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America's Cutting Edge CNC machining and metrology training

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Abstract

This paper describes the workforce development activities supported by America's Cutting Edge (ACE), a national initiative for machine tool technology development and advancement. ACE is supported by the Department of Defense Industrial Base Analysis and Sustainment (IBAS) program from the Office of Industrial Policy. Both the online and in-person components of the computer numerically controlled (CNC) machining and metrology training programs are summarized and participation information is provided.

Peer-review under responsibility of the Scientific Committee of the NAMRI/SME.
Keywords: Education; training; workforce; machining; metrology

1. Introduction

The existing shortfall in the US manufacturing workforce has been well-documented and broadly discussed. For example, a 2018 Deloitte report predicts up to 2.4M manufacturing jobs may go unfilled by 2028 and that these workforce limitations could place $454B in production at risk in the US [1].

Due to the increasing connectivity between systems and widespread automation, including computer control of nearly all manufacturing equipment, the required skills are evolving with the new digital manufacturing paradigm. This places new demands on efforts to prepare the next generation workforce. Not only must the education and training efforts evolve, but the target audience is broad. The existing workers must be up-skilled to keep pace with new technology. Community college and trade school curricula must be expanded to provide not only a fundamental understanding of manufacturing processes, but must also provide exposure to digital communication and cybersecurity. Universities must prepare machine designers and entrepreneurs, for example, to energize the US machine tool industry.

To address workforce challenges in the machining industry, the America's Cutting Edge (ACE) training program was developed at the University of Tennessee, Knoxville and launched in December 2020 in collaboration with Oak Ridge National Laboratory and IACMI – The Composites Institute through support from DoD's Industrial Base Analysis and Sustainment (IBAS) program. There are currently two modules; both are offered at no cost.

The online computer numerically controlled (CNC) machining training curriculum is composed of:

- a machining tutorial, which covers topics including chip formation, tool wear, machining processes, machining equipment, CNC machining, computer aided manufacturing (CAM), and work holding
- CAM instruction through multiple lessons using an example part

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- a machining dynamics tutorial, which describes the importance of considering machining vibration when selecting machining parameters in CAM software
- CAM lessons that leverage CAM+, a stand-alone app that simulates machining performance
- an introduction to machining cost
- multiple choice quizzes to assess learning and track progress.

The online metrology training curriculum is composed of:

- an introduction to manufacturing measurements, which covers measurement transducers for displacement, velocity, acceleration, strain, temperature, part dimensions, surface finish, and internal geometry
- an introduction to measurement uncertainty, which includes a definition of terms, a description of measurement uncertainty evaluation, and a case study for density measurement
- multiple choice quizzes to assess learning and track progress.

The intent of the ACE program is to educate and train the next-generation machine tool workforce, including future manufacturing engineers, machine tool designers, entrepreneurs, machinists, metrologists, and others.

2. ACE information and execution

2.1. CNC machining

Since its December 7, 2020 launch, the program has grown rapidly. As of November 18, 2021, there were 1696 online participants from 47 states. These participants include 612 from industry (36%) and 1084 students from four-year colleges and universities, two-year community colleges, and high schools (64%). The group includes 243 females (14%). While this value is lower than desired, it is 2.5 times the national employment percentage for female CNC machinists of 5.6% [2].

The US locations for the participants are displayed in Fig. 1. The industry locations are shown in Fig. 2. The student breakdown includes: 910 from colleges and universities, 57 from community colleges, and 117 from high schools; see Fig. 3. Among the 1696 participants who have started the online training, 618 (36%) have completed all training modules and had certificates awarded from IACMI. This completion rate is high among online, no-cost training programs. Typical rates are 2% to 10% [3].

Figure 1 shows that the registrations have the highest density in the Eastern US, although the upper Midwest, Texas, and West coast are also well-represented. The 10 states with the highest numbers of online participants are listed.

