

ALIGNING TECHNOLOGY AND TALENT DEVELOPMENT:

Recommendations from the APLU-
and NCMS-led Expert Educator Team

Final Report



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Chapter 1: Introduction



Manufacturing is becoming more cutting-edge every day, requiring that workers have advanced math skills and scientific prowess to join the workforce and continue driving innovation. At the same time manufacturing occupations are becoming more complex, the sheer demand for this talent is also increasing. Looking specifically at lightweighting technologies—those that help us make vehicles, ships, airplanes and other equipment lighter and thereby increase efficiency and reduce cost—the need for skilled workers has increased in recent years and is expected to

continue to increase going forward. In Lightweight Innovations for Tomorrow's (LIFT) five-state region of Michigan, Ohio, Indiana, Tennessee and Kentucky, there were more than 2.68 million workers in lightweighting-related occupations in 2018. Since LIFT started tracking lightweighting-related employment in 2012, online ads for these jobs have almost doubled across this same region.¹

Lightweighting technologies touch a broad spectrum of manufacturing jobs from skilled trades, such as machinists and industrial machinery mechanics; to engineering and design, such as electrical and mechanical engineers; to administrative occupations, such as safety specialists and cost estimators. Historically, much of this manufacturing workforce has been developed in two education silos: the technician, assembly, and skilled trade workers through apprenticeships and skilled trades training programs in vocational education and community colleges; and the engineers and administrative roles in university programs of study.

Now, the infusion of technology across all manufacturing sectors and at all levels of design and production requires the workforce to have higher level skills and a significant set of competencies related to new technologies, materials, and processes. Strong partnerships are needed between post-secondary education and industry to ensure students of all levels are developing the skills needed to succeed in industry. If community and technical colleges and universities are not incorporating the evolving needs of industry into their curriculum and training opportunities, their students will not be prepared for the world of innovation in advanced manufacturing.

To this end, the Aligning Technology and Talent Development initiative was developed as an effort to “bring upstream” the conversation about education and workforce strategies around emerging technologies. That is, the effort sought to begin planning for education and workforce needs related to emerging technologies at LIFT while the technologies were in development, rather than waiting until technologies were fully developed and deployed. Led by the Association of Public and Land-grant Universities (APLU) and the National Center for Manufacturing Sciences (NCMS), in partnership with the Lightweight Innovations for Tomorrow (LIFT) manufacturing institute, the initiative included an Expert Educator Team (EET) from universities and community

¹ LIFT: Lightweight Workforce Quarterly Summary, Q2 2018. Retrieved from <https://lift.technology/education-workforce-development/>.

colleges to help identify the knowledge, skills, and abilities workers at all levels will need to deploy the technologies, materials, and processes created at LIFT (See page 113 for the full EET roster). The team helped strengthen the connection between LIFT technology development plans and educational programs by identifying the competencies needed for using these technologies in the design or production environment and by recommending strategies to better prepare students to enter the workforce after graduation.

Ultimately, the initiative aimed to encourage more industry-driven, technology-aligned work-and-learn curricula in university and community college programs to produce graduates more capable and confident in using new manufacturing technologies and processes. Further, the effort targeted the skills development needs of the incumbent workforce and sought to engage higher education institutions in addressing these needs. The work also recognized that STEM skills developed in K-12 are critical in developing postsecondary learning opportunities for both production and design, in particular, a re-emphasis on materials science in high school will be significant.

To complete this work, the EET convened at the LIFT innovation facility in Detroit for quarterly meetings, during which the group reviewed LIFT technology and process focus areas in coordination with the related LIFT technology project teams and subject matter experts. The EET then identified supporting and critical competencies required to implement these emerging technologies. The EET then developed strategy recommendations for LIFT and education providers to partner to address education and workforce development needs related to these emerging lightweight technologies. This report outlines the comprehensive technology review, competency mapping, and recommendation development undertaken by the EET over the course of the Aligning Technology and Talent Development initiative.



HOW TO USE THIS REPORT

While many of the recommendations in this report are directed at LIFT, it should be noted that LIFT cannot and should not address them alone. While LIFT can serve in a convening and coordinating role to address the opportunities laid out in this report, LIFT will need partners from both education and industry to contribute expertise, time, and funding to effectively implement these recommendations. Throughout this report, such opportunities to partner are identified by an  ICON. If you feel your organization can partner with LIFT in implementing one or more of these recommendations, contact Emily DeRocco, LIFT Vice President of Education and Workforce Development- ederocco@lift.technology.

In addition to identifying which recommendations your organization can partner with LIFT on, we have suggested approaches for how your organization can engage with the content in this report below.

If you are at a LIFT member organization: this report outlines multiple opportunities for LIFT and its partners to more fully leverage LIFT's assets to address manufacturing workforce needs. As a LIFT member, your industry or academic organization can partner with LIFT in these efforts by offering your time, expertise and resources. It is important that you reach out to leadership at LIFT to let them know where you see opportunities in this report and offer partnership and support for implementing those opportunities.

If you are at a college or university: this report can be used as a guide to introduce modifications to curriculum to better prepare students with the competencies needed for emerging lightweighting technologies. You and your colleagues in materials engineering or materials science programs should review the recommendations and consider which could be adopted or adapted. Look for opportunities that are ready for implementation as well as larger-scale initiatives for which your institution might pursue funding.

If you are in industry: review this report with a discerning eye to determine whether the competencies mapped reflect what will be needed in the future workplace. If anything is missing or inaccurate, we urge you to reach out to LIFT leadership to share your insights.

Further, we encourage you to look for ideas that can help you improve education and training for incumbent workers, and also for opportunities to partner with colleges and universities, or with LIFT, to advance workforce readiness of technical and engineering students. One of the overarching recommendations made in this report is to incorporate more work-and-learn models into technical education, and industry will need to place a critical role in both expanding and innovating work-and-learn models.

If you are in a government agency or at a funding organization: consider how you can use the ideas in this report to advance technical and engineering education. Think about how future policy or funding programs could be shaped to encourage the kinds of changes in education suggested in the report.

Chapter 2: Education and Workforce Strategy Recommendations

Over the course of the Aligning Technology and Talent Development initiative, several broad themes beyond those specific to individual technology projects began to emerge. Indeed, each of these cross-cutting issues was consistently raised in discussions across technology project teams to the extent the EET determined the following themes are critical to address across manufacturing education and workforce development. The following cross-cutting themes were considered when developing the recommendations in this section:

- Leveraging **LIFT- Supported Facilities and Resources**, including the LIFT High Bay, LIFT Learning Lab, and LIFT/IACMI Learning Hub to address education and workforce development needs related to emerging technologies.
- Promoting **Work-and-Learn Expansion** through the development of more prevalent and innovative models that immerse students in real-world work environments throughout their education.
- Introducing **Agile Curriculum Development** to ensure educational programs are responsive to rapidly changing industry needs.
- Facilitating **Engineer/ Technician Cross-Collaboration** to expose both engineers and technicians to one another early in the educational process to ensure they have context for one another's roles in manufacturing processes.
- Employing more **Virtual Learning** resources to expand access to educational programming related to emerging technologies to more audiences.
- Enhancing **Educator Development** opportunities so that instructors can integrate technology advancements and processes into their classrooms.

The EET has made a series of recommendations that will begin to address these cross-cutting themes as well as technology-specific needs for education and workforce development. While many of these recommendations are directed LIFT Leadership, both educators and industry will play critical roles in developing and implementing these strategies.

LIFT SUPPORTED FACILITIES AND RESOURCES THEME RECOMMENDATIONS

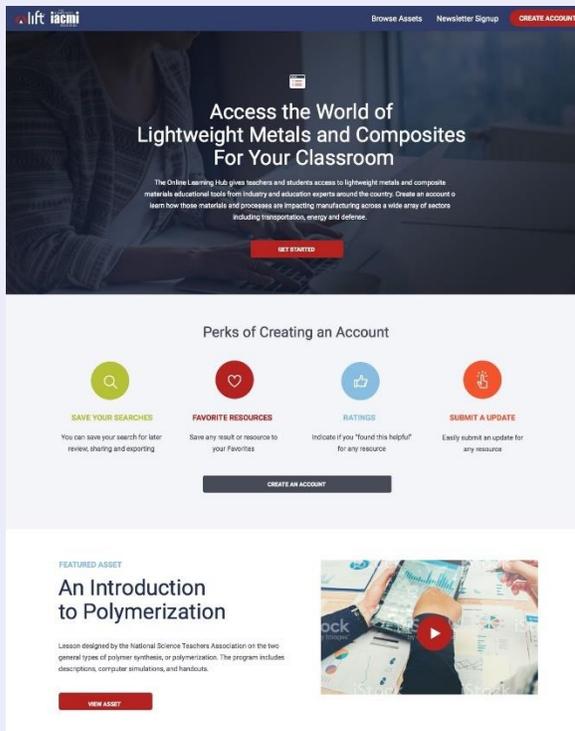
LIFT has already invested significantly in a wide array of technical and intellectual infrastructure that can support the delivery of the kinds of education and workforce strategies outlined in this report. These resources include the LIFT High Bay, LIFT Learning Lab, and LIFT Learning Hub, all described in further detail below. These resources represent a compelling opportunity to bring together industry and education professionals to deliver world-class education and training, and recommendations on how to leverage these resources are listed below and are referenced throughout the remainder of the report as well. Each of these resources is described in more detail below.

LIFT High Bay

The LIFT High Bay is the nation's premier lightweighting applied research and development facility. Featuring full-scale equipment installed for both LIFT and IACMI – The Composites Institute, the facility is uniquely positioned to help revolutionize manufacturing through lightweight innovation and education. The LIFT High Bay features 80,000 square feet of equipment directly related to the technologies reviewed by the EET, including:



- Linear Friction Welder, one of the largest in the world
- Robotic Blacksmithing cell
- Tilt Pour Casting
- An Extrusion Press capable of producing up to 400” long sections
- State-of-the-art Metrology Lab
- Hydroforming Press



LIFT Learning Hub

The LIFT/IACMI Learning Hub is a joint education and workforce development initiative between LIFT and IACMI (The Manufacturing USA Composites Institute), providing the first nationally relevant, open source and scalable online library of lightweighting and composites related educational materials for use by educators and students at all levels. The Learning Hub currently features more than 2,450 resources providing educational tools related to lightweight metals and composite materials for any age group, topic or duration. Since the Learning Hub was launched, over 2,000 visitors have searched the site for materials. Top searches have included "composites," "car," "titanium," "metal," "alloy," "graphene," "casting," and "plastic."

