, thermal exposure, and contact mechanics. This allows the designer to procure and function as a cost-effective tool for low-volume prototyping and educational forging applications. The integration of casting and forging within a single AM-driven framework enabled closed-loop evolution of process structure property. Relationship across manufacturing stages; further improvement in dimensional accuracy, surface integration, microstructural behavior, and tool wear. This is systematically characterized to validate performance overall. This approach or metrology demonstrates a scalable, digitally enabled manufacturing strategy that bridges the gap between AM casting and forging. Offering a significant advantage in tooling agility, advanced workforce training, and manufacturing research [17].

2. Literature Gaps / Overview of the Developed Program

Despite extensive documentation of AM's educational and technological benefits, its direct contribution to the rural innovation ecosystem and workforce readiness remains an underexplored area. Rural regions often face persistent challenges, including limited access to advanced manufacturing infrastructure, reduced exposure to innovative technologies, and skill gaps. This paper addresses this gap by examining a series of intensive, week-long AM bootcamps designed to integrate AM into traditional manufacturing training pathways, thereby supporting innovative ecosystems, education, and workforce training.

The reviewed literature collectively highlights that AM is playing a pivotal role in strengthening innovative ecosystems by adding rapid prototyping, fostering collaborations, and lowering barriers to technology access among academia, national innovation initiatives, and government stakeholders. Prior studies focused on the impact of maker spaces, educational integration, and the national innovation initiative in accelerating workforce development and technology diffusion. However, these efforts trade AM in isolation or focus on singular outcomes, such as the evolution and sustainability of education policy. In addition, only limited attention is given to hands-on training and workshops that integrate AM with downstream manufacturing processes, such as Lost PLA casting and AM polymer forging dies. Notably, a clear gap remains in integrating application-driven frameworks that connect AM-enabled design with casting and forging operations. While systematically evaluating ecosystem-level outcomes, this clear gap motivates the present work.

Table 1: Innovation Ecosystems Education and Workforce Training Literature Review

Reference	Authors	Title	Method / Data	Key Findings / Contributions	Reported Gap
[18]	Sharma, G.	Innovation dynamics within makerspaces and fabrication labs	Systematic literature review	Identifies drivers of innovation in makerspaces	Lack of quantitative impact metrics
[19]	Dehghan et al	The Integration of AM into Industry 4.0 and Industry 5.0: A Bibliometric Analysis	Policy + market analysis	Shows staged AM ecosystem growth	Weak firm-level adoption linkage
[20]	Huang et al	Additive manufacturing: Current state, future potential, gaps and needs, and recommendations	Survey and trend analysis	AM accessibility improved via makerspaces	Limited scale-up validation
[21]	Mathur et al	Effects of Immersion on Knowledge Gain and Cognitive Load in AM Process Education	Review study	Highlights of the role in constrained regions	Outcome evaluation missing
[22]	Loy J	Understanding the scope for a product design education discourse on additive manufacturing	Conceptual + empirical	Explain innovation under resource constraints	Needs performance KPIs
[23]	Prabhu et al.	Exploring the Effects of AM Education on Participants ' Engineering Design Process and Its Outcomes	Multi-cohort survey	Improves student engagement and skills	No longitudinal outcomes
[24]	Fidan et al	Unique Instructional Delivery of Additive Manufacturing: A Holistic Review	Systematic review	Identify skills gaps	No unified competency framework
[25]	Kaya. et al.	Design for AM Education of Process Engineering Participants on an Industrial Challenge	Workshop synthesis	Defines national priorities	Execution frameworks missing

The paper advances a cohesive program that positions AM not only as a prototyping tool but also as an improved platform for experimental training, casting, forging, and advanced workforce innovations within a unified advanced manufacturing ecosystem. AM in manufacturing education and training, and challenges in rural and regional contexts.

