Integrating Computer-Aided Manufacturing Users with Directed Energy Deposition Guidelines

Dr. Kenton Blane Fillingim, Oak Ridge National Laboratory

Dr. Kenton Blane Fillingim is R&D staff for human factors in advanced manufacturing within the Manufacturing Sciences Division at Oak Ridge National Laboratory. His research at ORNL's Manufacturing Demonstration Facility focuses on process development to accelerate the industrialization of directed energy deposition (DED) convergent manufacturing platforms. He aims to improve the user experience and increase the success of designers and operators in convergent manufacturing environments. Blane received his B.S. in Mechanical Engineering from the University of South Alabama, and his M.S. and Ph.D. degrees in Mechanical Engineering from the Georgia Institute of Technology.

Dr. Lauren Heinrich, Oak Ridge National Laboratory

Dr. Lauren Heinrich is a technical staff member who provides research support with her experience in hybrid manufacturing in the Manufacturing Science Division at Oak Ridge National Laboratory. She received her bachelor's in mechanical engineering from Lipscomb University in 2020 then completed her master's degree in mechanical engineering with a focus on wire arc additive manufacturing processing from Georgia Institute of Technology in 2022. Heinrich started at ORNL in 2022 and her work at the Department of Energy's Manufacturing Demonstration Facility consists of utilizing hybrid manufacturing, a combination of additive and subtractive (machining) manufacturing, to further support manufacturing in the tool and die, aerospace, energy systems, and automotive industries.

Dr. Ashley Gannon, Oak Ridge National Lab

Dr. Ashley Gannon is a Research and Development Professional specializing in simulation and visualization at Oak Ridge National Laboratory. Ashley's work focuses on combining finite element simulations, in-situ monitoring, and toolpath optimization strategies to optimize additive manufacturing processes by reducing residual stress and geometric distortion in printed parts. Ashley earned her Ph.D. in Computational Science from Florida State University, her Master's in STEM teaching, and Bachelor's degrees in Chemical & Biomedical Engineering and Biological Sciences.

Dr. Thomas Feldhausen, Oak Ridge National Laboratory

Dr. Thomas Feldhausen is a research staff member in the Manufacturing Science Division at Oak Ridge National Laboratory in addition to being a joint faculty member of the University of Texas at El Paso as a research assistant professor in the department of Aerospace and Mechanical Engineering. He received his bachelor's and master's degree in mechanical engineering from Kansas State University, with a focus on curriculum development for mechanical engineering education, and a Ph.D. degree from the Georgia Institute of Technology in the field of hybrid (additive and subtractive) manufacturing. Thomas started at ORNL in 2019 and has been the technical lead for hybrid manufacturing. Before working at ORNL, Thomas worked at Honeywell Federal Manufacturing and Technologies in Kansas City where he focused on multi-axis additive techniques for direct ink-write technologies.

Dr. Feldhausen has made significant contributions to the field of additive manufacturing with his innovative research at the Department of Energy's Manufacturing Demonstration Facility. His research utilizes hybrid manufacturing, a combination of additive and subtractive (machining) manufacturing, to provide industrial solutions for component repair, tooling and tooling repair, advanced energy systems, aerospace, and automotive applications.

Dr. Feldhausen's work has been recognized with numerous awards, including an Outstanding Young Manufacturing Engineering Award by the Society of Manufacturing Engineers, selected as a 30 under 30 individual by the Society of Manufacturing Engineers, National Nuclear Security Administration Defense Program Award of Excellence, R&D 100 award winner, attendee of the Grainger Foundation U.S. Frontiers of Engineering symposium hosted by the National Academy of Engineering, and currently

serves on the technical committee for manufacturing processes for the American Society of Mechanical Engineer's Manufacturing Engineering Division.

Currently, Dr. Feldhausen is leading ORNL's portfolio on the industrialization of emerging manufacturing platforms, which aims to develop advanced systems that will support DOE's efforts in establishing a strong and resilient domestic supply chain. Dr. Feldhausen's enthusiasm and technical expertise have positioned him as a leading figure in the field of additive manufacturing, and his work has the potential to revolutionize the manufacturing industry.

Integrating Computer-Aided Manufacturing Users with Directed Energy Deposition Guidelines

Kenton Blane Fillingim[1], Lauren Heinrich[1], Ashley Gannon[1], Thomas Feldhausen[1,2]

[1]Oak Ridge National Laboratory

[2]University of Texas El-Paso

Abstract

Convergent manufacturing platforms integrate heterogeneous systems (such as additive, subtractive, cold-working, and inspection processes) more seamlessly throughout the manufacturing workflow. However, this leaves operators reliable for several processes on platforms that are still emerging with limited knowledge transfer readily available. The lack of process guidance, especially for directed energy deposition (DED) additive manufacturing, hinders computer-aided manufacturing (CAM) users from taking full advantage of their design space. CAM users require an intuitive understanding of additive toolpath strategy performance which is not well-represented in current training practices, leading to programming delays that often run over the estimated project timelines. Therefore, this study aims to understand how to better equip CAM users through communicating the CAM strategy impact on parts in a convergent DED process. CAM users, inexperienced with DED process development, were placed within operator environments to promote increased cognitive and affective mental processes. Participants took part in four modules overviewing DED convergent manufacturing through in-depth system overviews, visual presentations, and hands-on part production and judgement. Post-survey feedback includes self-reported confidence to produce DED-focused CAM programs, as well as feedback on the individual training modules. This feedback will drive the next iteration of improving knowledge transfer in DED convergent manufacturing, enabling CAM users to achieve greater programming efficiency and effectiveness.