1. Tennessee, 381
2. North Carolina, 223
3. Ohio, 79
4. Alabama, 60
5. Florida, 55
6. Pennsylvania, 49
7. California, 45
8. Illinois, 44
9. Texas, 42
10. Michigan, 38

Fig. 1. Locations for 1696 CNC machining participants from 47 states [4].

Fig. 2. Locations for 612 industry participants for CNC machining [4].

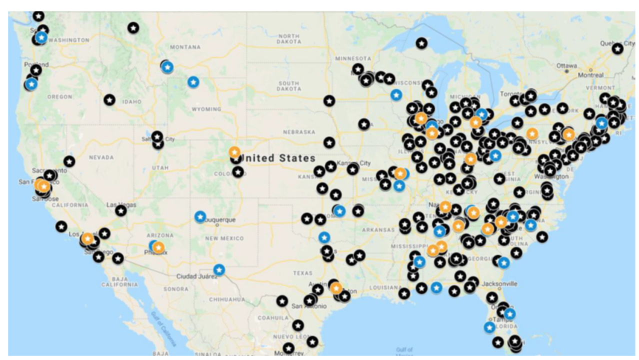


Fig. 3. Locations for 1084 students in CNC machining. Black symbols are for colleges and universities, blue symbols for community colleges, and orange symbols for high schools [4].

Eight one-week, in-person CNC machining training sessions were also completed from May to August, 2021 at three locations in Knoxville, TN. Those participants that completed the online training were eligible.

- May 10-14, 7 participants, University of Tennessee, Knoxville
- May 24-28, 10 participants, University of Tennessee, Knoxville

- June 7-11, 9 participants, University of Tennessee, Knoxville
- July 19-23, 11 participants, University of Tennessee, Knoxville
- June 7-11, 5 participants, Pellissippi State Community College
- June 14-18, 6 participants, Pellissippi State Community College
- July 19-23, 9 participants, Oak Ridge National Laboratory's Manufacturing Demonstration Facility
- August 9-13, 10 participants, Oak Ridge National Laboratory's Manufacturing Demonstration Facility

Fig. 4. Toolpath programming using CAM software.

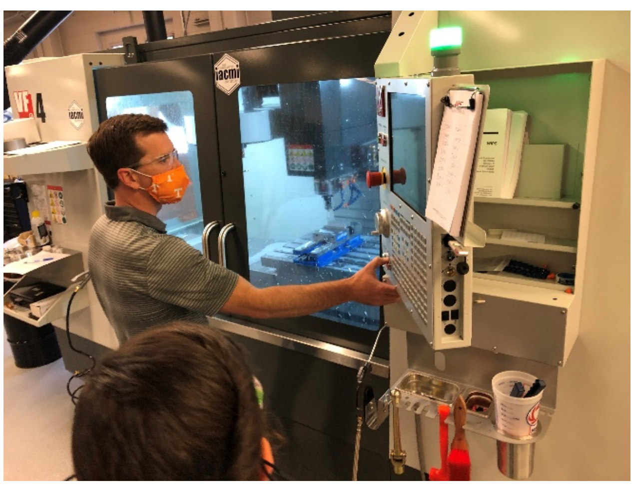


Fig. 5. CNC machining by participant.

The 67 in-person participants represented nine states and included: 45 students (six high school), three educators (university, community college, NIST MEP), five engineers, six machinists, and eight veterans. The gender breakdown was 58 males and nine females (13%).

The five-day (8:30 am to 4:30 pm), in-person training included the use of CAM software to program toolpaths for four parts; see Fig. 4. These toolpaths were then used by the participants to machine the parts; see Fig. 5. Finally, the participants assembled the parts to produce an oscillating piston air engine; see Figs. 6 and 7. The oscillating piston air engine was selected to provide the following course advantages. First, the air engine performance (continuous rotation, rotation speed) is dependent on the accuracy and assembly of the components. This provided a discussion of metrology and uncertainty. Second, three materials (aluminum, steel, and polymer) provided experience with machining different materials and understanding the limitations imposed by each. Third, the valve block included complicated internal passages (to enable air entry and exit required to drive the piston in and out), so it was well-suited to fused filament fabrication (FFF). This provided an opportunity to discuss additive manufacturing and its combination with machining. The valve block mating surfaces were machined to reduce friction by improved surface finish.