LIFT Learning Lab

The LIFT Learning Lab is being designed as a state-of-the-art interactive learning facility, located in the LIFT High Bay, with curated resources that will create an immersive learning environment. The Lab will feature:

- **Flexible Learning Space**- designed to flex to the needs of the students and industry, with moveable partitions, lab tables, and other equipment to accommodate a variety of hands-on activities and learning modules.
- **Computer and Virtual Reality Lab**- housing state-of-the-art operating stations and computer-based programming related to lightweighting and advanced manufacturing that will also be accessible via a digital learning portal.
- **Fundamental Skills Development Lab**- serving as the centerpiece for the LIFT Learning Lab, which will showcase equipment and curricula designed to provide students with introductory advanced manufacturing skills in an industry research and development setting.
- **Robotics Lab**-will allow students to familiarize themselves with basic robotics principles on digital twins of real-life robotics cells.
- **Materials Science and Project Fabrication Lab** will host teachers at ASM Materials Science Camps and introduce materials properties and principles in multiple educational activities.
- **CNC (Computer Numerical Control) Operations Training Center**- an online curriculum aligned to NIMS national credentials coupled with a hands-on CNC training space, complete with mill and lathe, will be embedded in the LIFT High Bay and computer lab to address the critical skills gap in CNC operations and provide priority training to veterans.
- **Welding Technician Training Center**- A curriculum aligned to AWS national credentials combined with virtual and hands-on welding training equipment will be installed in the LIFT High Bay to address the critical skills gap in welding.



Recommendation: Enhance Learning Lab Build Out Plans. EET believes the LIFT Learning Lab can be used as a central tool in advancing education and workforce development and achieving the development of competencies identified by the team. As mentioned in later recommendations, the EET encourages LIFT leadership to realize ideas like the following by implementing the Learning Lab vision:

- On-site training using the latest technologies available at LIFT, which could be made available to LIFT members and academic and research partners. For example, if a LIFT member needs people trained in the use of robotics for incremental forming, offer work-and-learn experiences to train the incumbent workforce.
- Offer a "software toolkit" workshop that introduces software capabilities available through LIFT. Beginner and follow-up advanced training could be provided. LIFT could also offer workshops on Integrated Computational Materials Engineering (ICME) success stories to increase awareness and introduce people to the available tools.
- Provide tours and career exploration workshops.
- Leverage the work-and-learn capacity provided by the Learning Lab. The main difference between the Learning Lab compared to labs at colleges is the opportunity to work directly with new tools while the equipment and processes are still emerging.
- Use expanded Learning Hub features recommended above to extend the Learning Lab virtually. Online, video webcast training sessions with schools that have makerspaces, or with companies that want to provide convenient training sessions.

Recommendation: Encourage the LIFT-supported education and workforce initiatives to incorporate the High Bay and Learning Lab into their plans. LIFT has already supported more than 40 education and workforce development initiatives, and the High Bay and Learning Lab can likely be vital resources to the existing LIFT supported education and workforce activities. Program leaders for these initiatives should be encouraged to develop mechanisms to incorporate the High Bay, Learning Lab, and the Learning Hub, into their efforts. Future solicitations for LIFT education and workforce funding could even require such integration in proposals. LIFT will benefit from the broad dissemination of their valuable infrastructure, and the initiatives will benefit in many ways too.

Recommendation: Build connections between existing LIFT-supported education and workforce initiatives and industry associations. Industry associations and professional societies like the American Foundry Society (AFS) and the North American Die Casting Association (NADCA) can play an important role in the dissemination of relevant knowledge. This kind of dissemination strategy is likely an essential part of the education and workforce mix for all of LIFT's technology projects and all technology plans should be reviewed for building connections to industry organizations and professional societies. Among other approaches, LIFT should consider ways to connect industry association content to existing LIFT investments in education and workforce. (See page 89 for additional LIFT investments.) These existing LIFT education and workforce initiatives could also collaborate with, for example, ASM, ASTM, SME, and ASME on design-specific projects and engage them on development and dissemination of course materials. Generally, linking the societies more closely with the education community can help advance education and workforce goals. A first step will be to task someone (perhaps a graduate student) with developing an inventory of the societies and their education and workforce assets.

WORK-AND-LEARN THEME RECOMMENDATIONS

Perhaps one of the most common themes throughout EET convenings was the need for individuals to gain hands-on experience in an industry setting. Work-and-learn models can teach students many of the critical competencies identified by all technology teams, including problem-solving, context for real-world applications, as well as critical employability skills. Work-and-learn models have been recognized as a high-impact practice because students learn better when they can apply what they learn in the classroom in a real-world environment with hands-on experiences. While work-and-learn models are somewhat common across postsecondary education—often in the form of apprenticeships, internships, and co-ops— it was acknowledged that these models are not widely implemented enough, and often still do not adequately prepare students for careers in manufacturing.

This issue of needing to address work-and-learn models was so prevalent in EET discussions that it prompted LIFT, APLU, and NCMS, in partnership with Manufacturing USA, to organize a two-day workshop focusing on innovating work-and-learn models in university engineering education. The recommendations resulting from that workshop are available in a separate publication, [*Engineering Work-and-Learn: Imperatives for Innovation*](#).

 **Recommendation: Develop a toolkit for the design and implementation of work-and-learn models.** Work-and-learn practices—apprenticeship, internship and co-op experiences—for college students, engineers, and shop floor workers are critical to developing competencies in many of the technologies reviewed. Work-and-learn models also present new lessons and learning opportunities to students that they cannot get in the classroom. Simply put, work-and-learn practices create students that are both more knowledgeable about technology and better able to work with technology—and people—in the workplace.

There are challenges, however, to successfully designing and delivering such experiences. Some of these challenges relate to the design of meaningful educational experiences. Other challenges are presented by the need for college or university departments or programs to work closely with business and industry partners in developing and delivering these experiences and the differences in time scales, cultures, and other aspects of the education and work contexts. The EET recommends that LIFT support development of a toolkit to support the design and delivery of these types of work-and-learn models. The toolkit could draw on known effective practices and the challenges faced by institutions and their industry partners that have already implemented effective work-and-learn experiences. LIFT should work with existing initiatives to develop train-the-trainer modules to aid in the dissemination of the practices in the toolkit for those states/institutions offering work-and-learn programs.

 **Recommendation: Develop a ‘Technology Liberal Arts’ curriculum.** The EET members repeatedly heard LIFT Technology project teams cite the need for individuals working in a manufacturing environment, especially engineers, to have the capability to work as a team, adapt to new technologies and environments, and bring a broader ‘systems’ perspective to their work. To that end, the EET determined there may be grounds for the development of a ‘Technology Liberal Arts’ curriculum that integrates soft skills, business principals, and economics with foundational technical coursework. The purpose of such a curriculum would be to provide students with a foundation for understanding technology with broad enough knowledge to equip

them with the capability to quickly adapt to new circumstances and parameters, while still allowing for them to develop deep expertise in a specific technology or skillset.

Because many of the kinds of skills addressed by a 'Technology Liberal Arts' curriculum are best learned in the workplace context, work-and-learn experiences should be core to this curriculum, reinforcing what students learn in the classroom and providing them with a greater understanding of the manufacturing environment.

AGILE CURRICULUM DEVELOPMENT THEME RECOMMENDATIONS

Technology teams regularly told the EET that the competencies required for the future manufacturing workforce are changing and will continue to evolve as technologies rapidly advance. This will require colleges and universities to be able to efficiently modify curricula to respond to changing industry needs.



Recommendation: Convene a curriculum development summit with deans and department heads. The EET recognizes the need to help colleges and universities align curriculum with emerging technologies under development by LIFT technology teams. LIFT could invite the deans and department heads of mechanical and manufacturing engineering, metallurgical and materials science, and engineering departments of universities. Deans and department heads could be asked how they could help to align their curriculum with LIFT projects (for example, by developing senior design capstone projects), and to provide some ideas regarding future research projects.



Recommendation: Develop and disseminate an inter-disciplinary course content design playbook. Many of the technologies reviewed require the development of competencies across multiple disciplines, and ideally, these competency domains should be developed in an integrated way. The EET recommends that LIFT work with an appropriate partner(s) to create and disseminate a course content design playbook to help colleges and universities develop courses that combine objectives for competency development across multiple disciplines. In addition to dealing with content design, such a playbook could also include a module about agile curriculum development, which has been discussed among members of the EET as a critical need for colleges and universities. The module would consist of recommendations and practical ideas about how to develop curriculum in a way that is more iterative and responsive to rapid changes in technology.

The EET also recommends the development of an industry problem-based learning design playbook or module to help faculty incorporate the development of these competencies into their courses. The playbook could recommend partnering with local industry partners to tie problem-based learning activities directly to real-world problems.

ENGINEER/ TECHNICIAN CROSS-COLLABORATION THEME RECOMMENDATIONS

Successful implementation of most, if not all, of the technologies reviewed requires technicians and engineers to work collaboratively. This collaboration should start early, while students are still in school to give production-level (community college) students and engineering (four-year university) students maximum exposure to one another before they start their careers in industry.



Recommendation: Create a multi-level, multi-disciplinary capstone design playbook.

To help encourage more cross-disciplinary exposure for students, LIFT, and an appropriate partner(s), can develop a capstone experience design playbook for faculty and program leaders at colleges and universities to help them design capstone projects which require groups from four-year and two-year colleges to work together. The playbook could also assist in designing capstones to require multidisciplinary (e.g., materials, chemical, mechanical engineering) and multi-trade (e.g., machinists, welders, etc.) student teams to work together. The playbook could be piloted with LIFT member institutions, with successful initial piloting leading to large-scale implementation with more institutions. LIFT could take an active role in providing incentives for institutions to develop capstones by sponsoring competitions for capstone design and student team capstone accomplishments.



Recommendation: Leverage the network of LIFT-supported education and workforce initiatives to organize lightweight materials grand challenges.

Prize and challenge programs are a proven mechanism for promoting innovation and learning, providing an excellent platform for both informing technology development and supporting education and workforce objectives. These types of challenges also encourage students to work across disciplines to solve a challenge. With more than 40 existing education and workforce initiatives underway, LIFT has created a unique network of practitioners deploying cutting-edge strategies for developing new manufacturing competencies. Combined with the technical expertise and vision of the LIFT technology teams and the network represented by team membership, LIFT can establish a powerful lightweight materials grand challenges program. The network can allow LIFT to rapidly organize grand challenge competitions to engage the current workforce, community college and four-year undergraduate students in developing lightweight materials solutions and, at the same time, develop creative ideas about how best to deliver education and training for such solutions. These challenges reach out to the innovation and creativity in people and could create out of the box ideas/processes/solutions that contribute to the technology as well as the education and workforce plans.

The EET was briefed on the Robotic Blacksmithing Challenge, which LIFT previously supported. The model of undertaking an educational initiative concurrently with technology development holds promise, but this first effort did not get the traction the technology team desired. The EET recommends that LIFT learn more about effective practices in prize and challenge programs and develop the organizational competency and capacity to use such programs in technology development and education and workforce.

VIRTUAL LEARNING THEME RECOMMENDATIONS

Many of the technologies reviewed will require training strategies that employ relatively costly equipment or access to an already limited pool of experts in these fields. It is unlikely that many educational institutions will be able to make the significant investments required to bring these resources on campus, so educators will have to increasingly rely on online coursework and virtual resources to provide students with exposure to these emerging technologies.