Introduction

Directed Energy Deposition (DED) is an additive manufacturing process that uses focused thermal energy (such as a laser or electric arc) at the deposition location to fuse materials (such as wire or powder metal) on a layer by layer basis [1]. Like other additive manufacturing processes, DED can significantly reduce production time compared to traditional manufacturing processes. However, a wide variety of production variables, known as DED processing parameters, must be understood, analyzed and evaluated to produce high quality parts. These processing parameters relate to factors such as the intensity of the thermal energy source, as well as the direction and speed at which material is deposited. Additionally, DED is becoming more common in convergent and hybrid manufacturing systems (systems that integrate both additive and subtractive machining). This places DED at the center of emerging technology where operators must be empowered to successfully gain experience navigating complex process planning and system interactions [2].

One operator-focused initiative, termed Operator 4.0, aims to improve these human-machine relationships, so the manufacturing sector can take advantage of emerging technology (Industry 4.0) and empower operators with new and useful skillsets to complement these technologies [3]. The importance of the human in manufacturing has become so recognized that industry leaders are now shifting into Industry 5.0, which focuses on resilient and human-centered manufacturing [4, 5]. The European Commission labels interdisciplinary knowledge and system complexity as key challenges to Industry 5.0, while human-machine interaction, specifically decision support that enhances cognitive human capabilities, as one of its key enablers [4]. To achieve resilient manufacturing, the human operator is "indispensable" and must be adaptable to ever-changing contexts – a key component of what is now the Operator 5.0 movement [6]. DED convergent manufacturing has been discussed as a critical area to integrate the operator 4.0/5.0 research space [7]. One way to advance such work is to improve decision support, communication and mutual understanding between operators and Computer-Aided Manufacturing (CAM) users throughout the DED process.

CAM user strategies, particularly for convergent DED, rely on operator input due to process complexity [8]. Operator experience leads to critical intuition with certain system constraints, design features and materials. For example, an operator might influence the decision at which point in the process to transition from additive to subtractive processes, in order to maintain tool reach and access to unique or internal features [8]. Additionally, an operator might discuss situations in which a material requires a pre-heating cycle, or when the deposition path designed by the CAM user is going to produce uneven layers due to thermal effects. There are efforts to automate and control DED processes [9]; however, process development generally requires some starting points based on experience and intuition, as well as significant process data to determine levels of process success.

Design guidelines have historically been systematically studied, extracted, and presented to new users in additive manufacturing [10, 11]. These heuristics are reliant on knowledge of and access to successful design experiences and the actions that increase the chances of design success. For DED processes, heuristics are also reliant on the operator's knowledge of process success. As we increase our knowledge of successful DED convergent processes, these heuristics will grow robust as well, but this requires DED operators and CAM users to be more in sync. In this study, we begin building the bridge between these two user groups with a workshop to familiarize CAM users with DED systems and standard operator guidelines. This is a novel attempt to situate designers of CAM toolpaths with DED guidelines in an operating environment, in hopes of producing high cognitive and affective levels of thinking in users who are not typically operating DED equipment.

Literature Review

The learning environment created for CAM users will benefit from incorporating elements of learning theory into the process. The domains of learning are traditionally broken into three categories: cognitive (skills related to thinking processes), affective (skills related to feelings and emotions), and psychomotor (skills related to actions and movements) domains. This study focuses more on the cognitive and affective domains rather than the psychomotor domain. The cognitive domain is often known as Bloom's taxonomy, revised to the following six levels of cognitive processes: remembering, understanding, applying, analyzing, evaluating, and creating [12, 13]. These levels are ordered in increasing cognitive effort. For example, evaluating a printed part requires more cognitive effort than remembering the material used for printing. The five levels of the affective domain are: receiving, responding, valuing, organizing, and characterizing [14]. These affective domain levels increase in emotional complexity (such as feelings, appreciation, motivation, and attitude). For example, listening to a person describe their feelings about the part outcome (receiving) is less emotionally complex than having a conversation or discussion about their part judgement (responding).

In manufacturing, the cognitive domain has been used to evaluate learning in a three-week course devoted to lean manufacturing, an eight step problem solving technique [15]. The assessment included a mix of closed and open-ended questions. Another study compared current training practices with job posting language for assembly workers [16]. This assessment highlights the training and upskilling needed for the modern workforce in the cognitive and psychomotor domains. For an undergraduate course, a mixed methods teaching technique was assessed for improved learning of welding processes in the cognitive, affective and psychomotor domains [17].