3. Conceptual Framework linking AM, Casting, Forging, and Workforce Development

This gap in the literature motivates the present work, which advances a cohesive program that positions AM not only as a prototyping tool but also as an advanced platform for experimental training in advanced casting and cold forging applications, supporting workforce innovations within an unfilled manufacturing ecosystem. Furthermore, the detailed integration of AM into lost PLA casting and purging die-making is explored, reinforcing advanced manufacturing concepts while accelerating learning and improving production efficiency.

3.1 Integration of AM in Lost PLA casting

The AM integration workflow for Lost PLA casting begins with the design and fabrication of lightweight polymer patterns via 3D printing. The participant first developed part geometry using advanced CAD software and intentionally used the concept of draft design and development needed for casting applications [17]. The participant uses lightweight filament for pattern making through thin-walled or hollow features. At the same time, it is necessary to maintain sufficient structural integrity for handling and coating, gating, and the riser system. It is digitally designed and fabricated using AM, enabling precise control over sprue runner, ingate, and riser geometry. The 3D-printed pattern and components are then assembled into a single pattern, known as a casting tree, using specialized casting glue, which ensures a sealed joint and a continuous metal flow path [26]. These systems are thoroughly examined using advanced simulation software, such as InspireCast and InspireForge. This advanced software tool simulates the flow of molten metal and addresses associated issues. Manufactured assembly enables rapid customization. The clear visualization and repeatability of the metal flow concept make it particularly effective in instructional and bootcamp settings.

Following assembly, the combined pattern and getting system is surface cleaned and deep-coated with a ceramic slurry to form an investment shell. This shell supports molten metal at high temperature, as shown in Figure 3. The Assembly is slowly dipped to minimize air entrapment and achieve uniform coating thickness, while excess slurry is removed. After coating the pattern, the assembly is air-dried and left undisturbed for approximately 24 hours to ensure complete drying. Once adequate shell strength is achieved, the ceramic-coated assembly is placed in a flask and supported with dry, loose sand having the correct Green Fineness Number (GFN). This step provides mechanical stability during metal pouring while eliminating the need for conventional rigid molds. The sprue opening is kept exposed to facilitate control of metal entry during pouring.

