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Bridging Design and Practice in Additive Manufacturing Education: A Framework of Best Practices

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Abstract

Additive Manufacturing (AM), commonly known as 3D printing, has become an integral part of modern life and is increasingly embedded across STEM education. From design and prototyping to laboratory and studio applications, educators are leveraging AM to enhance experiential learning, foster creativity, and strengthen students' understanding of manufacturing principles. However, despite its widespread adoption, both educators and students continue to face challenges in achieving high-quality printed outcomes. A significant portion of these issues arises from design-related errors and improper slicing configurations, which directly affect part accuracy, surface finish, and mechanical performance. This paper presents a comprehensive collection of best practices identified by experienced AM educators to mitigate common design and process errors. The study highlights critical considerations for parameter selection, feature design, and input optimization. Furthermore, it introduces a set of knowledge blocks and modular instructional units collaboratively developed by the authors, which are designed to improve educational outcomes, enhance print reliability, and promote deeper student engagement in AM education.

Keywords: Design for Additive Manufacturing, Experiential Learning, Instructional Modules, Manufacturing Education, 3D Printing in STEM Education,

1. Introduction

AM, widely referred to as 3D printing, has evolved from a niche rapid prototyping technology into a transformative manufacturing paradigm with far-reaching implications across industry, research, and education [1]. Its ability to fabricate complex geometries, enable mass customization, reduce material waste, and shorten product development cycles has positioned AM as a critical component of modern manufacturing ecosystems [2]. Consequently, AM has become deeply embedded in engineering, engineering technology, and broader STEM curricula, where it is increasingly used as a platform for experiential learning, creativity, and interdisciplinary problem-solving [3].

In educational settings, AM serves multiple roles. It functions as a design validation tool, a manufacturing process for functional parts, and a medium through which students can directly observe the relationship between digital models and physical artifacts [4]. Desktop and industrial-scale 3D printers are now commonly found in design studios, manufacturing laboratories, makerspaces, and capstone project environments. Through hands-on interaction with AM systems, students are expected to develop competencies in computer-aided design (CAD), materials selection, process planning, and quality assessment skills that align closely with workforce expectations in advanced manufacturing. Figure 1 illustrates the iMakerSpace laboratory at Tennessee Technological University, where students actively engage in additive manufacturing through hands-on, learning-by-doing experiences. The iMakerSpace integrates education and fabrication, supporting lectures, training activities, and innovation and entrepreneurship (I&E) events, including student competitions. Additionally, the facility plays a critical role in supporting senior design and capstone projects, with students fabricating functional components under the guidance of the iMakerSpace technical team [5].

Figure 1: 3D printing (3DP) section of iMakerSpace [5] (open access)

Despite its widespread adoption, the effective integration of AM into education remains uneven. Many students and novice users perceive AM as an automated or push-button technology, where successful outcomes are assumed to follow directly from a completed CAD model [6]. This perception often obscures the fundamental reality that AM is a manufacturing process governed by physics, material behavior, machine constraints, and parameter interactions. As a result, educators frequently observe a disconnect between design intent and printed outcomes, manifested through failed prints, poor surface finish, dimensional inaccuracies, internal defects, and mechanically weak parts [7].

A significant portion of these challenges can be traced to insufficient understanding of Design for Additive Manufacturing (DfAM) principles. Students often design parts using conventions inherited from subtractive manufacturing, such as uniform wall thicknesses, sharp internal corners, unsupported overhangs, and orientation-independent assumptions about material strength [8]. When these designs are translated into layer-by-layer fabrication, the mismatch between geometry and process capabilities leads to defects such as warping, delamination, excessive support requirements, and anisotropic mechanical behavior. In many cases, these issues are addressed through trial-and-error rather than informed design modification, limiting the depth of learning [9].

Compounding these design-related challenges is the role of slicing software, which represents a critical yet frequently underemphasized step in AM education. Slicing transforms a digital geometry into machine-specific instructions by discretizing the model into layers and toolpaths [10]. Decisions related to layer height, raster width, infill strategy, build orientation, support generation, and thermal management directly influence print time, material usage, surface quality, and mechanical performance. However, students often rely on default slicing profiles or make parameter changes without understanding their physical significance. This lack of process literacy further widens the gap between digital design and physical realization.