By enhancing the cognitive and affective domains through in-depth system interaction, one additional outcome for this style of workshop is the promotion of empathy in the design process. In this process, the designer immerses themselves in the user environment, gaining valuable insights and inspiration for their designs. Empathic design aims to improve the designer's cognitive and affective understanding of the end users and stakeholders, providing useful context aiding product development [18]. There are four key beliefs of empathic design, summarized in the list below [18, 19].

- People construct meanings that arise and change through interaction with the environment.
- Empathic design should explore these meanings in their natural setting.
- These meanings should be explored with design methods such as visualization and story boarding.
- The research methods for empathic design should be "visual and tactile," "inspiration-enhancing," "playful," "tested in reality," and "at the fuzzy front end of the design process [19]."

Ideally, CAM users can visually and tactilely interact with the DED process in a natural operator environment. This experience can aid their future work in CAM by considering what the operator will encounter, given the motion and path created.

Methods

To develop the modules of this workshop, it was critical to consider how to best elicit critical thinking from CAM users while in an operator environment. Modules needed to define key features of the DED convergent systems and process development, including process cues for instability and common issues in an operator's process. It was also essential for participants to understand why process order, process parameters and the sensory cues utilized by the operator during process development are critical for part success. This knowledge then could be demonstrated in application through a real DED production process, where users can personally analyze the relationships between process stability, part outcomes and CAM toolpath strategies.

The final workshop agenda included four modules: a walk-through of DED system features, a presentation of the standard process development (with operator strategies and troubleshooting), visual examples of past process development, and live, active process development demonstrations at the systems. Participants were guided through both wire and powder DED process development at hybrid manufacturing systems, with participants providing input to navigate and improve the parameter process. Following these four modules of knowledge transfer, participants provided feedback on module effectiveness, as well as their confidence to remember, understand, apply, analyze, evaluate, and create using the new process knowledge provided in this workshop. Additional open-ended feedback discussed what went well or not well with this experience and how this might be improved in future presentations. The workshop modules are described in more detail in the following subsections.

Participants

The participant pool was fourteen users that are experienced in CAM but relatively inexperienced in convergent DED processes. Participants were recruited from a larger workshop of CAM processes to participate on the DED modules and survey. The participants of this study have up to four years of experience with DED using CAM, which is low relative to the amount of subtractive manufacturing experience. For example, most participants had more than 10 years of experience with subtractive manufacturing. Only one participant had more than one year of experience with system features, the DED parameter development process, and standard operator actions. All participants were male, with a variety of formal job titles and educations levels. These experience levels can be found in Figures 1-2.

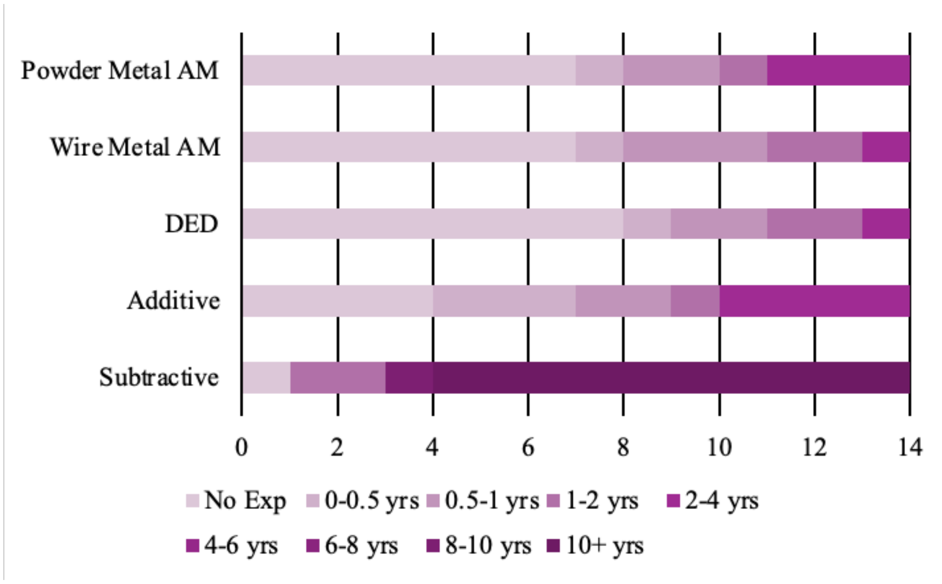

Figure 1 Participant CAM experience levels (N = 14)