Recommendation: Mine existing education and workforce initiatives, as well as resources available from other providers, for needed technology-specific learning modules and get them into the Learning Hub. The EET recognizes the value of the LIFT-IACMI Learning Hub and recommends that efforts be undertaken to significantly enhance that value, drive traffic to the site, and increase the use of the Learning Hub for curricular enhancement. The Learning Hub can and should represent a significant opportunity to share the assets of LIFT headquarters with teachers and learners everywhere.

Many of the existing education and workforce initiatives supported by LIFT may be developing learning materials related to emerging technologies. The initiatives should be asked to make materials available in the Learning Hub. Additionally, discipline- and trade-specific organizations and societies should also be called upon to provide materials for the Learning Hub, including materials related to product specifications and standards. Members of the EET have also noted that some educational institutes and professional organizations have already developed sound course materials or lab experiments in metallurgy and welding, as an example. These types of materials should be added to the Learning Hub.

Recommendation: Add new features to the Learning Hub. LIFT can leverage the High-Bay and also its access to experts by expanding the kinds of resources that are available in the Learning Hub by adding resources like a regular "ask the expert" item and a series of "LIFT Talks,." Experts on the technologies can be interviewed in "ask the expert" style. LIFT could invite experts who are also good speakers to give "LIFT Talks," like TED Talks which could be webcast live and/or recorded for inclusion in the Learning Hub. A regular "On the Hub" blog could be developed, with guest educators authoring Learning Hub round-ups, pointing to multiple Hub resources on a given topic, and providing tips on how and where to use Learning Hub resources in the curriculum.

 **Recommendation: Turn the High Bay into a Learning Hub Modules Production Site.** Expert Educator Team members have consistently noted the need for technology-specific modules that college faculty can use to enhance existing curricula and develop new curricula. Many of the needed competencies are already being addressed in college technician and engineer programs, but additional teaching material is required to relate the competencies to the emerging technologies being developed by LIFT and its industry and academic partners. The High Bay represents an unprecedented opportunity to produce media-rich modules demonstrating emerging technologies and their link to core technical and design concepts and skills. LIFT should identify and deploy resources to regularly produce materials to be posted in the Learning Hub and mapped to the competencies advanced by the EET.

The EET recommends that LIFT use the High Bay and Learning Lab to develop a virtual reality environment designed to support remote learner interactions with simulated expert knowledge, skills, and abilities. Students across the country would be able to use this environment remotely to learn about newly developed materials processing techniques. There are several resources

provided by simulation software companies, and LIFT could use existing products as the basis for simulation resources and tools. These materials can be included in the Learning Hub, along with instructor resources to assist with including them as a part of the existing curriculum. LIFT could also conduct faculty development workshops to enhance adoption.

 **Recommendation: Create a click-and-mortar field trip program to enhance student learning in lightweight materials technologies.** Students themselves can benefit from exposure to the machines and learning tools being installed in the LIFT High Bay and Learning Lab. It will be important for LIFT to develop a strategy that makes access to such exposure available as widely as possible. The EET recognizes that LIFT has developed a [virtual tour](#) of the High Bay but recommends that additional resources be designed to complement that asset. The EET recommends a click-and-mortar field trip program, combining online and virtual learning modules that expose students to equipment and related instruction with the opportunity to visit the LIFT High Bay to access the equipment in person. Such a program could be made available to college and university instructors to build into their courses, whereby students could develop a project that includes manufacturing elements tied to High-Bay equipment. A portion of the learning and related project could be completed through online access to equipment walk-throughs or simulations, and students could then have a culminating project experience in a trip to Detroit to visit the High Bay and Learning Lab. Technical and engineering program instructors could partner with social sciences and arts/culture faculty at their institutions to extend the value of the field trips to include other aspects of an experience in a new city.

Of course, the ability to build in the travel component of the click-and-mortar field trip will be limited, so LIFT should consider extended virtual field trip experiences where students can experience, through real-time videocasts and virtual reality, instructors and technicians using the machines. LIFT could conduct live, online “ask the expert” sessions in which an equipment expert is available to answer student questions about a specific piece of equipment. An additional expert, knowledgeable about specific applications of the equipment’s use, could also be available so students can ask both “how it works” kinds of questions and also “what can be done with it?” questions.

Simple virtual tours of the equipment can be created using a GoPro camera mounted on a helmet. The wearer could walk through different machine components, reaching into the shot to point out specifics while narrating what the viewer is seeing. Live connections with classrooms could be established that allow students to see machines in action and to ask questions of operators. Live connections could follow [this example](#) at Lorain County Community College where students interact with an expert at the top of a wind turbine at Case Western Reserve University.

 **Recommendation: Perhaps as an extension of the Learning Hub, develop a database or multiple databases of experimentally produced parts and develop guidelines and specifications to produce parts using LIFT technologies.** Through the ongoing project research being undertaken by LIFT technology teams, valuable data is being generated. The collection and organization of the data in a format that can be searched and analyzed would create a resource that could be used by many in industry and academia. The basics of many of the LIFT technologies are covered in existing comprehensive courses on manufacturing processes. However, to enhance the course contents, this database of experimentally produced parts could be incorporated into existing coursework to create more robust curriculum, responsive to the workforce needs emerging from these developing technologies. If LIFT developed standard

metadata for experimentally produced parts, this could help make to make this data accessible in a standard format.

 **Recommendation: Develop a Learning Hub materials integration toolkit.** Recognizing the challenges of developing new courses and including them in the curriculum, the EET recommends that LIFT and college/university partners explore ways to incorporate short modules and resources found on the Learning Hub into existing courses provide lesson plans and other supporting content for course integration. The EET recommends the development of a Learning Hub Materials Course Integration Toolkit. Toolkits specific to individual emerging technology areas could also be developed.

Recommendation: Increase access to shared modeling and simulation software. Use of modeling and simulation software would be beneficial to both companies and academia, but the high costs can prohibit their adoption. LIFT could develop a way to create more access to simulation software and offer some initial training on its use. Such an effort could provide access to tools that are otherwise out of financial reach.

 **Recommendation: Provide virtual training on equipment not available at all colleges and universities.** The EET recommends that LIFT provide virtual training on the advanced facilities of the reviewed technologies, which may not be available at all college and universities. The EET noted the need for exposure to die casting and ICME, but the need is also relevant to a number of the other emerging technologies explored. Courses could be offered online and co-taught by experts from LIFT member universities. The course could easily be made available for students at other universities. If centrally coordinated by LIFT, three or four such courses could be developed through member institutions and organized into a certificate program offering.

EDUCATOR DEVELOPMENT THEME RECOMMENDATIONS

Like students, educators will also need more access to training and development opportunities in emerging technologies, so they can integrate them into their coursework. The EET found that many educators, despite their best efforts, are often not aware of LIFT's technology developments, which will hinder the dissemination of information to students and the future workforce.

 **Recommendation: Establish the LIFT High Bay and Learning Lab as a premier educate-the-educators facility for lightweight materials manufacturing technologies and processes.** The LIFT High Bay promises a world of learning opportunity for instructors and learners alike. Many of the existing LIFT education and workforce initiatives include a teacher training component. These programs should be reviewed for potential opportunities to deliver on-site training at LIFT. LIFT should also reach out—through APLU, NCMS, and other academic and industry partners—to colleges and universities and manufacturers' human resources and training departments to offer access to the High Bay and Learning Lab for incorporation of these facilities into faculty development and teacher training programs. While space and time limitations will not allow for extensive portions of such programs to be delivered at LIFT headquarters, even one- or two-day learning experiences could be incorporated into educator training programs. Additional time could be spent in the LIFT Learning Lab classroom with presentations by members of LIFT technology teams.

Recommendation: Use online videos and webinars to communicate the value of new technologies and processes. The Expert Educator Team observed that LIFT needs to communicate the importance of emerging technologies. The EET recommends increasing awareness through LIFT by hosting weekly/ monthly webinars. Webinars would be for raising awareness only, not for in-depth knowledge sharing. Currently, the EET observes that such awareness outside the LIFT community of members and partners is sparse. Many faculty, even those teaching manufacturing processes courses, do not seem to be aware of the work that is being done at LIFT. Webinars can be an easy way to increase awareness – even if faculty does not attend the webinar, the announcements themselves can raise awareness of the work being done, and they will know where to look for information when the need arises.



Recommendation: Build on the Advanced Manufacturing Teacher Externship. The Expert Educator Team observed that the Teacher Externship Program undertaken by the Kentucky LIFT Education & Workforce Team and the Northern Kentucky Industry Council could provide a model for LIFT teacher externships. Such externships could be focused on building awareness of lightweighting technologies and other resources available at LIFT. Teacher externships and teacher networks established through other LIFT Education & Workforce investments could be used to convey messages about the novel and innovative lightweighting technologies being developed at LIFT. As teachers develop this awareness, they can further promote awareness among the younger generation of students. Students can learn about types of manufacturing careers and how cutting-edge they are, countering current perceptions of manufacturing careers as dirty and dangerous. The EET feels this model can also apply to educators at the university level and can provide them with much-needed industry context for what they are teaching in the classroom.



Recommendation: Provide faculty development opportunities and case examples. For faculty to begin to integrate these new technologies and processes into broader technical or engineering courses, they will need to have greater familiarity with them. Faculty training modules should be developed to provide faculty with technology basics and examples of them in practice. These modules should also include real-life case examples to demonstrate how the technologies are utilized in manufacturing applications. Development of faculty training modules should be designed and produced so that they can then be used by faculty in their existing courses as appropriate.

TECHNOLOGY-SPECIFIC RECOMMENDATIONS FOR LIFT

The EET reviewed 12 LIFT Technology Projects to identify the knowledge, skills, and abilities workers will need to deploy the technologies, materials, and processes being created. Recommendations for all but one of the technologies, Nanoparticle Reinforced Aluminum, which is no longer being pursued by LIFT, is described in the section below. The chart below depicts how each of these technologies intersects with LIFT's technology pillars: Joining and Assembly; Coatings; Novel/Agile; Thermo-Mechanical; Powder Processing; and Melt Processing. See Chapter 3 for the detailed competencies that were identified for each technology. Upon review of these projects, the EET developed recommendations for how workforce and education can address specific competencies needed to successfully implement those technologies.

Joining & Assembly	Coatings	Novel/Agile	Thermo-Mechanical	Powder Processing	Melt Processing
Integrated Computational Materials Engineering (ICME)					
Distortion Control		Metamorphic Manufacturing	Friction Stir Extrusion	Powder Consolidation	Thin-Wall Aluminum Die-Casting
Titanium to Steel		Agile Fabrication of Sheet Metal			Thin-Wall Ductile Iron Casting
Stir Spot Welding					Nanoparticle Reinforced Aluminum
					Inorganically Bonded Sand Molds

The EET recommends LIFT develop the following technology-specific education and workforce development strategies in partnership with community colleges and/or 4-year universities.

Thin Wall Ductile Iron Castings

Thin-wall ductile iron casting (TWDIC) is a method of using ductile iron (DI) to produce thin-wall iron castings that leverages the high stiffness and strength of DI castings. Currently, DI-manufactured components have section sizes that are thicker, and therefore heavier, than is necessary for the components to meet specified mechanical requirements. This over-design is due to process and material limitations. Integrating and implementing improved process methods and improved DI alloys will create the potential to decrease wall thicknesses of DI cast parts by up to 50% allowing for light-weighting of components in transportation manufacturing. Depending on component loading, weight could be reduced as much as 30-50% by using TWDIC.