From an instructional perspective, AM education is also shaped by practical constraints. Shared laboratory environments, limited print time, material costs, and heterogeneous student backgrounds challenge educators to balance conceptual depth with operational efficiency [11]. Instructors must ensure that students achieve successful prints within restricted timeframes while also fostering meaningful understanding of manufacturing principles. Without a structured approach, AM activities risk becoming tool-centric exercises rather than opportunities for manufacturing insight.

Recognizing these challenges, there is a growing need for pedagogical frameworks that explicitly connect design decisions, slicing strategies, and printed outcomes. Rather than treating design, slicing, and fabrication as isolated steps, AM education should emphasize their interdependence as elements of an integrated manufacturing system [12]. Such an approach aligns with industry practices, where successful AM implementation relies on coordinated decisions across design, process planning, and quality assurance.

This paper is motivated by the need to systematically bridge the gap between design and practice in additive manufacturing education. Drawing on the collective experience of AM educators and iterative classroom implementation, this work proposes a structured framework of best practices that integrates DfAM principles, process parameter understanding, and pedagogical strategies. By formalizing these best practices and organizing them into reusable knowledge blocks and modular instructional units, the framework aims to improve print reliability, deepen student engagement, and promote a more authentic understanding of AM as a manufacturing process rather than a black-box technology.

2. Challenges in Additive Manufacturing

The effective integration of additive manufacturing into formal education presents a unique set of technical, cognitive, and logistical challenges. While AM systems are often marketed as accessible and user-friendly, their successful operation requires a nuanced understanding of design principles, process physics, material behavior, and machine constraints. In educational environments, where learners are still developing foundational knowledge, these challenges are frequently amplified [13]. A recurring issue in AM education is that students encounter failures without a clear conceptual framework to diagnose or resolve them. Unlike traditional manufacturing processes, where cause–and–effect relationships are often visible and well-documented in curricula, AM failures may appear opaque or inconsistent to novice users. This section discusses the primary categories of challenges that hinder effective learning outcomes in AM-focused courses.

2.1 Design-Related Challenges

Design deficiencies represent one of the most significant barriers to successful additive manufacturing in educational settings. Students often approach AM using design heuristics derived from subtractive manufacturing or purely aesthetic considerations. As a result, they may unintentionally violate fundamental DfAM principles, leading to poor print outcomes. Common design-related challenges include unsupported overhangs that exceed process limitations, thin walls that fall below minimum printable feature sizes, excessive aspect ratios that promote buckling or vibration, and abrupt geometric transitions that create localized stress concentrations. Additionally, students frequently neglect the influence of building orientation on mechanical anisotropy, assuming isotropic behavior similar to injection-molded or machined components. Leung et al. reviewed the design of functional parts fabricated using additive manufacturing processes and materials, and identified areas that have received limited attention, along with potential directions for future research in design for AM, as shown in Figure 2 [14].