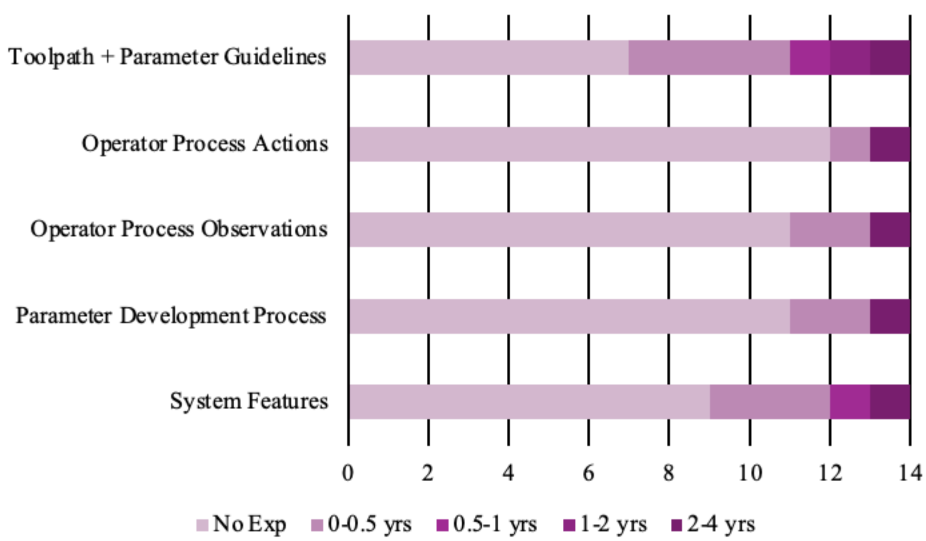

Figure 2 Participant DED knowledge experience levels (N = 14)

System Overview

The workshop started with splitting participants into two groups and moving between two systems, spending twenty minutes per system. The two systems were one Mazak VTC800G SR AM HWD and one Okuma MU8000V-L LASER EX. These are both commercial DED convergent manufacturing systems, one using wire feedstock (Mazak) and the other using powder feedstock

(Okuma) [20, 21]. Therefore, participants visualized key components of DED convergent manufacturing in two different formats. For both systems, the overview consisted of the following:

- General system measurements (number of motion axes, maximum part size, etc.)
- Processing head size, features, and operation
- Gases and material storage/feeding system
- Digital monitoring aids (in-situ data collection)
- Human-machine interfaces

Presentation and Visual Parts

Participants were then moved to a conference room setting for a presentation on the DED process. Three main sections were presented: DED process parameter development, impact factors, and operator action/guideline communication. First, the presentation highlighted process development challenges associated with single bead depositions, single layer deposition, and multi-layer deposition characterizations. It showed how in-situ process monitoring can become helpful as the parts become more complex, and the lessons learned during the typical process parameter development.

Table 1 Example checks and parameters for an operator – CAM user process development

Pre-Production System Checks	• *Gas Delivery* (proper delivery from storage to deposition) • *Material Delivery* (proper delivery from storage to deposition) • *Laser Nozzle Quality* (proper laser intensity) • *Substrate Setup* (proper work offsets for accurate deposition)
Mid-Production Visual Process Cues	• *Excessive Sparking* (detect deposition quality) • *Meltpool Imaging* (detect deposition quality) • *Underbuilding* (detect if accurate geometry is being obtained)
Post-Production Part Quality Cues	• *Voids* (visible pores / lack of material present across geometry) • *Thermal Failure* (lack of material buildup due to overheating) • *Geometric Inaccuracy* (part does not match desired dimensions)
Modifiable CAM strategies and parameters	• *Dwell Times* (time allotted between layers to allow cooling) • *Pre-heating* (heating the substrate to improve fusion) • *Stepover* (distance between two beads in a single layer) • *Laser Power* (amount of power provided from energy source) • *Layer Height* (incremental change in laser height between layers) • *Laser Spot Diameter* (size of the laser focal point)

Following this overview, individual slides were dedicated to examples showing how the following may impact or impede the operator's development process: toolpath strategies, melt pool stability, laser spot diameters, deposition materials, and build geometries. Considering these factors, the operator must make intuitive judgements about what parameters to keep constant and what to modify to achieve satisfactory production. An example set of checks and parameters for an operator during this process development can be found in Table 1. Lastly, example guidelines were presented on how operators assess parts, evaluate toolpath strategies, and adjust their parameters. Emphasis was placed on the number of variables that an operator may need to consider and communicate back to the designer of the CAM toolpath when issues arise. The conclusion highlighted what to focus on as the "operator" in future sessions, acting as active observers of the system. Key factors included geometrical inaccuracies, excessive sparking, thermal failures, and part defects such as voids.

During the presentation, participants were provided visual examples of parts, which could be passed around the room, as the presentation was delivered. These samples included examples of single beads, single layer, and multi-layer geometries representing varied process parameters. These sample deposition sets, shown in Figure 3, highlight changes in print outcome and what operators consider when judging part quality in the parameter development process.