 **Recommendation: Encourage training in physical metallurgy, solidification, and casting and foundry operations.** LIFT should encourage training in physical metallurgy, solidification, and casting and foundry operations through webinars and other online methods. LIFT should also leverage their relationships with trade societies by introducing students and the workforce to these organizations. These groups may be an underutilized vehicle for delivering content. Also, the EET recommends exploring a partnership with the AFS Institute, formerly Cast Metals Institute, which hosts practical courses, seminars and workshops annually on all metal casting processes, materials and disciplines, both in-person online. AFS Institute could leverage existing curriculum or partner to develop new courses specific to this technology.

 **Recommendation: Develop an education and training network among hands-on casting sites and foundries at colleges and universities.** Perception of casting in the US is of an "old school" technology that is not cutting edge or exciting, so the industry is having a hard time attracting quality candidates to fill these jobs, which are actually quite high tech. At the same time, very few schools (4-year or community college) offer any hands-on casting experience (likely less than a dozen schools have this capability in the U.S., while it's widespread in Europe).

LIFT could develop a network of hands-on facilities that do exist to create satellite resources to provide exposure and training videos as well as additional sites for internships, immersive

experiences, and summer camps. Such a network would allow LIFT to encourage training in physical metallurgy, solidification, and casting and foundry operations through hands-on foundry experiences for students. LIFT could also broker tours of foundries for and/or create virtual tours. Schools without foundries could send faculty or students to these select LIFT schools for a few days, weeks, or even a semester to engage in casting-related projects (potentially supported by LIFT or specific industry members).

Powder Consolidation Processes

Powder consolidation processes are metal forming techniques that build on the advantages of using composite powders as opposed to a liquid melt to form a solid structure. Metal powder is squeezed, sintered and/or sprayed to form parts, sheet or plate, allowing great control over the final composition of the end product, its properties, and yield. Powder forming is more costly than liquid casting; however, powders produce solids that have a different and better structure than liquid melts. Powder composites combine powdered materials, such as aluminum and ceramics, to create components that can perform better. Specifically, powder metallurgy technologies can fabricate aluminum-based, sub-micron reinforced metal matrix composites (MMCs), or metals with another reinforcing material dispersed, that have superior strength-to-weight properties. Even better results can be achieved by employing new techniques for creating metal matrix composites that mechanically combine smaller particles which consolidate better. The result is a totally even distribution of the combined materials in the formed component.



Recommendation: Develop an education and training network among powder consolidation facilities at colleges and universities. Similar to the situation discussed in the previous section regarding hands-on casting facilities, there are few schools with powder consolidation facilities. The EET recommends connecting these facilities in a network and leveraging that network in the same way the EET has recommended connecting and leveraging casting facilities.

Agile Sheet Metal Fabrication

Agile sheet metal fabrication is a type of robotic blacksmithing, or a way of using robots to shape sheet metal parts while forming. It differs significantly from metal stamping that involves pressing sheet metal into a shape with heavy stamping machines. Agile sheet metal fabrication can be done with computer numerical control (CNC) machining, which means the process can be used to design unique parts without purchasing expensive individual stamping presses and tooling for each. Currently, the process is envisioned to be analogous to 3-D printing, using a metal stylus, directed by computer, that moves round and round in a specific pattern across sheet metal to form a part through incremental deformation without stamping. Agile sheet metal forming leverages a standard CNC machining platform to allow for the on-demand production of sheet metal parts that meet material property and design specifications in a fraction of the time and at a much lower cost than conventional techniques.

There were no separate recommendations made for Agile Sheet Metal Fabrication, however all of the general recommendations made in the previous section apply to this technology.

Integrated Computational Materials Engineering (ICME)

Integrated Computational Materials Engineering (ICME) defines a set of computational processes for working with many new manufacturing technologies by integrating materials information, captured in computational tools, with engineering product performance analysis and manufacturing process simulation. With ICME, sophisticated computational databases and tools are used to simulate design and performance, allowing for simulation-based identification of failures in materials, construction, and performance before costly use of materials to test and build. This new approach requires different skills and different workflow design; however, the tradeoff is considerable savings in time, materials, and cost.

Recommendation: Provide case examples for ICME use. ICME can be a nebulous umbrella term that is difficult to define or understand for educators, and even sometimes engineers and designers. Developing and disseminating some concrete examples of a successful ICME approach being applied to material development or process optimization, with specific technological or economic impacts, would be very beneficial.

Metamorphic Manufacturing

Metamorphic manufacturing is a metal working process by which a machine bends and squeezes metal into shape at varied temperatures and with varied deformation that can improve the material properties of metal. Often referred to as “robotic blacksmithing,” metamorphic manufacturing is a process poised for disruptive growth in deformation processing of lightweight metallic parts. Many of the core elements involved in achieving this malleability within manufacturing processes are beginning to mature; however, the complete vision for metamorphic manufacturing has not been fully realized and the technologies have not yet been synthesized into a cohesive whole. Metamorphic manufacturing is envisioned to allow for agile, rapid, and affordable production of small volumes of high-quality metallic parts, with a low environmental footprint, while reducing the need for expensive tooling and reducing fabrication time.

 **Recommendation: Use online videos and webinars to communicate the value of incremental forming:** LIFT should develop webinars to introduce this emerging technology to students and the incumbent workforce. A LIFT ambassador could also visit partner universities to give a seminar and engage student groups, perhaps in partnership with Materials Advantage chapters. Since incremental forming may not be possible in the laboratory in many partner universities, LIFT should leverage the capabilities available in the High Bay for work-and-learn experiences for students. There is also an opportunity for exposure to the technology through online videos. Since this technology is being pursued in automotive industrial applications already, LIFT could partner with automotive manufacturers to show that this technology is practical. Videos would be helpful in motivating students and industry alike to learn more about incremental forming processes.

 **Recommendation: Host a Metamorphic Manufacturing Hackathon.** LIFT has made clear the transformative potential of metamorphic manufacturing and should undertake an education and workforce initiative as soon as possible to focus on this technology. A weekend Metamorphic Manufacturing (MM) hackathon could be an exciting opportunity for LIFT, students and faculty. A hackathon could bring together multidisciplinary teams comprised of students and faculty with backgrounds that span programming, robotics, data acquisition systems, sensors and diagnostics, digital design, metallurgical and materials engineering, metalworking, manufacturing, and ICME. Each university involved could partner with a local community college to promote

collaboration and learning exchange among students at technical and engineering levels. Advance preparation for the hackathon would be required. Subject matter experts could give virtual demonstrations in advance of the weekend hackathon. Teams could also be provided with a problem statement and a kit of parts ahead of time, allowing the teams to show up prepared and having considered the concept of MM and how it might relate to the stated problem.

Expert Educator Team member Fazleena Badurdeen from the University of Kentucky has already worked with Glenn Daehn from Ohio State University to produce an introductory video, "Metamorphic Manufacturing aka Robotic Blacksmithing," now posted on the Learning Hub. Development of lesson plans with case examples and supplementary videos can enhance faculty readiness to incorporate modules on MM in their existing manufacturing processes courses, further helping with hackathon readiness. Crafting the right problem statement for the hackathon is critical—something that inspires revolutionary thought, engages students, and is at the same time simple enough that the emerging MM capabilities at LIFT can successfully demonstrate to be feasible. The weekend hackathon could complement the planned second implementation of a Metamorphic Manufacturing design challenge. The hackathon could be scheduled in advance of the challenge and potentially be used to generate team excitement and to announce the design challenge. Alternatively, it could be scheduled in the middle of the design challenge to baseline the teams and cross-pollinate ideas. A third option would be to hold the weekend hackathon at the end of the design challenge to get all the teams together and move the best practices forward. LIFT could work with maker spaces across the U.S. to hold regional hackathons on the same weekend. Teams at the LIFT high bay could be connected via videoconference with remote teams



Recommendation: Extend the robotic blacksmithing challenge to a regional approach to include multi-level (technical and engineering) teams. Again, building on the success of the Robotic Blacksmithing Challenge, LIFT could extend this strategy by requiring entrants to be regional teams that include both technical and engineering level students. This type would address a frequently identified (by the EET) need of students getting this type of multilevel work experience. These experiences will help students develop not only the skills required to undertake metamorphic manufacturing at either the production or design level, but also the team and communication skills necessary to successfully integrate technical and engineering work.

Friction Stir Extrusion (FSE)

Friction stir extrusion creates seamless lengths of material with a near net shape. An example of the benefits this process affords is found through an improvement upon a process called hydroforming which engages high pressure fluid to work material into a die, because friction-stir-extruded materials allow for the use of higher-strength aluminum alloys in the hydroforming process. The stir technology makes these alloys more resistant to cracking that can occur during hydroforming and improves their granular structure. This advance means that manufacturers can produce lighter, higher-strength parts with a smooth finish that has the added benefit of being corrosion resistant. The transportation industry will realize the benefits of this technology because it can reduce vehicle mass, promote more efficient builds, and increase component life. Friction stir extrusion will also benefit the heat exchanger industry by improving the life of process tubing in marine applications. Like the other friction stir technologies described in this report, friction stir extrusion involves generating friction heat to soften metal below the melting process to: weld parts, as commonly done in ship-building; spot weld components, as done in automobile manufacturing; or extrude metals, that is, force metals through a die.

 **Recommendation 2.11.1: Develop new coursework to enhance existing curriculum for Friction Stir Extrusion.** Most institutions have existing coursework in mechanical deformation, microstructures and mechanical properties which can prep students for the complexities of FSE. However, the curriculum should contain relevant modeling and simulation modules, solid-state joining processes, metal forming, and severe plastic deformation. In addition, demonstration videos and case studies of this technique would be useful to improve exposures and understanding to students.

Distortion Control

Distortion control is the elimination of factors that produce distortion in the product, materials, or process in manufacturing applications. Distortion control in heavy manufacturing involves controlling factors that cause the following conditions: longitudinal shrinkage, transverse shrinkage, angular distortion, bowing, buckling, twisting, or bending.² In manufacturing settings, distortion control is a system property and must follow a systems-oriented approach.³ Distortion control in lightweight manufacturing is particularly important because lightweighting often involves joining many different types of materials, making the joining process specific to the properties of each and their changing dimensions and performance in the manufacturing process. Also, joining or welding techniques traditionally used in the manufacture of thick steel, which has been used in shipbuilding, often cause distortion in the lightweighting environment.

 **Recommendation: Leverage Weld-Ed for module development.** Weld-Ed (www.weld-ed.org) has several regional partners, including in a couple of states within the LIFT region. Material developed through the LIFT projects workforce and education plans can facilitate the incorporation of required content into the curriculum offered by programs such as Weld-Ed. There may be an opportunity for Weld-Ed to propose/develop a project for training in lightweight materials. The module could become part of a suite of “train the trainer” modules offered on an ongoing basis.