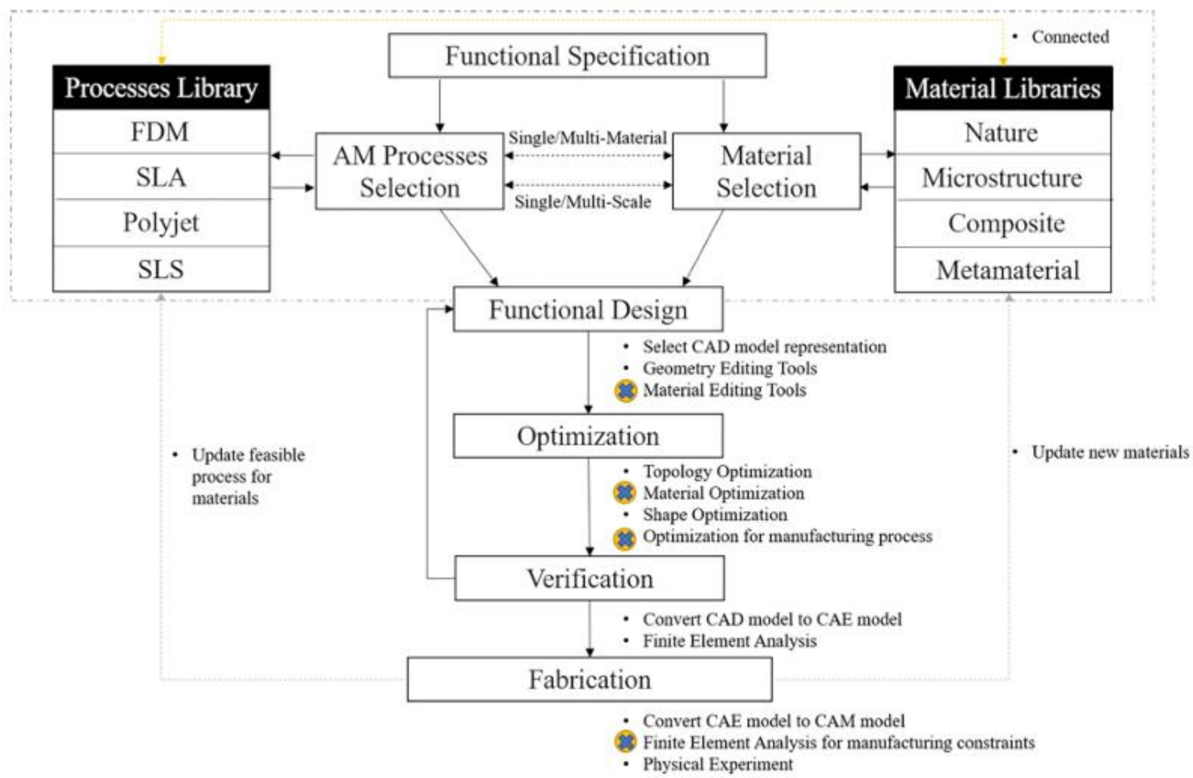

Figure 2: A design framework for functional additive manufacturing. Crossed bullet points suggest the directions [14] (open access)

These issues are exacerbated by the increasing availability of complex CAD tools that enable intricate geometries without conveying manufacturability constraints. While such tools empower creativity, they can also distance students from the realities of layer-by-layer fabrication. Without explicit instruction in DfAM, students may rely on repeated printing attempts to achieve success, resulting in inefficient use of time and resources.

2.2 Slicing and Process Planning Challenges

Slicing software serves as the critical intermediary between digital design and physical fabrication, yet it remains one of the least understood components of AM education. Students often treat slicing as a procedural step rather than a manufacturing planning activity, relying heavily on default profiles or anecdotal advice. Inappropriate layer height selection, inefficient infill strategies, excessive support material, and suboptimal build orientations are common issues observed in student-generated prints. These decisions directly influence print duration, surface quality, dimensional accuracy, and mechanical performance. Furthermore, a lack of understanding of thermal history, cooling rates, and interlayer bonding can lead to defects such as warping, delamination, and residual stress accumulation. In AM, 3D slicing and path planning play a key role in determining how a part is printed, influencing the process parameters, shape, and performance of the final component, as shown in Figure 2.

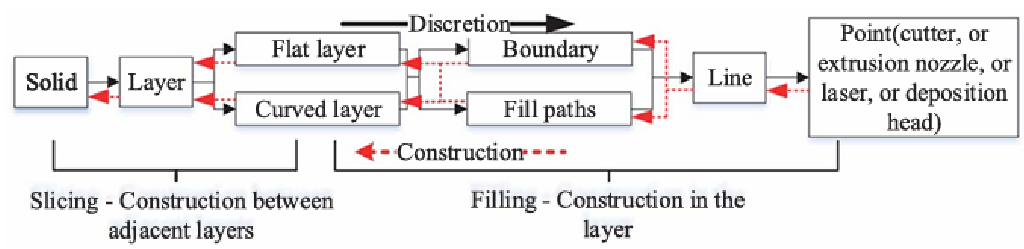

Figure 3: Procedures of 3D slicing and path planning [15] (open access)

The challenge is compounded by the diversity of slicing software platforms and machine architecture. Each system introduces its own parameter sets, terminology, and limitations, increasing the cognitive load on students. Without a structured approach to slicing instruction, learners may struggle to generalize principles across platforms.

2.3 Educational and institutional constraints

Beyond technical considerations, AM education is shaped by institutional and logistical constraints. Shared laboratory spaces, limited machine availability, and constrained instructional time require educators to prioritize efficiency and reliability. Failed prints can disrupt course schedules, delay project milestones, and reduce opportunities for reflection and iteration. Additionally, AM courses often enroll students from diverse academic backgrounds, including mechanical engineering, engineering technology, industrial design, and non-engineering disciplines [16]. This diversity enriches the learning environment but also necessitates adaptable instructional strategies that accommodate varying levels of prior knowledge. These realities underscore the need for a coherent, scalable framework that supports both instructors and learners.