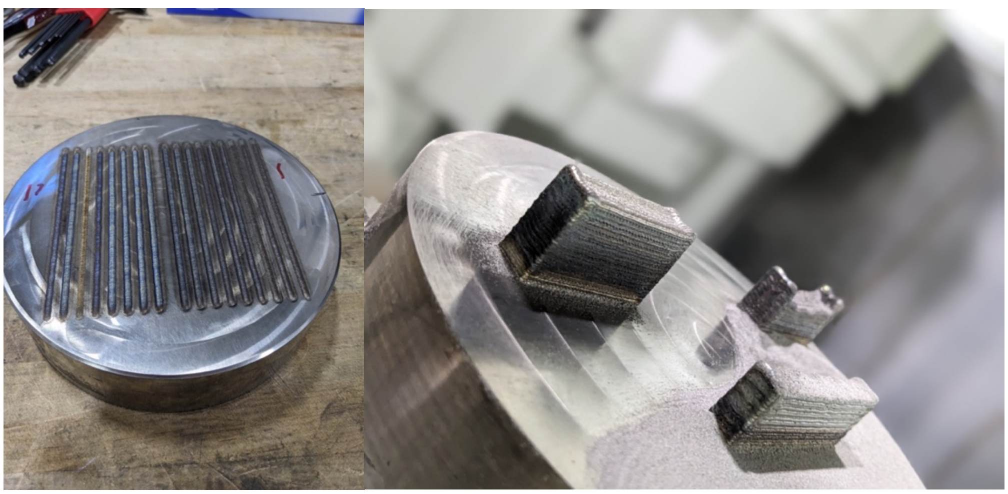

Figure 3 Samples visualizing part impact by varying process parameters. For reference, substrate diameter is 152.4mm.

System Demonstrations

For live demonstrations, the participants split again into two groups and were assigned to one of the two separate systems. Demonstrations took place over a two-day period, with each group of participants attending one demonstration per day at a single machine. Each system had a 90-minute demonstration.

For the demonstration using the Mazak system, participants observed and modified parameters for single-bead and single-layer geometries. For the demonstration using the Okuma system, the objective was to actively observe and modify parameters for simple multi-layer geometries. A program was pre-loaded into the machine interface for both systems, generalized for modifying several variables such as beads per layer, deposition speed, laser power, and layer height. There were several system aspects that participants centered themselves around during operation, to consider process observations and system troubleshooting. These were the same main factors overviewed during the preliminary system tour: laser nozzle features, gases and material storage/feeding, digital monitoring, and human-machine interfaces.

After each deposition, participants observed and made commentary on the part and discussed what actions to take next. The researcher (participating as the system operator) then made the desired changes and restarted the deposition. For example, for the multi-layer deposition, if a part was discussed as being "underbuilt" (a form of geometric inaccuracy), participants might choose to modify the programmed layer height or the deposition speed for the next iteration. Both actions may increase geometrical accuracy, although the magnitude of modifications would determine if the flaw was completely resolved. An example set of iterations went as follows: modify programmed layer height, modify speed, modify number of beads per layer, modify programmed layer height. The set of samples for multi-layer geometry can be found in Figure 4. Between the two groups, different sets of parameters were used based on insights from participation.

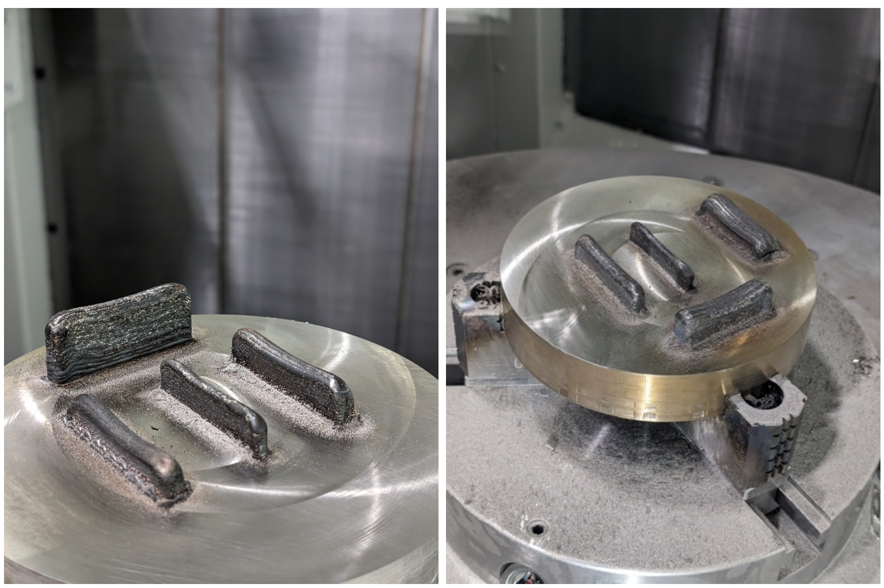

Figure 4 Example test samples during active participation. For reference, substrate diameter is 152.4mm.