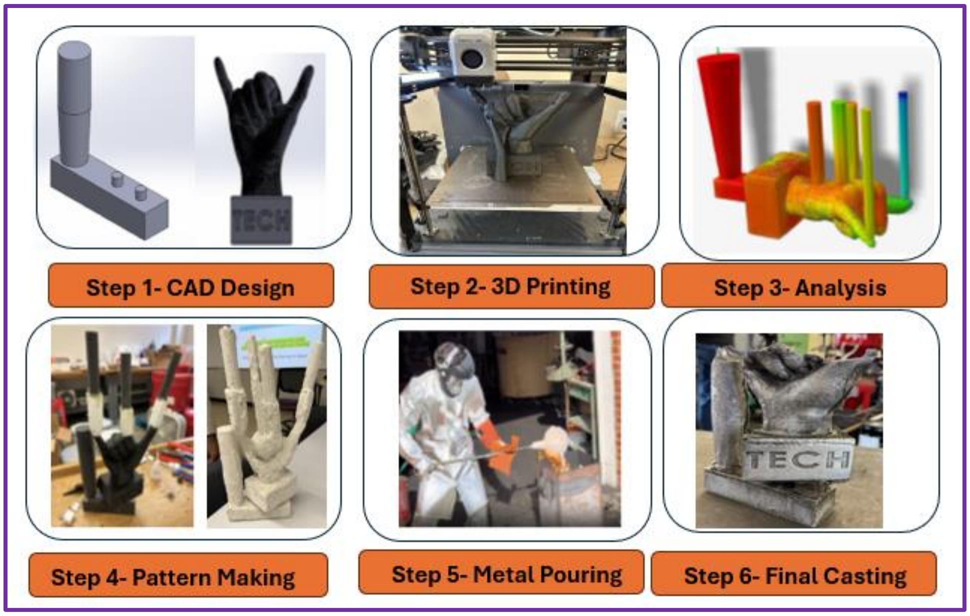

Figure 3: Integration AM in Lost PLA casting

Aluminum is melted and poured at approximately 1550 degrees Fahrenheit into the sprue, where the polymer pattern thermally decomposes and evacuates rapidly. As molten metal fills the cavity, it replicates the part geometry defined by the 3D painting pattern. After solidification and cooling, the loose sand and ceramic shell are removed to retrieve the casting tree. The gating and risers are then cut off, followed by standard post-processing steps. Post-processing includes sandblasting, grinding, deburring, and surface finishing. By integrating AM-fabricated patterns and gating systems directly into the Lost PLA casting workflow, the overall casting cycle time is reduced by approximately 20%. This happens primarily due to the faster tooling preparation, elimination of traditional pattern-making steps, and streamlined mold setup, as shown in Figure 3. This timesaving, combined with the flexibility and visualization enabled by AM, provides a bootcamp participant with a strong, hands-on understanding of innovative AM casting integration. Also, reinforcing advanced manufacturing concepts while accelerating learning and production efficiency.

3.2 Integration AM in Forging Die Making

The integration of AM parts into forging die making begins with designing the forging die in CAD. Key features, such as geometry, parting lines, draft angles, and fillets, are incorporated to support control of material flow during cold forming. The finalized die design is then fabricated using 3D printing, with nylon material selected for its higher strength and toughness compared to standard polymers. Printing parameters, such as build orientation, wall thickness, and infill density, are optimized to improve the die's load-bearing capacity and dimensional stability during cold forming.

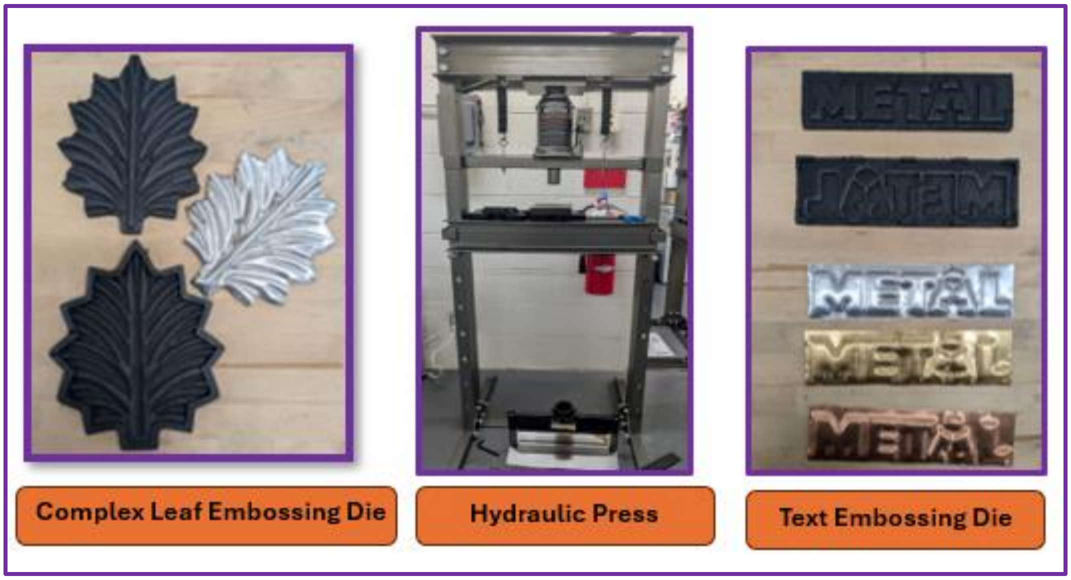

Figure 4: Integrating AM into Forging Die Making

AM nylon dies are subsequently tested in a cold-forging experimental setup using a thin metal stock to limit forming loads and ensure the safe operation of polymer tooling, as shown in Figure 4. The complex leaf embossing die is tested in a 20-ton hydraulic press. During forging, the metal is compressed between the printed dies, improving performance, material flow, and part accuracy. This AM die development approach significantly reduces tooling time and cost while providing participants with a clear, hands-on understanding of how AM can be effectively integrated into forging process innovations.