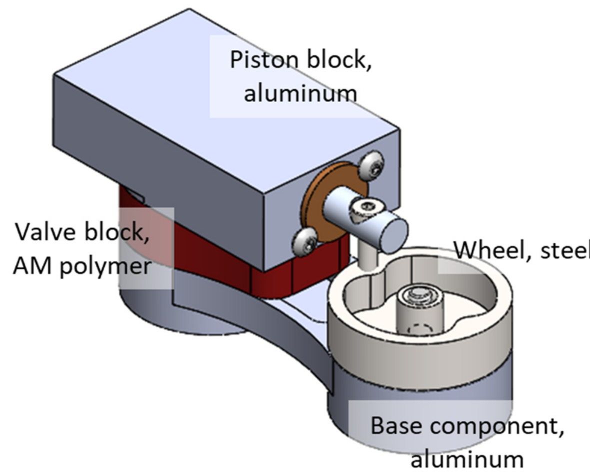


Fig. 6. Oscillating piston air engine produced during in-person CNC machining training.

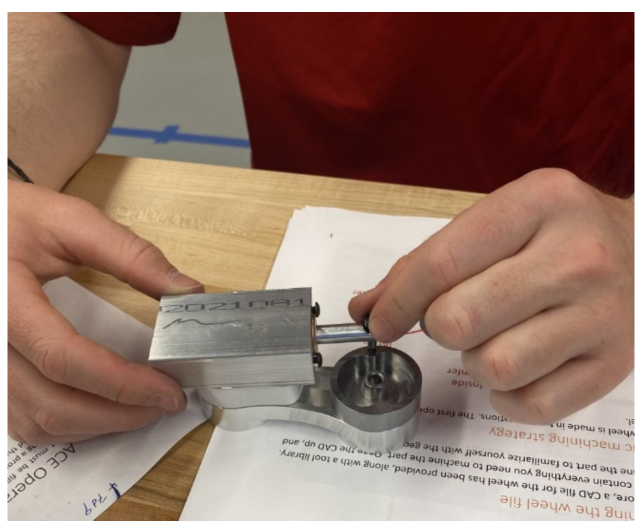


Fig. 7. Assembly of oscillating piston air engine by CNC machining training participant.

The topics for each day of the five-day schedule are summarized. These activities include both classroom and laboratory sessions.

1. Monday – machining review, M/G code introduction, machine air engine base component
2. Tuesday – machining dynamics review, workholding, datums, machine piston block
3. Wednesday – machining cost review, machine valve block
4. Thursday – metrology review, machine wheel, assemble air engines; see Fig. 7
5. Friday – CAM+ review, on-machine tap test and chatter example, air engine part swap/assembly, logo machining, program evaluation

A screenshot of the CAM+ app is provided is Fig. 8. This standalone executable enables a virtual tap test to predict the frequency response function (FRF) for a user-selected tool-holder-spindle combination (left panel), generates a stability map using the frequency response function and user-selected workpiece material which defines the cutting force model (top right panel), and performs a time domain simulation with the user-selected cutting parameters (bottom right panel). At the conclusion of the time domain simulation calculations, the cutting force and vibration are plotted and the machining sound is played to provide a virtual machining experience.

The CAM+ input data is provided using an Excel spreadsheet, which includes descriptions of each variable and graphics to aid the user in understanding the relationships between the tap test, stability map, and time domain simulation. A user's guide and examples which illustrate the app use together with the CAM software are also provided as part of the training.