 **Recommendation: Partner with America Welding Society to develop work-and-learn toolkit and modules.** In the context of Distortion Control, development and implementation of a work-and-learn toolkit should engage the principal professional society and certifying body, the American Welding Society (AWS), to create and deliver, through curricula and new content related to joining lightweight materials. AWS could consider including such modules in their certification programs. Also, in the Distortion Control context, work-and-learn modules could be an essential aspect of shipyard apprenticeship programs, given the Navy's significant 30-year shipbuilding plan.

²Challenges in Heavy Manufacturing, Part I, EWI website training.

³ B. Clausen, T. Lu'bben, and R. Rentsch, Stiftung Institut fu'r Werkstofftechnik, Distortion Engineering, ASM International, Retrieved from asminternational.org.

Refill Friction Stir Spot Welding (RFSS)

Refill friction-stir spot welding (rFSSW) is a developing technology that builds on the traditional friction stir welding (FSW) process to join metals without changing their surface geometry. FSW is a metal joining process that uses a tool “to join two facing workpieces without melting the workpiece metal.” The heat generated by “friction between the rotating tool and the workpiece metal leads to a softened region near the FSW tool.⁴ Friction stir spot welds (FSSW) have many of the same solid-state benefits of traditional friction stir welds (FSW) but can be localized and therefore be more readily implemented into robotic assembly systems. FSSW avoids the use of additional fasteners, such as rivets, to join metal pieces, but currently has limited applications because use of the welding tool leaves an imprint/depression in the joined metals. This imprint effectively changes the surface geometry, thus eliminating potential uses where an un-marred surface is required.

 **Recommendation: Develop and enhance coursework on Refill Friction Stir Spot Welding at both the technician and engineer level.** While welding is part of many two-year programs, courses on welding and solid-state joining/solidification processes are not generally included in materials engineering programs. Such courses, as well as courses in physical metallurgy and materials characterization (microstructure and properties), should be considered for development and inclusion in the engineering curriculum. Other helpful courses include those related to metallurgy, modeling tools like SYSWELD, quality specifications and standards, data informatics, machine learning, engineering drawings, and lab experiments. Competencies might also be addressed through enhancement of existing courses, perhaps using cases focused on FSSW. Courses in advanced manufacturing or existing courses that cover friction stir welding (but not RFSSW) could include a RFSSW case study, for example.

Thin-Wall Aluminum Die Casting Development

Thin-wall aluminum die casting is a new lightweighting technology that allows manufacturers to build lighter and stronger aluminum parts while maintaining energy efficiency in the overall die-casting process. Thin-wall die casting, also called high-pressure die casting (HPDC), ideally can reduce the wall thickness of die castings to less than 3mm in parts with larger mold-fill area and still achieve complete mold fill. The technology is currently in the development stage; problems to be resolved include reducing variability of HPDC castings and increasing the minimum mechanical properties. These limitations currently restrict its use for some structural applications in the automotive and aerospace industries. Current die casting design methods apply the minimum mechanical properties of cast alloys uniformly to the whole casting, which can result in over-design of a casting, especially when a large safety factor is used. Thin-wall die casting can eliminate over-design and costly over-use of materials. This can be achieved by producing statistically accurate custom processes for thin-wall castings that account for mechanical properties at different stages in the design process; doing so can result in greater design efficiency overall.

⁴ Friction stir welding. Retrieved from https://en.wikipedia.org/wiki/Friction_stir_welding.

 **Recommendation: Work with the North American Die Casting Association (NADCA) and American Foundry Society (AFS).** The members of the EET agreed it would be important for LIFT to disseminate knowledge relevant to this technology project through existing professional societies such as NADCA and AFS and their professional development or education/training efforts. LIFT can also work with trade groups to develop and disseminate metal casting and casting design content. LIFT could work with NADCA to build on their content (e.g., develop licensing agreement) to distribute to technical schools, colleges, and universities for training of students and local manufacturers. LIFT could capitalize on its relationship with Learning Blade to provide an online delivery platform.

 **Recommendation: Provide virtual training not available at college and universities.** The EET recommends that LIFT provide virtual training on the advanced facilities on super vacuum die casting, which may not be available at the college and universities. In conjunction with the development of virtual training, LIFT could create a handbook of principals for high vacuum die casting processes and using modeling and simulation software for die casting processes.

Joining Titanium to Steel

The ability to join dissimilar materials, such as titanium and steel, has gained attention recently as manufacturers strive to design and produce lightweight components that can meet the performance, reliability, and cost standards of the automotive, aviation, aerospace and defense industries. To lower production cost, titanium and its alloys are often welded to steel to achieve high performance and cost-efficiency. However, reliable titanium/steel joints can be difficult to produce due to poor compatibility and the formation of hard and brittle characteristics in the joint. Developing advanced computational methods that accurately predict material and joint properties of titanium-to-steel joints will significantly impact lightweight component design for transportation industries. Eliminating more complex joints will lead to more efficient designs, reduced weight, and reduced production time and cost.

 **Recommendation: Development and enhance coursework.** Joining Titanium to Steel technology advancements require curriculum enhancement at both the technician and engineer level. While welding is part of many two-year programs, courses on welding and joining are not generally included in materials engineering programs. Such courses, as well as courses in physical metallurgy, materials characterization (microstructure and properties), multi-metal joining, and product design with multi-material joints should be considered for development and inclusion in the engineering curriculum. As with the previously-described technology, other helpful courses or course content include that related to metallurgy, modeling tools like SYSWELD, quality specifications and standards, data informatics, machine learning, engineering drawings, and lab experiments. Competencies might also be addressed through enhancement of existing courses, perhaps using cases focused on Joining Titanium to Steel. Courses in advanced manufacturing, computation, and design for assembly could include a Joining Titanium to Steel case study, for example.

Inorganically Bonded Sand Molds

Inorganically-bonded sand molds contain inorganic materials used to bind sand for building molds for metal casting. Inorganic binders reduce some of the problems caused by organic binders, such as coal, because they produce few or no off-gases in the molding process and reduce the possibility of resulting defects in the mold. Also, because no organic binders are used, mold sand

can be reclaimed and used again. Because inorganic binders reduce mold defects, parts that require high safety tolerances can be produced using inorganically bonded sand molds. Inorganically bonded sand molds can also be produced and replicated using 3-D printing, reducing the need for expensive metal dies and allowing for more flexible, less costly mold designs.

 **Recommendation: Address gaps in current curriculum.** If institutions have courses that cover sand casting at all, it is likely in passing and not addressing the advances in this technology. Courses in microstructure and mechanical characterization and exposure to statistical process control as it impacts this new technology should be considered for development and inclusion in the materials engineering curriculum. Also, institutions should develop or add modules to include iron casting, metal metallurgical properties, and 3D sand printing technology (additive manufacturing).

As noted in previous sections, very few schools (4-year or community college) offer any hands-on casting experience. The EET recommends, in support of advancing competencies in Inorganically Bonded Sand Molds, development of an education and training network among hands-on casting sites and foundries at colleges and universities.

Chapter 3: Technologies and Competencies

The EET reviewed each LIFT technology project to, not only understand how they will impact manufacturing education, but also to identify critical competencies the workforce will need to successfully use and implement these technology innovations. The following section outlines key competencies related to each technology, as well as detailed Thinking-and-Doing Maps that define the extent to which students will need to employ each competency.

THINKING-AND-DOING MAPS

The EET developed Thinking-and-Doing Maps to help educators understand how students will need to utilize each of the competencies identified. The Thinking-and-Doing Maps are an adaption of Bloom's Taxonomy and categorize the competencies identified for each technology evaluated. The Thinking-and-Doing Maps provide a visualization of how students must be able to understand and perform, and in doing so, provides educators with a common language to discern the extent to which students need to master these competencies and the outcomes that are needed for them to be successful. The Thinking-and-Doing Maps measure student outcomes on two dimensions, 'Thinking' and 'Doing,' each of which includes a continuum.

How to Use Thinking and Doing Competency Maps

To aid educators in considering how best to address needed competencies for the emerging technologies being developed at LIFT, the Expert Educator Team (EET) has created "Thinking and Doing Competency Maps." These maps are meant to provide guidance regarding the depth of knowledge and application needed for readiness to work with the technologies.

About the Maps

The Thinking and Doing Competency Map is based on conceptual work done in the early 2000's by scholars in education and engineering. In 2001, Lorin Anderson and David Krathwohl adapted Benjamin Bloom's (with whom both Anderson and Krathwohl had studied) earlier work laying out an order of cognitive skills.⁵The Anderson and Krathwohl adaptation made it simpler for educators to apply the taxonomy to the design of educational experiences. In 2005, Timothy Ferris and Mahfuz Aziz, both engineering faculty, developed a conceptual framework that extended Bloom's Taxonomy—which had largely dealt with cognitive (thinking) and affective (feeling) aspects of learning—into the psychomotor (doing) domain (while Benjamin Bloom identified the need for a psychomotor aspect to the taxonomy, he and his colleagues did not develop a psychomotor

⁵ Anderson, L.W. (Ed.), Krathwohl, D.R. (Ed.), Airasian, P.W., Cruikshank, K.A., Mayer, R.E., Pintrich, P.R., Raths, J., & Wittrock, M.C. (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's Taxonomy of Educational Objectives* (Complete edition). New York: Longman.

component)⁶. The Ferris and Aziz extension of the taxonomy made the framework more relevant to the needs of teaching and learning in engineering. The EET has adapted the work of these scholars into a matrix we are calling the Thinking and Doing Competency Map, with Anderson and Krathwohl's work the basis of the vertical dimension (Thinking) of the map, and the Ferris and Aziz work the basis of the horizontal dimension (Doing) of the map.

The Thinking (vertical) dimension of the map presents a range of cognitive skills. The dimension begins with “remember” at the lowest end of the range, then proceeds with “understand,” “apply,” “analyze,” “evaluate,” and finally “create” at the highest end of the dimension. Following are descriptions of each skill from Leslie Owen Wilson’s discussion of the Anderson and Krathwohl adaptation⁷:

Remember: Recognizing or recalling knowledge from memory. Remembering is when memory is used to produce or retrieve definitions, facts, or lists, or to recite previously learned information.

Understand: Constructing meaning from different types of functions be they written or graphic messages or activities like interpreting, exemplifying, classifying, summarizing, inferring, comparing, or explaining.

Apply: Carrying out or using a procedure through executing or implementing. *Applying* relates to or refers to situations where learned material is used through products like models, presentations, interviews or simulations.

Analyze: Breaking materials or concepts into parts, determining how the parts relate to one another or how they interrelate, or how the parts relate to an overall structure or purpose. Mental actions included in this function are *differentiating, organizing, and attributing*, as well as *being able to distinguish between* the components or parts. When one is analyzing, he/she can illustrate this mental function by creating spreadsheets, surveys, charts, or diagrams, or graphic representations.

Evaluate: Making judgments based on criteria and standards through checking and critiquing. Critiques, recommendations, and reports are some of the products that can be created to demonstrate the processes of evaluation. In the newer taxonomy, *evaluating* comes before creating as it is often a necessary part of the precursory behavior before one creates something.