3.3 Training and Bootcamp Structure

The training bootcamp structure is designed as a five-day, hands-on, intensive program that systematically integrates AM into the casting and forging workflow, as shown in Table 2. At the start of the bootcamp, participants are oriented through registration, safety training, and an overview of the metal program's objective deliverables and expectations. This establishes a strong foundation in laboratory protocols and manufacturing safety. The early sessions mainly focus on core manufacturing fundamentals, including casting principles, foundry applications, and pattern design. This session also includes the use of computer-aided design tools such as Fusion 360 and SolidWorks. Participants then transitioned to an AM-enabled workflow, where they designed and 3D-printed lightweight polymer patterns. Further assembled the patterns, received the system, and were introduced to the Lost PLA casting concept, supported by casting simulations such as Inspire Cast and Inspire Forge. The bootcamp progresses through hands-on activities, expanding to ceramic coating, mold preparation, aluminum pouring, demolding, and post-processing, followed by material characterization, mechanical testing, and quality control exercises. The bootcamp also exposes participants to forging simulations and polymer-based forging demonstrations, further reinforcing the link between digital design, AM tooling, and downstream manufacturing processes.

Table 2: Sample Bootcamp Agenda

TTU METAL Bootcamp Agenda for Monday, August 11, 2025 through Friday, August 15, 2025
All Times are in CENTRAL

Day	Time	Activity	Notes	Responsible Person	Location
Day 1 – August 11 Monday	8:30 - 9:15	Registration Welcome Introduction	Agenda Forms Procedures	Faculty Staff Student	LEWS 101
	9:15 - 9:45	About Bootcamp and METAL Program	Need Tasks Deliverables	Dr. Vondra Dr. Fidan	LEWS 101
	9:45 - 10:00	Break			
	10:00 - 10:50	Introduction to Casting	Fundamentals, historical relevance, and modern industrial applications	Dr. Vondra	LEWS 101
	10:50 - 11:00	Break			
	11:00 - 11:45	Safety	PPE, foundry/forging shop hazards, and lab protocols	Dr. Fidan	LEWS 101
	11:45 - 12:00	Walk to Lunch Area			
	12:00 – 1:00	Lunch			LEWS 201
	1:00 - 1:15	Walk to LEWS 102			
	1:15 – 2:45	Foundry Practices	Scaled-down tin pour to illustrate key casting principles and safety in practice	Graduate Assistants	LEWS 102
	2:45 - 3:00	Return to the Computer Lab			
	3:00 –4:30	Pattern Design (Fusion 360 or SolidWorks)	Creating casting patterns using design tools	Graduate Assistants	LEWS 101

Table 2 above gives a sample structure of day one. This structure directly supports the paper's objective by demonstrating that AM is not a standalone technology but an improved platform that connects design simulations, casting, forging, and inspections within a unified, innovative manufacturing ecosystem. Progression from CAD-based design to AM-fabricated tooling, followed by real foundry and forging operations, highlights how digital manufacturing can accelerate learning, reduce tooling time, and provide rapid iteration. The bootcamp also features industrial talks, facility visits, and networking opportunities and sessions that further expand the ecosystem by connecting participants with workforce boards, professional societies, and industrial partners, and also emphasizing and improving participants' career readiness and innovative technology transfer. Embedding AM in every stage of the bootcamp, from pattern to die creation to process validation and quality control assurance, the training model in the bootcamp illustrates how AM technologies foster innovations, cross-disciplinary integration, and workforce development, which aligns directly with the broader innovation ecosystem framework advancing in this work.