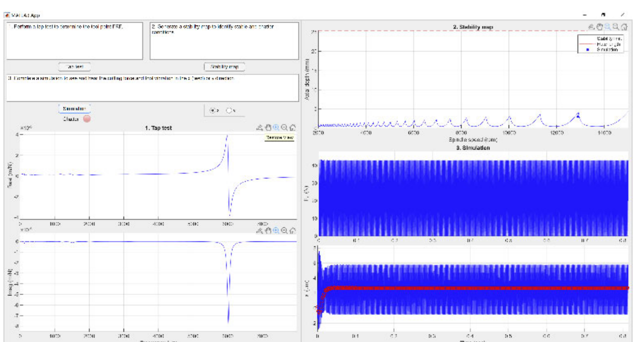


Fig. 8. Screenshot of CAM+ app (a larger view is provided in Appendix A).

As noted, each day includes a number of learning topics and on-machine activities. The Monday agenda is included. The agendas for Tuesday through Thursday are similar.

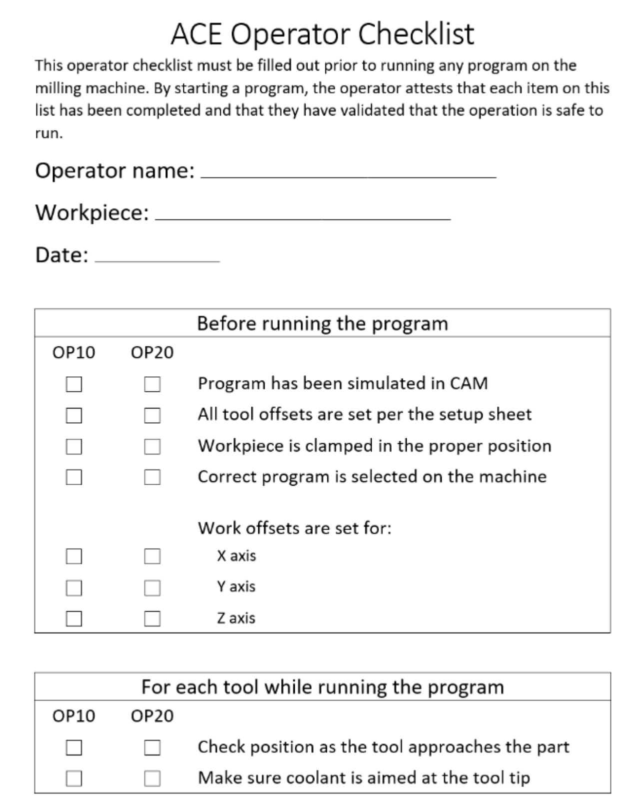
8:30 am – Classroom session 1
- Welcome
- Distribute copies of operator checklist; see Fig. 9
- Run CAM simulation of base component to show the operations
- Distribute safety glasses
- Participants take laptops to laboratory

9:30 am – Laboratory session 1
- Divide into two team (five participants each, two milling machines)
- Demonstrate air engine (two instructors, one at each milling machine)
- Show individual components and identify those that will be machined
- Demonstrate machining of base component
- Machine base component
- Two participants at each machine with instructor (one active, one observing, active participant rotates out after machining part), remaining participants follow instructions to prepare toolpaths in CAM (one CAM instructor) [Note: participant CAM is not uploaded to the CNC machines for safety, but it is validated by simulation within the CAM software.]

12:30 pm – Lunch (provided)
1:30 pm – Classroom session 2
- Machining review
- Review basic M and G code instructions
- Participants take laptops to laboratory

2:45 pm – Restroom break
3:00 pm – Laboratory session 2
- Divide into two teams
- Demonstrate basic machine control
- Show tool assembly/load/unload/change

4:00 pm – Classroom session 3
- Questions
- Cleanup (two students)



ACE Operator Checklist

This operator checklist must be filled out prior to running any program on the milling machine. By starting a program, the operator attests that each item on this list has been completed and that they have validated that the operation is safe to run.

Operator name: ____________________

Workpiece: ____________________

Date: __________

Before running the program		
OP10	OP20	
☐	☐	Program has been simulated in CAM
☐	☐	All tool offsets are set per the setup sheet
☐	☐	Workpiece is clamped in the proper position
☐	☐	Correct program is selected on the machine
		Work offsets are set for:
☐	☐	X axis
☐	☐	Y axis
☐	☐	Z axis

For each tool while running the program		
OP10	OP20	
☐	☐	Check position as the tool approaches the part
☐	☐	Make sure coolant is aimed at the tool tip

Fig. 9. The ACE operator checklist is completed by each student prior to each machining operation.