⁶ Ferris, T.L.J. & Aziz, Syed. (2005). A Psychomotor Skills Extension to Bloom's Taxonomy of Education Objectives for Engineering Education. 1-5.

⁷ Owen Wilson, L. (2016). *Anderson and Krathwohl – Bloom's taxonomy revised*. In *The Second Principle: The Work of Leslie Owen Wilson*, Ed.D. Retrieved from <https://thesecondprinciple.com/teaching-essentials/beyond-bloom-cognitive-taxonomy-revised/>.

Create: Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing. Creating requires users to put parts together in a new way or synthesize parts into something new and different creating a new form or product. This process is the most difficult mental function in the new taxonomy.

The Doing (horizontal) dimension of the map presents a range of psychomotor skills. The dimension begins with “recognition” at the lowest end of the range, then proceeds with “handling,” “basic operation,” “competent operation,” “expert operation,” “planning,” and finally “evaluating” at the highest end of the dimension. Following are descriptions of each skill from Ferris and Azziz:

Recognition: The most basic level of practical skill competence involves the ability to recognize the tools of the trade and the materials. This level of skill requires that one learn what the tools are so that when presented with a sample of a particular tool one has the ability to recognize it as such.

Handling: Tools and materials are appropriately handled in certain ways. Thus, particular processes for picking up, moving and setting down tools and materials must be learned. The processes are required in order that the objects can be handled without damage to either the object or other objects in its environment or hazard to any person, either the person moving the object or someone else nearby.

Basic Operation: The basic operation of tools concerns the ability of the student to hold the tool appropriately for use, to set the tool in action and to perform elementary tasks that abstract tasks of work into their most basic, unitary form. The tasks that can be performed at this level are the specific detail tasks which, when assembled into a sequence, result in the completion of a piece of significant work. This level of competence concerns learning how to operate the tools and how to attend to matters of safety associated with the fundamental operational characteristics of the tools.

Competent Operation: At this level the student becomes able to fluently use the tools for performing a range of tasks of the kind for which the tool was designed. This level is distinguished from the preceding by the student being able to assemble a significant sequence of tasks which when brought together enable the completion of designated work associated with the use of the tool. The work produced will be of a sound standard, being work that could be delivered as part of a finished product. Examples of such work in electronics would include the ability to drill holes in a circuit board consistently located correctly within the boundary of the solder mounting pads, or the ability to consistently solder all the mounts on the circuit board with mechanically and electrically sound joints with consistent solder quantity in each joint. Competent tool use includes being able to use the tools to achieve consistent, effective work outcomes in a manner that is consistently safe.

Expert Operation: The ability to use tools with ease to rapidly, efficiently, effectively and safely perform work tasks on a regular basis. The expert user of the tool is able to produce the right outcome with attention being placed on the broader context of the work that is being done rather than the narrow context of the tasks being performed to do the work.

Planning: At this level of competence the student is able to take a specification of a work output required and perform the necessary transformation of the description of the finished outcome into a sequence of tasks that need to be performed on the material in order to achieve

the desired outcome and bring to fruition the finished product intended. The process of planning work operations requires an intimate understanding of the particular work operation in the required repertoire and the ability to discern matters such as the order of operations to efficiently and effectively produce the desired output product.

Evaluation: At this level of competence the practitioner is able to look at a finished output product and review that product for quality of manufacture, with the ability to identify particular deficiencies and the actions which could be taken to either correct the faults or to prevent the faults through appropriate planning of the manufacturing operations. This level of competence parallels the 'Evaluation' and 'Characterization by a value complex' levels at the highest achievement in each of the other two domains. Again, the domain is capped by a level of achievement involving the critical review of actions that have been taken.

We have plotted each of the “critical competencies” identified by the EET—that is, competencies that are important for each emerging technology but likely not yet addressed in the two-year technical or four-year engineering curriculum—on the Thinking and Doing Competency Map. In so doing, the EET’s aim is to provide guidance to educators regarding how and where to address the critical competencies in the curriculum.

Using the Maps

To use the maps, educators should:

1. Review the competencies and their placement in the map.
2. Considering the competency level at which technical or engineering students need to be able think about and do the knowledge or skill identified by the competency.
3. Identify appropriate places in the curriculum to address each competency.
4. Design learning experiences that will develop the appropriate level of depth in thinking or doing.
5. Assess student learning at the appropriate level of depth in thinking and doing for each competency.

TECHNOLOGIES

Provided here is an overview of each technology reviewed as well as specific competencies that will be required for each. Refer to the recommendations section of this report for some strategies that might be employed for addressing competency needs.

THIN-WALL DUCTILE IRON CASTING

What is Thin-Wall Ductile Iron Casting?

Thin-Wall Ductile Iron Casting (TWDIC) is a method of using ductile iron (DI) to produce thin-wall iron castings that leverages the high stiffness and strength of DI castings. Currently, DI-manufactured components have section sizes that are thicker, and therefore heavier, than is necessary for the components to meet specified mechanical requirements. This over-design is due to process and material limitations. Integrating and implementing improved process methods and improved DI alloys will create the potential to decrease wall thicknesses of DI cast parts by up to 50% allowing for light-weighting of components in transportation manufacturing. Depending on component loading, weight could be reduced as much as 30-50% by using TWDIC. “The object of current TWDIC research by LIFT [Lightweight Innovations For Tomorrow (www.lift.technology)] is to optimize manufacturing methods using available ductile iron alloys” (*Foundry Management and Technology*, www.foundrymag.com, July 13, 2015). The ability to make thin-wall ductile iron (DI) castings is important for leveraging the high stiffness and strength of these materials when creating lightweight parts and components.

Thin-Wall DI Castings Produce Lighter Manufactured Components

Thin-Wall Ductile Iron Casting (TWDIC) takes advantage of the ability of ductile iron (DI) to be stretched, while maintaining stiffness and strength. Fully developed TWDIC technology will produce lightweight, high-strength castings for many applications, including transportation, to reduce cost and increase energy efficiency. Metals with ductility properties, like DI, can stretch without damage and can therefore be used to form wires, for instance. Metals with malleability, such as malleable iron (MI), have the ability to “deform under compression”; MI can be rolled or beaten into sheets (<https://www.quora.com/What-are-the-differences-between-ductility-and-malleability>). Both DI and MI contain less carbon than ordinary cast iron (grey iron), but DI has a higher yield strength than MI, so “it can bear greater loads and [withstand] higher temperatures” (<https://www.hunker.com/13401251/difference-between-ductile-iron-malleable-iron>). The material composition of DI provides its ability to stretch. The graphite (carbon) fragments in DI have the microstructure of nodules or spheres; hence, DI is sometimes called spherical graphite iron or nodular iron. By contrast, the graphite in gray iron appears more like flakes. It is the nodular structure of the graphite components that give DI its capacity to stretch and make it suitable for lightweight metal casting. In short, DI can produce lighter and stronger cast components. The overall technical challenge to making a successful DI casting is to create the right metal thickness for design optimization of any given component.

Workers Who Make Thin-Wall DI Castings Require Special Skills and Precision

The skills required to produce quality thin-wall DI castings for transportation components are those required to develop all lightweight innovations. First, both design and optimization requirements are at stake in TWDIC. When designing a part/component, new tools for topology analysis allow designers to consider what is minimally required

for a proposed part to work safely. When topology analysis is complete, these specifications can be loaded into computer-aided design (CAD) software to enable the designer to refine a component’s geometry and reduce waste. Algorithms employed by analytical-software tools allow engineers to use thinner metals more efficiently in their design by showing how optimization happens and by providing different design strategies. Designing with the required precision demands special skills to visualize what needs to be done, given the analyses provided by the software.

Second, design optimization routines for thin-wall castings that tolerate very little error must involve quality controls and measurement processes that globally analyze the effects of all steps in their manufacture. This means both designers and production engineers must share responsibility for error at all points in the design and production of thin-wall metal castings. Specifications and rules for design manufacturability must offer many points of in-process control, including: analysis of consistency of the metal pour, refined tolerances on the molding machine, and constant in-process monitoring. Greater precision can require increased sampling to assure quality and additional gauges and sensors to monitor processes, both of which can increase cost. Another challenge is for the designers and production personnel to learn what to do with the data these controls produce. For educators, this may mean giving students and workers more practice with employing statistical analyses to solve practical manufacturing problems, possibly through using simulations.

Third, more sophisticated design and manufacturing processes require greater knowledge of the metal alloys and composites involved. Success requires “system design” with several kinds of engineers and scientists — mechanical, metallurgical, and materials — working as an interdisciplinary team. Metallurgical engineers and materials scientists will have more precise knowledge of how microstructure influences the properties of metals involved, and mechanical engineers will have greater input on how part geometry influences those properties. This presents a problem for small companies

that can't afford to employ, perhaps, more than one design engineer. New software can provide some of this analysis without adding personnel; however, the training of specialized engineers is often still required. Additionally, companies' decisions about what material to use for a product can affect both value and cost. Foundries can make new parts easily with 3D printing, but successfully casting the parts may come down to whether the material chosen can perform in the new pattern successfully and safely.

All the design parameters noted above imply that implementing thin-wall ductile-iron casting technology will require a multi-disciplinary workforce, with materials and mechanical engineers working collaboratively to design and manufacture the parts. Educators who prepare students for the workplace should be offering more opportunities for students to apply knowledge in practical settings and develop hands-on familiarity with manufacturing processes that change as products are produced. Some basic skills required include the ability to:

- Visualize in three dimensions (valuable for designers and for technicians running CAD software);
- Hypothesize and design experiments (DOE);

- Use math and statistical methods to analyze the variability of products;
- Find relevant information and use it efficiently;
- Employ shop-floor controls; and
- Work collaboratively in teams.

Both students and the incumbent workforce will need the knowledge and skills to optimally design Thin-Wall Ductile Iron Castings for manufacturability, to manage process performance, and to ensure part specifications are satisfied.