4. Evaluation Metrics, Results, and Discussion

The evolution phase of bootcamp mostly emphasized quantitative and qualitative assessment methods to validate the effectiveness of AM parts in casting and forging workflows. Participants assess the dimensional accuracy and surface quality of the cost components produced through the Lost PLA process by comparing final part dimensions with original CAD models. Tools, including digital calipers and coordinate-based dimensional checks, are used to quantify dimensional deviations. At the same time, surface roughness testers are used to evaluate the consistency of surface finishes across different regions of the cast parts. These measurements enable participants to directly correlate the quality of the AM pattern, ceramic coating integrity, and pouring condition with the final casting accuracy. This exercise reinforces the importance of design-for-manufacturing principles. Participants also address mechanical characterization, defect formation, and process repeatability concepts in Lost PLA, which are evaluated through visual inspection, destructive and non-destructive assessments (as shown in Table 3), and microstructural analysis [27].

Participants identify common casting defects, such as misrun, porosity, surface roughness, surface inclusion, and incomplete filling, and relate these defects to the system's coating thickness and metal-pouring parameters. Repeatability is assessed by comparing multiple castings produced with similar AM patterns and process settings, highlighting the role of AM in achieving consistent tooling and reducing variability, thereby deepening understanding at the microscale. Participants also examine selected samples using Scanning Electron Microscope (SEM), which provides information on surface morphology, dispersion, and agglomeration behavior, as well as micro porosity and metal interactions that are not visible through optical inspection alone. This exposure underscores the importance of SEM [28]. In advanced manufacturing, quality analysis and failure diagnosis are key.

Table 3: Quality control Assessment sheet

TTU METAL Bootcamp

Quality Control Design of Experiment Analysis

Leeb Hardness Test

Sample No	Surface Hardness Reading 1 (HL)	Surface Hardness Reading 2 (HL)	Surface Hardness Reading 3 (HL)	Surface Hardness Reading Mean (HL)
1				
2				
3				
4				

In addition to casting evolution, participants also assess the mechanical performance and durability of AM polymers through control cold-forging experiments. The dies are inspected both before and after forming to evaluate where deformation and surface damage occur, providing practical insight into the load-bearing limits of polymer-based tooling. Mechanical characterization of cast parts is further supported through hardness testing, as shown in Table 3 above, using Rockwell and Leeb hardness testers [29]. This enables students to relate solidification behavior and post-processing steps to material hardness and overall part quality by integrating dimensional inspection, surface roughness analysis, hardness testing, and SEM-based microstructural capabilities. The participants demonstrate a comprehensive, data-driven approach to assess the AM-integrated manufacturing process [30], highlighting both the technical and absolute world-class quality assurance needed for improvement in an innovative ecosystem for workforce development.

4.1 Participant Feedback Analysis

At the conclusion of each bootcamp, participants fill out an online evaluation survey administered by the Institute for Advanced Composites Manufacturing Innovation (IACMI). To assess the overall effectiveness of the training program, survey responses were systematically analyzed to identify key strengths, areas for improvement, and overall participant satisfaction. This feedback mechanism provides valuable insights into how well the bootcamp structure, technical content, and delivery methods met the learning objective defined at the outset.

Overall, the bootcamp leadership team's goal of achieving high satisfaction with the bootcamp offerings was met, as illustrated in Figure 5. Participants from the bootcamps reported that learning objectives were fully achieved, and all respondents indicated their willingness to share their positive experience and learning with their peers and colleagues, underscoring the program's effectiveness and impact as seen in Figure 6