3. Framework of best practices for AM education

To address the challenges outlined above, this paper proposes a comprehensive framework of best practices designed to bridge design intent and manufacturing execution in AM education. The framework is informed by classroom experience, iterative refinement, and alignment with industry-relevant competencies. Rather than prescribing rigid rules, it emphasizes principled decision-making and process awareness [17]. The framework is organized around three interconnected pillars: design best practices, process and parameter best practices, and pedagogical best practices. Together, these pillars provide a holistic approach to teaching AM as an integrated manufacturing system.

3.1 Design Best Practices

Designing best practices emphasize the translation of functional requirements into geometries that are compatible with additive manufacturing processes. Students are encouraged to consider support minimization, feature resolution, load paths, and build orientation early in the design phase. Instruction within this pillar focuses on self-supporting geometries, appropriate wall thickness selection, gradual cross-sectional transitions, and the strategic use of fillets and chamfers. Comparative case studies are used to illustrate how minor design modifications can significantly improve print success and performance [18]. Through guided design reviews, students learn to justify their geometric decisions based on process capabilities rather than convenience.

3.2 Process and Parameter Best Practices

The second pillar addresses the relationship between slicing parameters and physical outcomes. Students are introduced to the physical significance of layer height, extrusion width, infill topology, and print speed. Emphasis is placed on understanding trade-offs, such as resolution versus build time or strength versus material usage. Rather than relying on fixed parameter sets, students are encouraged to develop parameter selection strategies tailored to specific materials, geometries, and performance objectives. This approach fosters adaptability and prepares learners to work with diverse AM platforms [19].

3.3 Best Pedagogical Practices

Pedagogical best practices focus on instructional design and assessment strategies that reinforce learning through iteration and reflection. Scaffolded assignments, failure-based learning exercises, and structured troubleshooting activities are central to this pillar. By integrating design reviews, peer feedback, and reflective documentation, educators can help students internalize the cause–and–effect relationships inherent in AM. These strategies promote deeper engagement and long-term skill development [16].

Based on collective teaching experience and iterative classroom implementation, this paper proposes a framework organized around three interconnected pillars: Design Best Practices, Process and Parameter Best Practices, and Pedagogical Best Practices.

4. Knowledge Blocks and Modular Instructional Units

To operate the proposed framework of best practices, the authors developed a series of structured knowledge blocks that serve as modular instructional units. These knowledge blocks are designed to translate abstract principles of additive manufacturing into tangible learning experiences that can be systematically deployed across courses and academic levels. The intent is to create reusable, adaptable content that supports consistent learning outcomes while allowing instructors flexibility in implementation. Each knowledge block targets a specific conceptual or practical competency related to AM and is constructed around four core components: (i) foundational theory, (ii) guided demonstration, (iii) hands-on experimentation, and (iv) reflection and assessment. This structure ensures that students not only acquire procedural skills but also develop an understanding of underlying cause–and–effect relationships.

4.1 Knowledge Block 1: Geometry–Toolpath Interaction

This knowledge block introduces students to the relationship between part geometry and generated toolpaths. Students explore how geometric features such as overhangs, curvature, wall thickness, and internal cavities influence slicing decisions and deposition behavior. Through visual inspection of toolpaths and controlled print experiments, learners gain insight into how design choices directly affect material flow, support requirements, and surface finish. Activities within this block emphasize comparative analysis. Students are asked to print geometrically similar parts with subtle design variations and document differences in print success, build time, and material usage. This exercise reinforces the concept that manufacturability is an inherent design attribute rather than a post-processing consideration. Pazireh et al.[20] investigated the interactions between different geometries and toolpaths in multi-layer deposition, establishing a foundation for the development of optimal toolpath generation strategies, as shown in Figure 4.