2.2. Metrology

Since its March 16, 2021 launch, the program has grown to more than 300 participants. As of November 18, 2021, there were 319 online participants from 36 states. These participants include 141 from industry (44%) and 178 students from four-year colleges and universities, two-year community colleges, and high schools (56%). The group includes 32 females (10%).

The US locations for the participants are displayed in Fig. 10. The student breakdown includes: 159 from colleges and universities, 12 from community colleges, and 7 from high schools. Among the 319 participants who have started the online training, 108 (34%) have completed all training modules and had certificates awarded from IACMI.

Again, registrations have the highest density in the Eastern US. The states with the highest numbers of online participants are listed.

1. Tennessee, 71
2. North Carolina, 23
3. California, 15
4. Florida, 10
5. Ohio, 9
6. Illinois, 7
7. New Mexico, 7
8. Alabama, 6
9. Indiana, 6
10. Pennsylvania, 6

Fig. 10. Locations for 319 metrology participants from 36 states.

3. Pedagogy discussion

Providing instruction on manufacturing processes is fundamental to manufacturing education, but the inherent complexity and lack of physical experience by many students makes effective teaching a challenge. Typical approaches are lecture-based, laboratory-based, or a combination of the two. The traditional classroom lecture describes the process, often with pictures and diagrams, provides a mathematical description to model the behavior, and provides examples that relate to industry applications. A powerful addition to these elements is videos that increase engagement and provide physical insight that may not otherwise be achievable [5-6]. Computer simulation can also be applied to relate process inputs and outputs and improve understanding [7]. As shown in section 3, the ACE program implements each of these approaches.

3.1. Learning objectives

The section 3 curricula were developed with two primary objectives:

- Ensure that participants are inspired, not intimidated, by the content. The approach was to assume no prior knowledge and move at a pace that is manageable for the participant, while covering an adequate range of topics with sufficient depth to enable next steps after completing the training. These steps could include, for example, an internship, a one-year trade school curriculum, a two-year community college degree, or a four-year education path.
- Expose participants to relevant technology. For the CNC machining training, a key consideration was the role of vibrations in machining parameter selection. The approach was to first introduce the geometry of CNC machining by providing step-by-step instructions for tool path generation using an example part; no prior experience with CAM software was therefore required (Fusion 360 was selected as the ACE platform based on its free availability to students and opportunity for free evaluation by non-students). Once the tool paths were generated using default machining parameters (depths of cut and spindle speed), the topic of vibrations was then introduced and connected to process performance through the machining parameters.

To support the latter objective, two elements were added to the CNC machining training. First, the CAM+ app was programmed in MATLAB and included at no cost to provide machining simulation capabilities. The physics-based models embedded within the app enabled process simulation, starting with tool tip FRF prediction using receptance coupling substructure analysis (RCSA) [8-12]. RCSA couples the spindle, holder, and tool dynamics analytically to predict the tool tip FRF in a virtual tap test approach. Each of these was selected by the user prior to executing the app. The FRF was then used as input to a stability map calculation that separates unstable combinations of spindle speed and axial depth of cut from stable combinations by a stability boundary [13]. The time-dependent force and tool displacement may then be calculated for user-selection combinations of spindle speed and axial depth using time-domain simulation [8]. Lessons were included to use the app for simulation of both stable and unstable cutting conditions. Audio feedback demonstrates the clear difference in machining sound between the two conditions.

Second, physical tap testing was described where an instrumented hammer is used to apply a known force to the tool tip and a low-mass accelerometer is used to measure the vibration response. Together, these signals are used to calculate the tool tip FRF. Test cuts were completed in the in-person training to select stable and unstable (chatter) machining parameters using the tap test data and associated stability map.