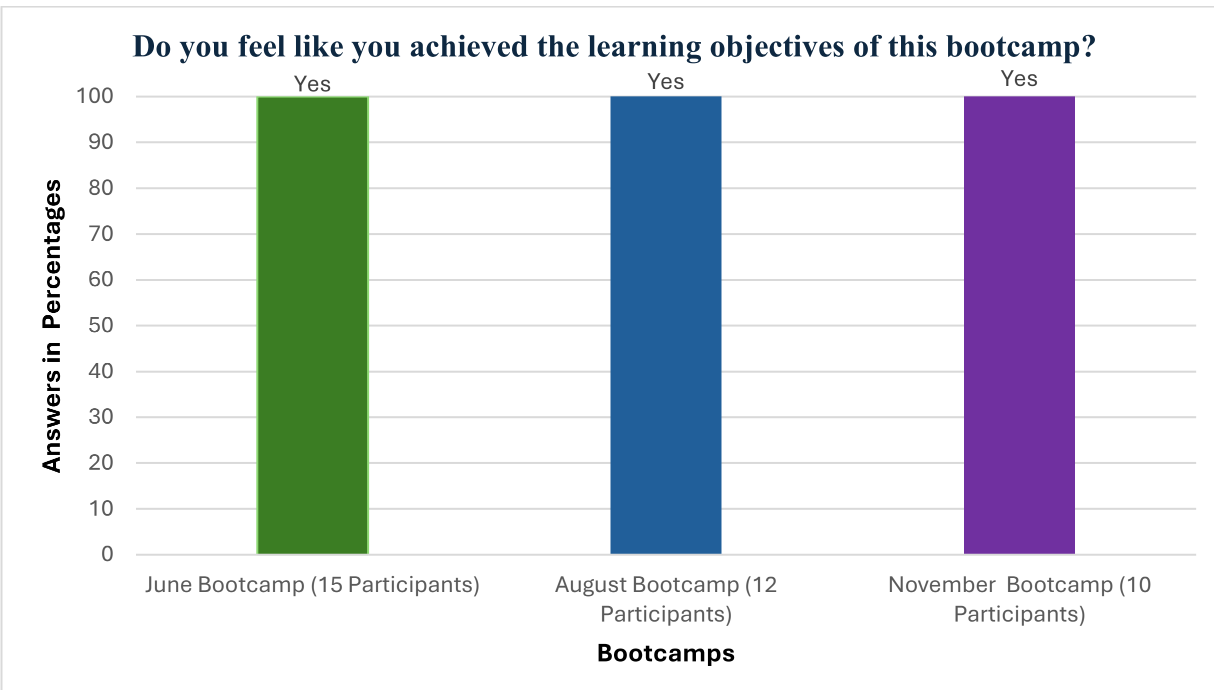

Figure 5: Responses of June (Green), August (Blue), and November (Purple) bootcamp participants to the question Do you feel like you achieved the learning objectives of this bootcamp?'