Technology Timeline

Estimated time by which Thin-Wall Ductile Iron-Casting will appear in production environments:

- **Late 2018:** LIFT technology project on Thin-Wall Ductile Iron-Casting concludes, deployment begins.
- **2020:** Thin-Wall Ductile Iron-Casting should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness for Thin-Wall Ductile Iron Castings, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for Thin-Wall Ductile Iron Casting are those that are likely already addressed in the two-year or four-year engineering/technology curriculum. These competencies are listed on the following page, along with information about where or how each is addressed, as follows:

• **Supporting Competency in Bold //** Course(s)
Where Competency is Likely Addressed



Supporting Competencies in 2-Year Community College Programs

- **Exhibit General Understanding of Iron Casting Processes** // Manufacturing Processes Course
 - Distinguish Between Different Manufacturing Processes: Forging, Extrusions, Casting, Forming, & Finishing
 - Describe Properties of Forgings, Castings, Extrusions & Fabricated Parts
- **Demonstrate Skill in Computer-Aided Design (CAD)** // Introductory CAD Course
 - Build 3D Parts From Sketches & Applied Features
 - Create Assemblies From Models
 - Create Detailed & Assembly Working Drawings
- **Conduct Process & Quality Control Measurements** // Quality Tools / SPC Course
 - Use Software to Apply Statistical Process for Quality Data Analysis
 - Prepare Control Charts & Estimate Process Capability
- **Demonstrate Basic Understanding of Materials Strength & Properties** // Strength Of Materials Course
 - Apply Scientific Principles to Analyze Strength & Property Characteristics of Engineering Materials
- **Display Knowledge of Metals Types, Structure, Composition, Properties & Applications** // Metallurgy or Materials Course
 - Describe the Behavior of Engineering Materials Subjected to Metallurgical Processes
 - Identify Differences Among Various Carbon & Alloy Steels & List Steels for General Use in Design

Supporting Competencies in 4-Year University Programs

- **Exhibit Advanced Knowledge of Iron Casting Processes** // Manufacturing Processes Course
 - Understand Key Parameters Affecting Manufacturing Processes: Forging, Extrusions, Casting, Forming, & Finishing
 - Assess Benefits of Using Different Manufacturing Processes: Forging, Extrusions, Casting, Forming, & Finishing
 - Select the Manufacturing Process(es) to Produce Parts that Meet Specifications
- **Apply Computer-Aided Design (CAD) & Finite Element Modeling (FEM)** // Introductory CAD Course or FEM Course
 - Build 3D Parts from Sketches & Applied Features
 - Create Assemblies from Models
 - Create Detailed & Assembly Working Drawings
 - Evaluate Part Designs Using FEM Software
- **Conduct Process & Quality Control Measurements** // Quality Tools or SPC Course
 - Use Software to Apply Statistical Processes for Quality Data Analysis
 - Prepare Control Charts & Estimate Process Capability
- **Demonstrate Understanding of Materials Strength & Properties** // Strength of Materials Course
 - Apply Scientific Principles to Analyze Strength & Property Characteristics of Engineering Materials
- **Display Knowledge of Metals Types, Structure, Composition, Properties & Applications** // Metallurgy or Materials Course
 - Predict the Behavior of Engineering Materials Subjected to Metallurgical Processes
 - Select Materials to Satisfy Product Functionality Requirements

Critical Competencies

Critical competencies for Thin-Wall Ductile Iron Casting are those that will likely require new materials, modules, or courses. These competencies are listed on the following page, along with information about where or how each could be addressed, as follows: • **Supporting Competency in Bold** // Course(s) Where Competency Could Be Addressed

Critical Competencies in 2-Year Community College Programs

- **Understand Challenges Associated with Thin-Wall Castings; Know What Parameters Need Special Attention & What Makes This Approach Practically Different from Traditional Casting** // Manufacturing Processes II Course
 - List the Critical Features of Thin-Wall Castings
 - Explain How the Critical Features of Thin-Wall Castings Influence Design
- **Display Working Knowledge of (Commercially Available Or In-House) Casting Design Tools, Including ICME, for Flow & Solidification Modeling** // Strength of Materials Course
 - Use Casting Design (Modeling) Software to Identify Appropriate Materials for a Casted Part
- **Demonstrate Working Knowledge of Design of Experiments (DOE)** // Quality Tools Course or Create a New Course
 - Create an Experimental Design Plan
 - Apply the Experimental Design to Solve a Simple Engineering Problem
- **Apply Finite Element Analysis (FEA) to Manufacturing of Parts** // Second Year Parametric CAD Course
 - Use FEA Models to Generate a Graphical Representation of Parts Under Defined Stress & Strain

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create			2				
	Evaluate				3			
	Analyze	1				4		
	Apply							
	Understand							
	Remember							

1. Understand challenges associated with thin-wall castings; know what parameters need special attention and what makes this approach practically different from traditional casting.
2. Demonstrate working knowledge of design of experiments (DOE).
3. Display working knowledge of (commercially available or in-house) casting design tools, including ICME, for flow & solidification modeling.
4. Apply finite element analysis (FEA) to manufacturing of parts.

Critical Competencies in 4-Year University Programs

- **Design & Optimize Thin-Wall Ductile Iron Castings to Ensure Manufacturability**
// Manufacturing Processes or Design for Manufacturing Course
 - Determine Specifications for Casting Designs
 - Evaluate Alternate Casting Design Performance
 - Select Optimal Casting Design Specifications
 - Apply ICME Tools for Design & Optimization of Castings
- **Recommend Changes to Casting Process Specifications to Ensure Part Quality** // Quality Tools/SPC Course
 - Evaluate Process Performance Using Control Chart Information
- **Identify & Recommend Process Changes/Improvements to Meet Part Specifications**
- **Relate Materials Processing, Structure, Properties & Performance to Recommend Casting Part & Process Specifications** // Metallurgy or Materials Science Course
 - Assess Impact of Using Different Process Parameters on Microstructure
 - Evaluate Casting Performance due to Microstructure Changes
 - Optimize Material Selection & Processing Parameters for Part Performance

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create						2	3
	Evaluate							
	Analyze						1	
	Apply							
	Understand							
	Remember							

1. Relate materials processing, structure, properties and performance to recommend casting part and process specifications.
2. Recommend changes to casting process specifications to ensure part quality.
3. Design and optimize thin wall ductile iron castings to ensure manufacturability.

POWDER CONSOLIDATION PROCESSES

What are Powder Consolidation Processes?

Powder Consolidation Processes are metal forming techniques that build on the advantages of using composite powders as opposed to a liquid melt to form a solid structure. Metal powder is squeezed, sintered and/or sprayed to form parts, sheet or plate, allowing great control over the final composition of the end product, its properties, and yield. Powder forming is more costly than liquid casting; however, powders produce solids that have a different and better structure than liquid melts. Powder composites combine powdered materials, such as aluminum and ceramics, to create components that can perform better. Specifically, powder metallurgy technologies can fabricate aluminum-based, sub-micron reinforced metal matrix composites (MMCs), or metals with another reinforcing material dispersed, that have superior strength-to-weight properties. Even better results can be achieved by employing new techniques for creating metal matrix composites that mechanically combine smaller particles which consolidate better. The result is a totally even distribution of the combined materials in the formed component.

Lightweight Innovations For Tomorrow (LIFT) is conducting a project that both creates high quality metal matrix compositions and lowers the cost of producing them. Specifically, this project addresses the cost of Aluminum-Silicon Carbide (AlSiC) MMCs that are derived from novel mechanically-alloyed powders. Considerations for successful development include process optimization, technical cost modeling, and assessment of novel consolidation methods. The methods being tested are believed to be lower in cost than the baseline hot isostatic pressing (HIP) to form a component (HIP makes metal less porous and denser) while, at the same time, yielding similar or greater strength-to-weight benefits in the resultant product.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

Powder Consolidation Potentially Can Produce Stronger Lightweight Products for Less

Material properties afforded by Powder Consolidation Processes used for metal forming cannot be achieved through traditional melt processes. However, powder composites are expensive and current powder mixes can result in uneven distribution of the mixed materials in the composite. New consolidation techniques “tweak” the process of creating the metal matrix composite by mechanically ball-mixing particles together to create particles that are smaller and better consolidated. This results in a totally even distribution of the combined materials in the resultant powders and a very high-quality product when such powders are used for metal forming. This quality can’t be achieved by adding a powder to a liquid metal melt which can result in uneven distribution of the new material throughout the mix.

A new ball-mixing process for metal alloys is under development that produces particles which are smaller and more evenly distributed in a resulting powder. Developers are exploring how to consolidate these powders with new approaches that reduce cost. These new composites potentially can be more effective than more expensive materials while delivering the same strength and stiffness. For instance, aluminum with hard particles can have greater specific strength (strength to weight ratio) than aluminum alone, potentially rivalling titanium, a much more expensive metal. Potentially, new Powder Consolidation Processes can also reduce design production time, steps, and scrap products; broaden and diversify the supply chain; and cut machine and materials costs for complex components.

Some problems yet to be solved in developing these new Powder Consolidation Processes include:

- How can mechanically mixed powders be best consolidated?
- Can new consolidation processes reduce

the cost of powder forming technologies?

- Can these new materials effectively replace more expensive materials in terms of performance and reliability?

New Powder Consolidation Processes Demand New Manufacturing Processes

Material properties afforded by both powders and powder consolidation technologies will require increased monitoring of manufacturing processes to assure that material properties are optimized during the powder production cycle. Engineers who produce the powders will need to learn how to scale the ball-milling technology so that it works for both small and very large cans of powder. Technicians will need to monitor many factors during material production and tag production batches with specific operating conditions. Technicians will also need to be able to communicate with process engineers during the production cycle to maintain optimum process control. Most importantly, material safety handling and storage procedures will need to be strictly followed.

Two factors are known to affect the production process for the novel “ball milling” technique; the milling process involves:

- A different “sweet spot” for each consolidated material developed, and this changes the manufacturing process for each; and
- A large-range of agglomerate size is produced by the process, making it different than conventionally produced powders in powder consolidation.

The powder input process in metal forming is affected by these factors. Processors need to decide whether to reduce the size of the agglomerate in one or more steps and determine how the powder can size affects the mix as well. Small and large particles together must be mixed appropriately to achieve good distribution in both small and large cans.

Engineers & Technicians Will Need to Communicate Well with Each Other

Designers and production workers will need to assure that the “digital thread” that is recording what is happening when the processes are occurring is appropriately monitored. This includes such factors as temperature variation, vacuum/no vacuum environment, and auditory feedback in the process. Both powder handling and consolidation will require workers to understand:

- How powders are made and fashioned into agglomerates;
- How to recognize powder defects, powder size and distribution range;
- How machining and tool selection will differ with these materials;
- What standards are required for achieving effective powders and consolidations; and
- How temperature affects residual stresses that can change dimensional stability.

To prepare technicians to use these new powder consolidation technologies, educators will need to assure they can handle:

- Data collection and use of data;
- Modelling processes using integrated computer materials engineering (ICME);
- Differing processes for handling alloys as opposed to elemental metals;
- Powder metallurgy, including handling and storing of powders;

- Ways to obtain standardized testing of the new processes and share information about them; and
- Actual experience with using these processes in addition to computer modelling of them.

Engineers designing these new powders and consolidation techniques will need to understand:

- Isotropic properties (same if stretched in all directions) and anisotropic properties (different if stretched in different directions) of metals formed using them;
- How to measure what happens to these new materials under different conditions (e.g., how heat treatment affects materials and restricts their uses); and
- Simple cost modelling, and quality control/quality management standards.