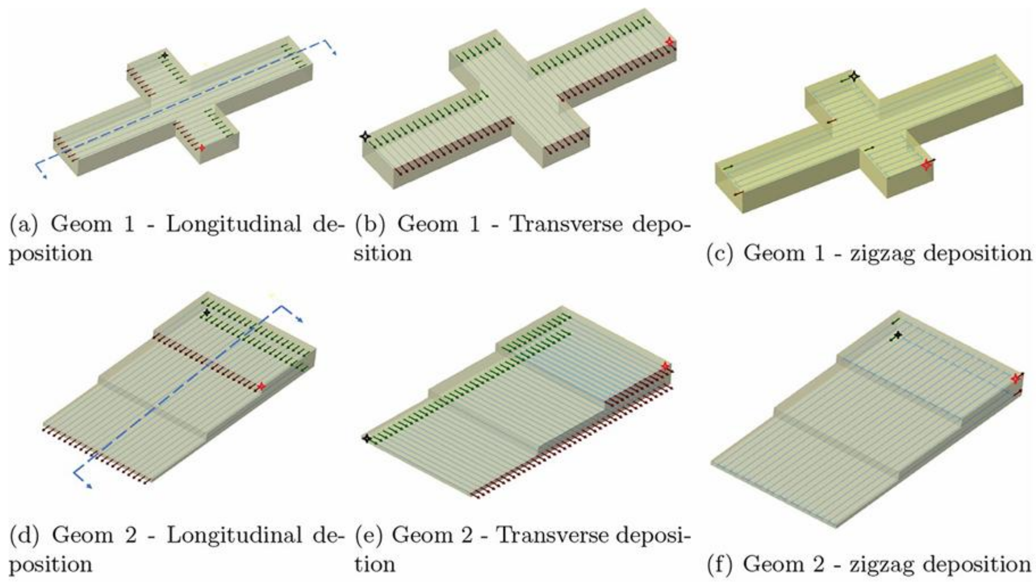

Figure 4: Toolpath vectors – the black star shows the start point of deposition, and the red star shows the end point of the deposition – cross-sections [20] (open access)

4.2 Knowledge Block 2: Material Behavior and Thermal History

The second knowledge block focuses on material-specific behavior during the additive manufacturing process, with particular emphasis on thermal history, heat transfer, and interlayer bonding. This block is designed to help students understand that material properties alone do not determine part quality; rather, it is the interaction between material behavior and process conditions that governs print success. Students are introduced to key material concepts relevant to AM, including glass transition temperature, melting temperature, viscosity, thermal conductivity, and coefficient of thermal expansion. These concepts are then directly linked to common print phenomena such as warping, residual stress development, poor bed adhesion, and interlayer delamination. By explicitly connecting material science principles to observable print outcomes, this knowledge block bridges the gap between theory and practice.

Through guided experiments and demonstrations, students systematically vary process parameters such as build plate temperature, extrusion temperature, cooling fan speed, and enclosure conditions. The resulting prints are evaluated for dimensional stability, surface quality, and layer adhesion. These controlled variations allow students to visualize how thermal gradients and cooling rates influence microstructural bonding and overall part integrity. In addition, students are encouraged to compare different polymer materials commonly used in educational settings, such as PLA, PETG, and ABS, to observe differences in thermal sensitivity and print behavior. This comparative approach reinforces the idea that parameter sets are not universally transferable across materials. Collectively, these activities help students develop an intuitive and practical understanding of thermal history and its critical role in determining the quality and reliability of additively manufactured parts.

4.3 Knowledge Block 3: Slicing Parameters and Mechanical Performance

This knowledge block explicitly links slicing decisions to mechanical behavior. Students investigate the effects of layer height, raster orientation, infill density, and build orientation on tensile strength, stiffness, and failure modes.

To support this learning objective, a representative slicing visualization is introduced. Figure 5 presents a sliced model highlighting perimeter, external perimeter, and infill toolpaths along with their relative contributions to print time and material usage. By examining this visualization, students learn how slicing choices redistribute material between load-bearing perimeters and internal infill, directly influencing structural performance. Using the figure, students are guided to analyze how increasing the number of perimeters shifts material toward the outer shell, how infill percentage and pattern affect internal load transfer, and how these parameters collectively impact print time and part mass. This visual approach helps students move beyond abstract parameter lists and develop an intuitive understanding of how slicing decisions translate into physical behavior during printing. By correlating slicing parameters with fracture surfaces and failure locations, students develop an understanding of anisotropy and load transfer in additively manufactured parts. Rather than focusing on absolute property values, the emphasis is placed on trends and relative comparisons.