Survey Feedback

Surveys were completed at the end of the workshop to understand each participant's experience and their perspective on the effectiveness of the modules, as well as their confidence to use this knowledge in future work. A mix of scale-based and open-ended responses were used to ensure feedback about the course. As previously shown in Figure 1, participants reported levels of experience across various sectors of manufacturing, including subtractive, additive, wire-based additive, powder-based additive, and directed energy deposition (DED). Participants were then asked to rate the effectiveness each portion of the workshop was in enhancing knowledge and understanding towards DED and its application to CAM. These portions were: system overview, process development presentation, visual examples, and active learning stations. Participants were asked to rate their confidence from the course from two perspectives: DED parameter development and CAM strategy development. These perspectives are driven in relation to what they see by inspecting the process stability and printed part quality. Survey questions were phrased to represent different levels of cognitive thinking for the respective application, as shown in the bulleted list below, followed by open-ended reflection on beneficial, confusing, or absent process factors to drive future workshop iterations.

- **Remember** common DED parameter development process and failures
- **Understand** how process parameters and toolpath strategies influence the print geometry
- **Apply** understand of DED processes to develop process parameters and toolpath strategies
- **Analyze** DED process stability and printed parts success
- **Evaluate** appropriate parameter/strategy changes given the process state or part outcome
- **Create** valid DED process parameters and toolpath strategies that satisfy design needs

For statistical analysis, a Friedman's related-samples two-way analysis was conducted to look for any significant differences within the DED and CAM confidence ratings (statistical analysis to compare multiple, non-parametric, related groups). A Bonferroni correction was used to adjust significance for multiple tests. Open-ended survey responses were binned into categories that summarize the overall feedback provided.

Results and Analysis

Survey Scale Responses

Survey scale responses were reported on a ten-point scale from 1-10. Module effectiveness was asked from two perspectives: (1) effectiveness in aiding your knowledge and understanding of DED processes, and (2) the usefulness of the module to your work in CAM software for DED applications. Results are broken into these two perspectives in Figure 5, which shows minimum changes across module effectiveness responses. There are no statistically significant differences in module effectiveness. However, it can be noted that modules trend towards increased effectiveness as the workshop progresses, from overview to active participation, with two exceptions. First, muti-layer geometry production on average was rated equal or less effective for both DED processes and CAM applications. This is potentially due to several new variables that come into play or become more complex as you move from single layer to multi-layer. Factors such as layer height, thermal effects, and CAM toolpath strategies become major influences that are less impactful on the single bead/layer activity. Additionally, a single bead may take only a few seconds to print, while a multi-layer print was estimated to be about ten minutes each. Therefore, participants do not get to see as many examples in the time provided.

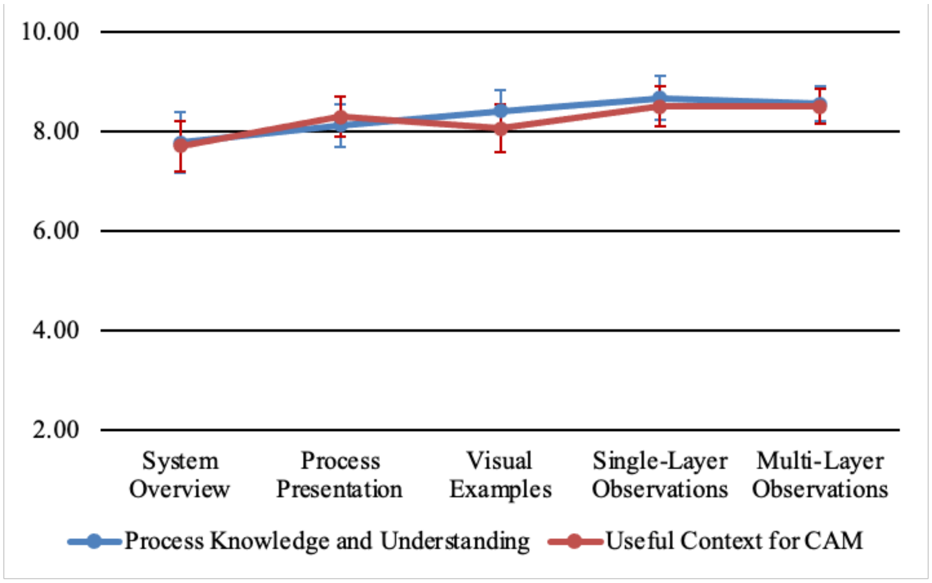

Figure 5 Average module effectiveness ratings (N=14)

The second takeaway is the slight dip in average effectiveness in visual aid examples for CAM contexts. It is hypothesized that this is due to visual inspection being effective for seeing what went wrong, but not necessarily what to change. For example, multiple factors can play a role in mitigating thermal failure, such as modifying the design, adding dwell times, decreasing laser power, or modifying print directionality. In future work, one might increase visual part effectiveness by providing more concrete parameters and toolpath descriptions alongside the visual parts to form an understanding of which CAM actions, if any, would be best. There is a similar sentiment shown in Figure 6. When asked about their confidence in different levels of cognitive thinking for DED processes and CAM strategies for DED, there is a dip in confidence for "analyze" compared to other levels of thinking such as "remembering" or "understanding."