For both the CNC machining and metrology modules, quizzes were included after each lesson. These quizzes test comprehensive and track progress through the curricula. After the successful submission of all quizzes, a certificate is awarded for each module. The certificate is conferred by IACMI with IBAS logo and recognition.

3.2. Lessons learned

Clearly, offering online training modules for CNC machining and metrology is not the same as face-to-face instruction. However, it does expand the number of participants that can be reached. There were two key efforts within the ACE program to enhance the learning experience.

First, because the content is online, it is more likely that distractions will occur. Therefore, the individual lessons were kept short (a few minutes to one hour) and animations, color schemes, and videos were selected to maintain the participant's attention despite the inherent distractions.

Second, the participants were treated as traditional students. When questions were submitted via email, the response was provided immediately. While virtual interactions cannot replace in-person interactions, it is important to honor the participant's time and interest by providing timely responses to technology or content questions that might otherwise interrupt progress and learning.

Fig. 11. Classroom instruction was provided during the in-person training events.

4. Conclusions

This paper provided a description of the workforce development activities supported by America's Cutting Edge (ACE), a national initiative for machine tool technology development and advancement. Both the online and in-person components of the CNC machining and metrology training modules were summarized and participation information was provided.

Details were given about the eight in-person CNC machining training sessions held at the University of Tennessee, Knoxville, Pellissippi State Community College, and Oak Ridge National Laboratory during Summer 2021. The 67 participants received training in both the classroom and laboratory; see Figs. 11 and 12.

Each of the participants rated the in-person training either 4/5 or 5/5 during the post-training assessment. All stated that they found both the classroom and laboratory sessions to be helpful. Selected quotes are included in the following paragraphs.

"As a mechanical engineer, this ACE bootcamp is helping me to have a practical mindset in terms of designing something with the latest machining equipment and technology that can be manufactured efficiently in the US." – Air Force active duty, graduate student

"The online portion of ACE has been beneficial because I have no prior experience with CNC machining and getting the foot in the door with the online learning and now seeing it first hand and physically be able to do it is a great advantage to me as a hands-on physical learner. Being able to do it myself has given me a lot more confidence in my abilities to continue." – Aerospace engineering student, Air Force veteran

"Unmatched machining development program. Before ACE, I must confess I was quite concerned for the machining industry. It seems the suppliers and in-house providers I work with base their entire machining experience on tribal knowledge and arbitrary experimentation. To find the online curriculum and hands-on training that ACE provided…was a godsend." – Practicing engineer in the forging and machining industry

Fig. 12. Laboratory instruction included CNC machining, tooling setup, fixturing, work offsets and probing, and part measurement.

“The tap test demonstration is for real. The industry has battled chatter for years but learning the science behind chatter and how to avoid chatter conditions is transformational.” – Third-generation machinist in family-owned company

“ACE on-line and hands-on CNC training has given me insight into a future career. ACE has shown me the importance of time and efficiency when producing a product and how energy and cost efficiency in CNC machining relates to environmental engineering.” – High school student from underserved community

“ACE has reassured me that women are made for machining! We have acute attention to detail, our ability to hear higher pitches will help diagnose issues sooner, and there is actually room to move up within the industry.” – Graduate student in materials science

“ACE hands-on experience with the CNC machines which will directly help me as a start a summer machining internship and pursue a career in manufacturing.” – High school student

“Our country has great value in untapped human resources and ACE training, at no cost, has immense potential to extract diamonds in the rough.” – Senior fitter

“Patriotism, that’s one reason I became interested in ACE. The US cannot progress without building back its domestic manufacturing. ACE has taught me improved methods of finding machining stability without requiring years of experience.” – Graduate student and Army veteran

Moving forward, additional partners to host the in-person events will be identified and training materials will be provided in the form of comprehensive “instructor kits”. This is part of an agenda that includes a national roll-out of the ACE program. To learn more about ACE or to register for the no-cost training modules, visit the following web sites.

CNC machining
https://mtrc.utk.edu/ace/

Metrology
https://mtrc.utk.edu/ace/ace-metrology/

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Appendix A: CAM+ app screenshot