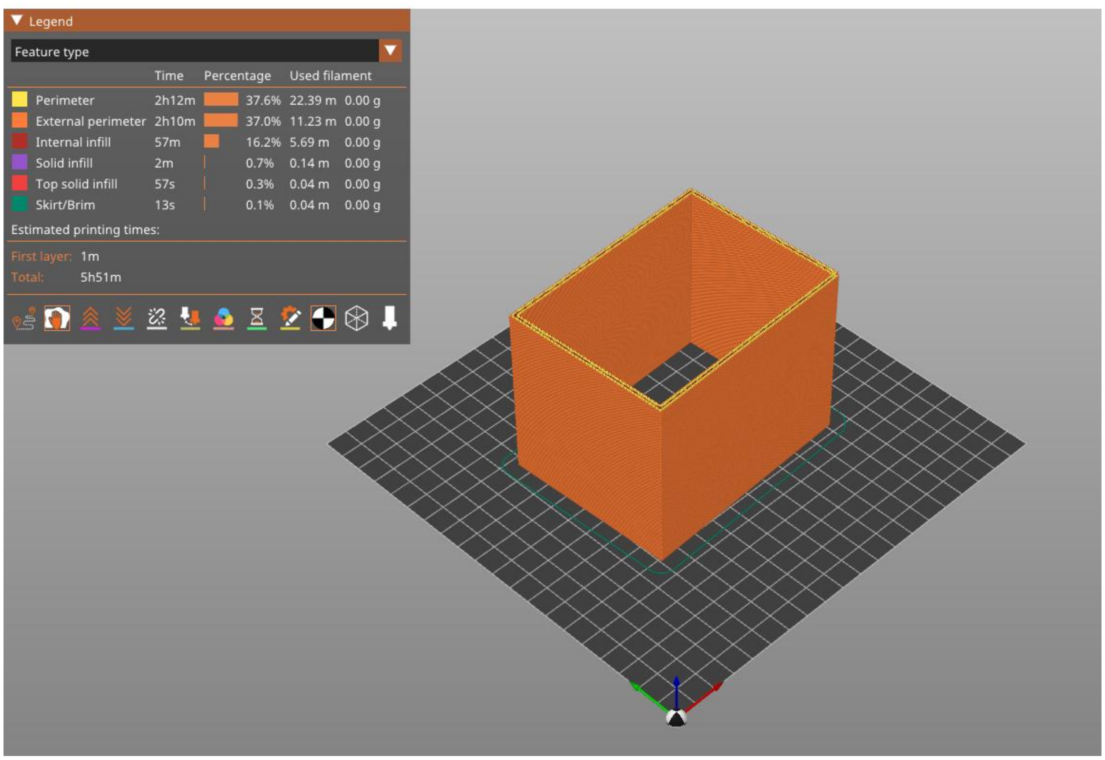

Figure 5: Slicing parameters of 3D block

4.4 Knowledge Block 4: Print Failure Analysis and Troubleshooting

The final knowledge block focuses on developing systematic diagnostic and troubleshooting skills by exposing students to common print defects and failure modes encountered in additive manufacturing. Rather than immediately correcting errors, students are encouraged to analyze printed parts to identify root causes related to design choices, slicing parameters, and process conditions.

To support this learning objective, Figure 6 presents representative printed specimens exhibiting visible defects such as surface irregularities, inconsistent layer deposition, and localized imperfections. These specimens are intentionally selected to illustrate how variations in slicing parameters, extrusion consistency, cooling behavior, and build orientation manifest as observable quality issues in finished parts. Using this figure, students are guided through a structured failure analysis process that includes visual inspection, comparison against expected tool paths, formulation of hypotheses regarding root causes, and proposal of corrective actions. This exercise reinforces the importance of linking observed defects to upstream decisions made during design and slicing, rather than attributing failures solely to machine malfunction. This knowledge block emphasizes documentation, critical thinking, and iterative improvement. By reframing print defects as diagnostic signals rather than errors to be avoided, students develop confidence, resilience, and problem-solving abilities that are essential for effective practice in additive manufacturing.