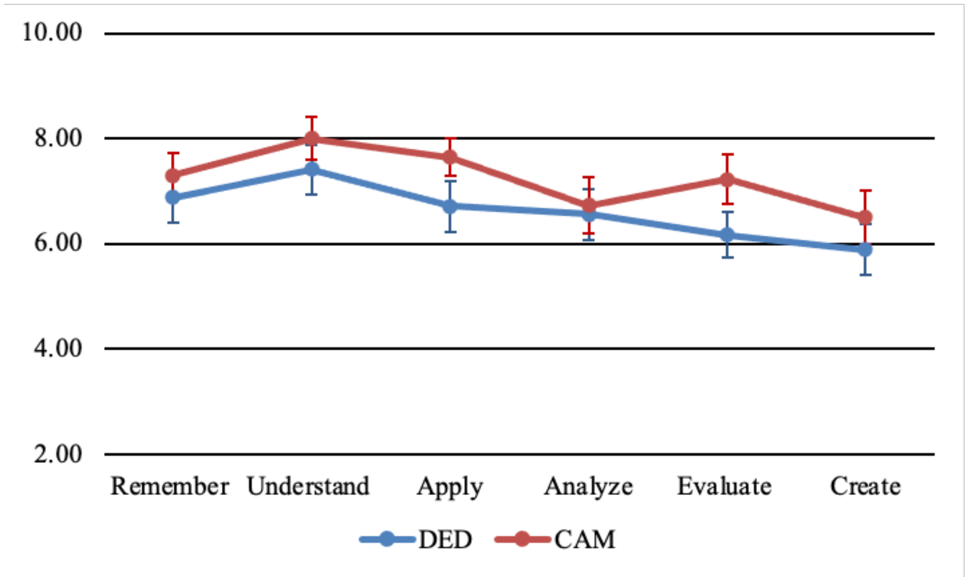

Figure 6 Average confidence ratings for DED processes and CAM strategies for DED (N=14)

Confidence rating visual trends show that participants report increased confidence moving from *remember* to *understand*, then decreased confidence moving from *understand* to *create*. *Remember* is likely lower than *understand* due to the amount of information provided. The participant can understand how this knowledge is applied but cannot easily recall due to the depth and breadth of knowledge to recall and recognize. This highlights how there is work needed to deliver this information in a more effective way. The *analyze* for CAM confidence rating is the exception to the trend and performs lower than the next level of cognitive skill, *evaluate*. There is work to be done to correlate visual analysis to explicit, satisfactory CAM guidelines that participants can internalize through the visual inspection. As previously stated, it is likely this visual analysis should be paired with available, documented data and ease of use guidelines.

Using the Friedman's related-samples two-way analysis, significant differences were found in both DED process confidence ($X^2(5) = 16.588$, $p < 0.005$) and CAM application confidence ($X^2(5) = 21.403$, $p < 0.001$). More specifically, the *understanding* confidence rating was statistically significantly higher than the *creating* confidence rating for both DED processes ($X^2(5) = 3.283$, $p = 0.015$) and CAM strategies ($X^2(5) = 3.687$, $p = 0.003$). This makes sense as the course goals did not provide specific activities for creating their own DED or CAM processes. However, participants also reported confidence for *analyzing* as significantly less than the confidence for *understanding* ($X^2(5) = 3.081$, $p = 0.031$). While these results highlight effectiveness in providing process understanding, it also shows a critical gap with room for improvement towards CAM user – system integration.

Survey Open-Ended Responses

For open-ended survey questions, responses were binned into emerging themes that summarize trends in the feedback provided. Each response was placed into one theme only and not split across multiple themes. Table 2 shows the survey question is italicized, followed by the respective response themes and the total number of responses found within each theme.

Table 2 Responses of each respective response theme (N=14)

"Please describe how you believe the lessons and activities were helpful for your DED CAM processes"	
Hands-on / practical experience with the system and testing programs	6
Observing / visualizing outside of the CAM software	2
Understanding various aspects of the process in a deeper way	4
Approaches, strategies, and processes about which new insights were gained	2
"Please describe the DED factors that you believe to be the most confusing, complicated, or complex"	
The large number of variables, parameters and impact factors	3
Complexity of combinations when finding the right parameter set	4
Finding, testing, configuring combinations of parameters	4
Clues and understanding what should be changed, given visual process/part inspection	2
Experience desired in metallic materials	1
"Please describe the DED factors critical to your CAM process that should be covered in more detail."	
Additive strategies such as start/end points, layer strategies, additive turning, and tolerances	6
Strategies for corrective actions like sagging edges and gaps in material	2
Starting points / acceptable parameter sets to begin testing	2
System advantages, disadvantages and future developments	1
No critical response	3
"Please describe any other comments you wish to provide here"	
Individual time, smaller groups or more access to decision-making changes on the machine	3
Insight into other printing or competing manufacturing technology	2
More analysis of final parts or how strategies influenced outcome of print	2
No comment, or comments on a positive experience	7