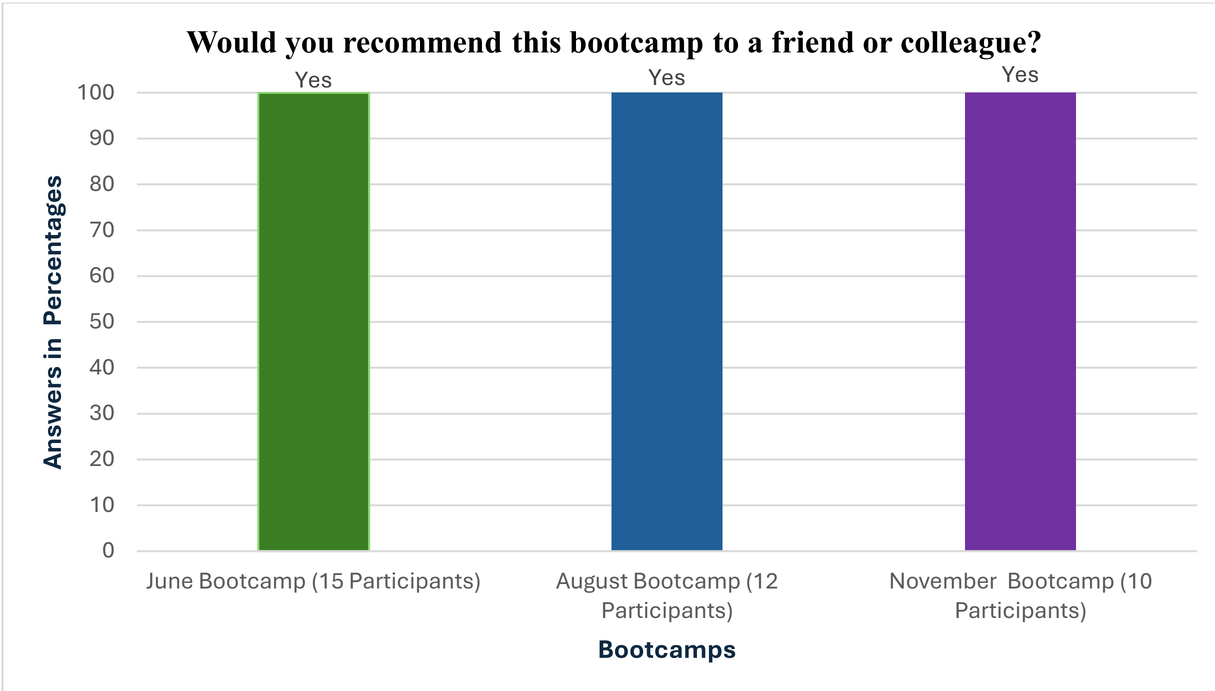

Figure 6: Responses of June (Green), August (Blue), and November (Purple) bootcamp participants on the question Would you recommend this bootcamp to a friend or colleague?'

4.2 Knowledge and Skills Assessment

The post-bootcamp survey results indicated a number of improvements in participants' knowledge and technical skills. Particularly in their ability to explain key process parameters, interpret casting and forging simulation results, and identify common manufacturing defects. Also demonstrated increased confidence in connecting design decisions and manufacturing outcomes. These results reflect the effectiveness of the integrated instructional approach. In addition, all respondents express a positive perception of the quality of instruction and the value of the hands-on learning experience. Also, reinforcing the role of exponential training and enhancing technical understanding in the innovation ecosystem.

4.3 Performance and Engagement Indicators

Performance and engagement were continuously observed and documented by bootcamp instructors throughout the program. At the start of the day's session, the rigorous review of the previous day's technical outcomes was discussed. This feedback was documented throughout the bootcamp, with a focus on teamwork, problem-solving, and active participation. As shown in Figure 7, the majority of participants exhibited high enthusiasm during hands-on activities, including pattern design, metal melting, casting, and forging. Every participant has poured their individual patterns, giving a strong collaborative behavior. Instructors also noted that implementing the gallery method significantly contributed to sustained engagement by encouraging peer learning, discussion, and reflection, thereby enhancing participants' overall involvement in the learning outcomes.

Figure 7. Bootcamp participants are measuring the finish quality of the cast part in terms of dimensional accuracy and surface roughness

5. Conclusions

This paper clearly demonstrates that AM can serve as a critical component in technology transfer within a broader innovation ecosystem. The workforce training program results from the week-long bootcamp, which involves AM in casting and forging workflows through 3D-printed patterns and AM-enabled gating and riser systems. The polymer-based forging dies significantly enhance hands-on learning while reducing tooling, lead time, and process complexity. The evolution matrix, including dimensional accuracy, surface quality, defect analysis, mechanical performance, and microstructural characterization, is innovative and engaging. Furthermore, participants successfully applied digital design simulation and AM-fabricated tooling to produce a functional, cast, and forged component. The survey results and instructional observation further indicated that participants made substantial gains in their understanding of process parameters, defect identification, and data interpretation, validating the technical effectiveness of the training model.

From the workforce development perspective, these works contribute a scalable application-driven framework for AM-based workforce training. The workshop extends beyond prototyping and emphasizes downstream manufacturing integration by linking CAD simulation, additive tooling, cold forging operations, and quality assurance. The bootcamp addresses a critical gap in the literature related to the AM role in rural economics and workforce development. The program model fosters job-ready skills, promotes cross-disciplinary collaborations, and strengthens connections among academia, industry, and regional manufacturing partners. In practice, the findings support the adoption of an AM-integrated curriculum as an effective strategy for modern manufacturing education, particularly in rural and regional contexts where access to advanced tooling and rapid iteration is minimal. Overall, this study confirms that the utilization of an AM strategy can play a transformative role in supporting innovative ecosystems by accelerating skill development, enhancing workforce readiness, and reinforcing regional manufacturing capacity.

Acknowledgements

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