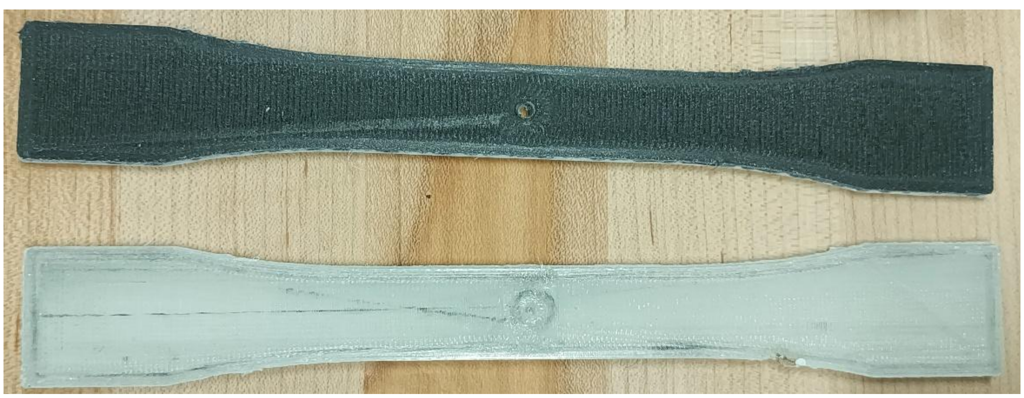

Figure 6: Surface irregularities observed in AM specimens

5. Implementation in AM-Focused Courses

The proposed framework and associated knowledge blocks have been implemented across multiple AM-focused instructional contexts, including introductory additive manufacturing courses, manufacturing laboratory modules, and senior-level design experiences. Implementation strategies were intentionally designed to integrate seamlessly with existing curricula while enhancing learning outcomes. In introductory courses, knowledge blocks are introduced sequentially, allowing students to build foundational understanding before progressing to more complex concepts. Assignments emphasize justification of design and slicing decisions, encouraging students to articulate the rationale behind their choices. This approach shifts assessment from outcome-based grading to process-oriented evaluation.

In laboratory-based courses, the framework supports structured experimentation and data-driven reflection. Students maintain detailed print logs documenting design parameters, slicing settings, observed defects, and corrective actions. These logs serve as both assessment artifacts and learning tools, reinforcing the iterative nature of AM. At the senior design level, students are expected to independently apply the framework to open-ended problems. Teams conduct design reviews, evaluate manufacturability constraints, and propose optimized printing strategies. Faculty feedback focuses on decision-making quality rather than mere print success, aligning academic evaluation with industry practices.

6. Discussion: Bridging Design and Practice

The expanded framework highlights the importance of treating additive manufacturing as an integrated system rather than a collection of discrete steps. By explicitly linking geometry, slicing, material behavior, and fabrication outcomes, the proposed approach addresses a critical gap in AM education. One of the most significant observations from implementation is the shift in student mindset. Learners increasingly view print failures as diagnostic signals rather than random events. This perspective encourages analytical thinking and reduces frustration, particularly in early stages of skill development.

From an instructional standpoint, the modular nature of the knowledge blocks enables scalability and adaptability. Instructors can tailor content based on course objectives, available resources, and student backgrounds without compromising conceptual coherence. Moreover, the framework supports alignment with accreditation outcomes related to experimentation, problem-solving, and continuous improvement. Collectively, these findings suggest that a structured best-practices framework can enhance both technical competence and educational effectiveness in additive manufacturing instruction. The proposed framework has been implemented across introductory AM courses, manufacturing laboratories, and senior design projects. Students are required to justify design choices, document slicing strategies, and correlate print outcomes with initial assumptions. Preliminary observations indicate improved print success rates, reduced material waste, and deeper conceptual understanding. Students demonstrate increased confidence in diagnosing failures and iterating designs with purpose rather than guesswork.

7. Conclusions and Future Work

The key conclusions drawn from this study are summarized below:

- AM education benefits significantly when design, slicing, and fabrication are taught as an integrated manufacturing system rather than isolated steps.

- A large proportion of print failures in educational settings can be traced to design-related decisions and improper slicing configurations, highlighting the need for explicit instruction in DfAM and process planning.
- The proposed framework of best practices provides a structured yet flexible approach that helps students understand the cause–and–effect relationships between geometry, process parameters, material behavior, and printed outcomes.
- The use of modular knowledge blocks enables scalable and adaptable implementation across introductory courses, laboratory modules, and senior design experiences, accommodating diverse student backgrounds and institutional constraints.
- Integrating failure-based learning and structured troubleshooting reframes print defects as learning opportunities, leading to improved student confidence, analytical thinking, and problem-solving skills.

Future work will focus on quantitative assessment of learning outcomes, longitudinal evaluation across multiple institutions, and expansion of the framework to include metal additive manufacturing, hybrid processes, and digitally connected AM systems. The long-term objective is to establish a shared, educator-driven best-practices model that evolves alongside additive manufacturing technologies and workforce needs.

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