Responses in Table 2 highlight how hands-on experiences provided an understanding of the process in a deeper way. This is beneficial as these individuals are not typically hands-on during the manufacturing process. They appreciated the visuals and observations, as well as the approaches and strategies discussed. Participants also indicated that the quantity and complexity of variables lead to confusion or complications when finding a proper parameter set. Furthermore, it is difficult to know what variables to modify just based on visuals of the process or the final part, as there needs to be a firm foundation on understanding the visual cues that certain parameters will produce. This confusion adds useful context to potentially explain the scale-based responses to visual aid effectiveness and analysis confidence. More than half of participants who provided feedback wished to incorporate more additive CAM strategies and modifications alongside operator parameter modifications. As much of the workshop time was spent for users to understand operator processes, these suggestions aim to better connect knowledge to the participant's own prior knowledge.

Discussion and Future Work

Based on the scale survey results and analysis, participants felt that this workshop environment is effective for process knowledge and understanding. Open-ended responses reveal that machine interaction was greatly valued and considered the most useful portion of their time. Responses also imply that the process complexity requires more system engagement to gain confidence in higher cognitive levels. Specifically, participants discuss desires for smaller groups for engagement, more additive strategies alongside operator actions, and to better grasp the quantity and complexity of process parameters. The reported lower confidence in analyzing printed parts compared to other cognitive domain levels. Moving forward, several areas have been identified where the researchers might improve learning outcomes. These are outline below and will be incorporated into future sessions.

Increasing our use of learning theory in these modules could produce workshop tools that build confidence in the application, analysis and evaluation stages. For example, concept maps can graphically provide knowledge structure for a significant number of concepts while highlighting the relationships between concepts [22]. Specifically, concept maps promote active learning to think critically about these relationships. They can be used to deliver complex information or evaluate one's understanding of complex topics. With concept maps, we can encourage users to better identify the relationship between process variables and their influence on the printed part outcome. We can utilize this aid during hands-on activities or during CAM development to reflect on how their programs are being assessed post-build.

Second, this workshop could implement universal design for learning (UDL) principles [23]. UDL encourages using multiple modalities that promote *engagement*, *representation*, and *action and expression*. While system demonstrations encouraged engagement, there was less engagement for other modules. Incorporating more CAM actions into the process iterations, rather than just a reduced set of changeable parameters, may encourage more engagement to a variety of design contexts. While information was represented in multiple modalities for this workshop, it would be improved by having informative aids at the systems during the hands-on portion. Therefore, they have multiple formats in parallel, not just in series. It is understandable for novices to have difficulty remembering all relationships while watching the system produce parts in real-time.

For action and expression, using process knowledge assessments or even a group case study may allow the participants to show what they know and actively recall strategies and knowledge from beginning to end of a sample design. Some reflection activities within course curriculum have been used to encourage higher levels of cognitive thinking [24, 25]. Analyses show that personal project designs, those which match the proficiency levels and experiences of the student, may encourage higher orders of thinking compared to traditional quiz assessments [25]. Similar reflection tasks have been assessed to promote higher levels of individual thinking after group design projects [26].

These assignment options may better reflect the user's ability to take their newfound system and operator knowledge and relate it back to their own interests.

Lastly, the modules can implement concepts of constructivism to improve many of the limitations of this work [27]. In this theory, learners construct knowledge rather than just passively taking it in. It is constructed within their pre-existing knowledge (schemas). Knowing this, it would be wise to actively probe their pre-existing knowledge. This was not explicitly performed during the modules, nor was any pre-workshop data collected. Moving into the pre-workshop assessment phase will be necessary in future work. Module topics, focused more on the systems and process parameters, can include more detailed examples of CAM strategy modifications. This would require considerable restructuring of the limitations of the current setup while maintaining focus on the operator's relationship with the system and CAM programs. However, this would also aid constructing new knowledge with pre-existing knowledge.

Conclusion

This study aimed to solidify the need for CAM education intertwined with DED systems to acquire process understanding for CAM purposes. Fourteen CAM users, more experienced with design for machining than for DED additive, were subjected to DED learning modules aimed to better integrate the CAM users with DED systems and operators. Participants received system overviews, a presentation on the DED process development, visual aids, and active engagement in process development on two DED hybrid systems. Survey results show that modules were equally effective across each modality with no significant differences. Participants did report significantly higher confidence in understanding of DED processes compared to other levels of cognitive thinking, such as creating their own DED processes or analyzing parts for CAM modifications. Open-ended feedback highlights the benefits of hands-on activity while acknowledging the complexity of the process as a setback for future applications. To aid this complexity, frameworks in learning theory could help improve delivering this form on information in future workshops. Namely, active learning, constructivism, and universal design for learning have been discussed with concrete examples of modifications for the next set of workshops.

Acknowledgements

The authors would like to acknowledge Mazak corporation, Okuma America Corporation, and OpenMind Technologies for their support in developing DED Hybrid manufacturing technologies. This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan(http://energy.gov/downloads/doe-public-access-plan).

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