Technology Timeline

Estimated time by which Powder Consolidation Processes will appear in production environments:

- **Mid 2019:** LIFT technology project on Powder Consolidation Processes concludes, deployment begins.
- **2021:** Powder Consolidation Processes should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness to employ new Powder Consolidation Processes, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for working with Powder Consolidation Processes are those that are likely to be already addressed in the curriculum. These competencies are listed below, along with information about where or how each is likely addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency is Likely Addressed.**

Supporting Competencies in 2-Year Community College Programs // All Supporting Competencies in 2-Year Community College Programs are likely to be covered in a Materials and/or Manufacturing Processes Course

- **Exhibit Basic Knowledge of Metal Working Processes**
- **Demonstrate a Fundamental Knowledge of Metal Materials & Alloys:**
 - Define Terminology Used in Steel Production & Forming
 - Describe How Steels are Made
 - Identify the Differences Among Various Carbon & Alloy Steels
- **Define a Typical Repertoire of Steels for General Use in Design of Components**
- **Distinguish Between & Describe the Properties of Different Manufacturing Processes Including Forming, Casting, Extrusion & Forging**
- **Identify the Limitations & Advantages of Different Heat Treatment Processes & Their Influence on Materials Selection**
- **Display Basic Understanding of What Happens to Composite Materials in the Forming Process (i.e., Phase Changes At Each Steps)**
- **Exhibit a General Knowledge of Powder Metallurgy by Describing Powder Consolidation Processes**
- **Show How to Control Production Parameters to Manage the Powder Consolidation Process**
- **Analyze the Effects of Process Control Steps in Consolidated Powder Production**

Supporting Competencies in 4-Year University Programs

- **Demonstrate Knowledge of Design Rules (Opportunities, Limitations, Typical Tolerances, etc.) for Powder Consolidation Metal Forming // CAD or Solid Modeling Course & Manufacturing Processes Course**
- **Apply the Design Rules for the Powder Consolidation Process Required to Obtain Parts with Accurate Dimensions & Tolerances**
- **Demonstrate Knowledge of the Microstructures Generated in the Powder Consolidation Process Due to Applied Pressure & Increased Temperature & Show How the Mechanical Properties are Dependent on the Microstructure // Engineering Materials Course for Mechanical Engineering Students**
- **Demonstrate Knowledge of Metallography Techniques to Characterize the Microstructures // Engineering Materials Course for Mechanical Engineering Students**
- **Conduct Metallography Technique Including: Preparing Samples Using Grinding, Polishing & Etching & Observing Samples Under Microscope to Characterize Microstructures**
- **Demonstrate How Material Properties of Metals/Alloys Change with Temperature & How This Can Affect the Part Quality // Engineering Materials Course for Mechanical Engineering Students**
- **Analyze the Effect of Pressure & Temperature on the Microstructural Composition & Mechanical Properties of Alloys & How These Changes Affect Part Quality in the Powder Consolidation Process**

Critical Competencies

Critical competencies for Powder Consolidation Processes are those that will likely require new materials, modules, or courses. These competencies are listed below, along with information about where or how each could be addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency could be Addressed.**

Critical Competencies in 2-Year Community College Programs // Materials or Manufacturing Processes Course

- **Create a Powder Material Safety Handling Procedure & Identify Critical Steps in the Procedure**
- **Analyze the Limitations & Advantages of Various Powder Consolidation Processes**
- **Define Parameters & Perform Job Planning for Machining, Milling & Grinding of Powder Consolidated Materials**



Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate		1					
	Analyze		2		3			
	Apply							
	Understand							
	Remember							

1. Create a powder material safety handling procedure and identify critical steps in the procedure.
2. Analyze the limitations and advantages of each powder consolidation process.
3. Identify considerations and job planning for machining, milling and grinding of powder consolidated materials.

Critical Competencies in 4-Year University Programs

- **Knowledge of Powder Consolidation Technologies: Hot Isostatic Pressing (HIP), Cold Isostatic Pressing (CIP), Powder Extrusion, Sintering** // Manufacturing Processes Course
- **Understanding of the Effect of Post-Processing (thermal treatments, HIP, etc.) on the Dimensional Accuracy of Parts** // Engineering Materials & Manufacturing Processes Courses
- **Capability to Design Parts & Components Suitable for Powder Consolidation Process** // Manufacturing Processes Course
- **Capability for Design & Optimization of the Consolidation Process** // Manufacturing Processes Course

Thinking & Doing Competency Map for 4-Year University Critical Competencies

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create						1	
	Evaluate					2	4	
	Analyze					3	4	
	Apply							
	Understand							
	Remember							

1. Knowledge of powder consolidation technologies.
2. Capability to design parts and components suitable for powder consolidation process.
3. Understanding of the effect of post-processing (thermal treatments, HIP, etc.) on the dimensional accuracy of parts.
4. Capability for design and optimization of the consolidation process.

AGILE SHEET METAL FABRICATION

What is Agile Sheet Metal Fabrication?

Agile Sheet Metal Fabrication is a type of robotic blacksmithing, or a way of using robots to shape sheet metal parts while forming. It differs significantly from metal stamping that involves pressing sheet metal into a shape with heavy stamping machines. Agile Sheet Metal Fabrication can be done with computer numerical control (CNC) machining, which means the process can be used to design unique parts without purchasing expensive individual stamping presses and tooling for each. Currently, the process is envisioned to be analogous to 3-D printing, using a metal stylus, directed by computer, that moves round and round in a specific pattern across sheet metal to form a part through incremental deformation without stamping. Agile sheet metal forming leverages a standard CNC machining platform to allow for the on-demand production of sheet metal parts that meet material property and design specifications in a fraction of the time and at a much lower cost than conventional techniques.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

Agile Sheet Metal Fabrication can produce custom steel parts with existing CNC equipment.

Agile Sheet Metal Fabrication is a game-changer because it allows for timely production of customized or legacy parts. Sheet metal parts are foundational for lightweight structural applications in the aerospace and automotive industries. However, the tooling required for traditional sheet-forming processes is large, heavy, and expensive, and requires a long lead-time to produce. Although this level of investment is often acceptable for high volume production, it can be crippling for low-volume production runs of custom parts or prototypes. Often, multimillion-dollar aerospace assets are grounded in need of just a few parts, and at present, only time-consuming conventional techniques for making new parts can be used. Conventional tooling is also expensive to maintain and store over long periods, making the production of spare and replacement parts challenging if the tooling is not readily available.

Agile sheet metal forming represents a paradigm shift in the production of sheet metal parts. Instead of the part geometry being defined by costly and bulky matched die sets, agile sheet forming can shift seamlessly among various designs within a single platform setup. Geometric changes can be made quickly, drastically reducing the design cycle required for a new part. Although this new technology is still in development, it will eventually be eligible for certification for civilian and military use in aircraft and vehicle applications, allowing innovation in low volume and custom production of sheet metal products.

Some challenges remain to be solved before agile sheet metal production can be widely used in manufacturing settings. Currently, the metal stamping industry has standards for part forming that account for the spring-back properties of metal that occur when metal is stamped. Sometimes, two or three iterations of a stamping die must occur in order to press metal into its final, stable shape. The incremental forming method used in Agile Sheet Metal Fabrication also must account

for spring-back. However, with this new process, the calculations for predicting spring-back are more complicated. Tool-path optimization routines are being developed for commercial deformation modelling software, however, this software does not yet account for spring-back prediction. The end goal is to have spring-back prediction incorporated in commercial production codes.

Business use of Agile Sheet Metal Fabrication is limited at present; some auto companies use it to build prototypes and the aerospace industry uses it for small non-critical parts. The process is ideal for small machine shops attempting to use existing equipment to produce small lots of custom parts with light weight metals. A small business need now exists to quickly create dimensionally precise components in aerospace (for repair and low-volume production) and in car manufacture (for repair, specialty, and legacy vehicles). As noted, this new technology is quickly emerging, but the major barriers to implementation are that commercial processes do not yet exist, including: proven design methods, simulation technology, and assured design allowables for use in failure-critical or Federal Motor Vehicle Safety Standards (FMVSS) critical applications.

In short, Agile Sheet Metal Fabrication has the potential to change the sheet metal forming industry. Traditionally, high quality production of sheet metal parts has been restricted to a select few manufacturers with the capital resources to invest in expensive forming and tooling capabilities. Agile sheet metal forming dramatically reduces the barrier-to-entry into the sheet metal forming business, allowing small machine shops with modest modeling and CNC capabilities to quickly enter the market. Basically, if you can stamp the metal, you can use this new process, regardless of whether the metal is steel, aluminum, or titanium. It also overcomes the problem of producing a deep draw, or 90-degree angle in stamping, which is generally limited to 70 degrees with a punch. Although the process is ideal for smaller parts, the production of larger parts may create local force issues which would need to be accommodated with a partial die. Also, the slower production process afforded by spiral etching does not make

Agile Sheet Metal Fabrication suitable for high-volume production.

Many metal handlers can easily adapt to Agile Sheet Metal Fabrication.

Workforce training for Agile Sheet Metal Fabrication can be done with short courses or on-the-job-training, providing the metal handler is familiar with CNC programming. As small machine shops adopt this new technology, there will need to be a slight change in shop-floor practices in terms of safe and appropriate handling of formed sheet products. Operators may need to learn best practices for handling formed sheet, moving the sheet around, and placing pallets to hold it. There will also need to be an increased involvement in the production process by the manufacturing engineer to insure proper toolpath planning, based on computer-aided engineering (CAE) analysis. Engineers will need to be trained to capture the unique stress-strain history of incrementally formed parts to guarantee final mechanical performance and geometric tolerances. Design engineers also are likely to need training in how to define the tool path for forming the metal, because design engineers today are more likely to be familiar with designing a die. Design models for Agile Sheet Metal Fabrication will naturally start in the programming-development stage and move to commercial code that can be used by engineers or computer-aided design (CAD) operators in the long run. Much of this re-training is expected to be accomplished as part of standard on-the-job-training and quality assurance practices.

Target industries for developing these new competencies will be metal machine shops. Two-year college training might include: familiarity with forging aluminum, titanium and other sheet metals; learning how to machine on a 3-axis to 5-axis machine; general robotics training; and familiarity with the effects of forming speed, as opposed to strain rates, on the product formed.

Coding under development will require employees with an M.A. or Ph.D. engineering background, familiarity with CAD and CAE processes, tool-path modelling, and finite element analysis (FEA). Machine shops now using dies can easily adapt

to tool-path modelling and include staff with CAE skills.

Agile Sheet Metal Fabrication is a process that is still largely unknown, yet its development is possibly the most advanced fabrication technology in terms of near-term commercial adaptation. The challenge is to build awareness among educational and industrial training facilities and professional societies dealing with metal processing, CNC machining, and state manufacturing centers.



Technology Timeline

Estimated time by which Agile Sheet Metal Fabrication will appear in production environments:

- **Late 2018:** LIFT technology project on Agile Sheet Metal Fabrication concludes, deployment begins.
- **2023:** Agile Sheet Metal Fabrication should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness to employ Agile Sheet Metal Fabrication, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for Agile Sheet Metal Fabrication are those that are likely already addressed in the two-year or four-year engineering/technology curriculum.

Supporting Competencies in 2-Year Community College Programs

- Operate Machining Tools
- Acquire Process Data during Incremental Forming
- Relate Critical Aspects of Mechanical Sheet Forming Operations to Part Quality, Including Clamping Pressure & Forming Speed

Supporting Competencies in 4-Year University Programs

- Correlate Metal Alloy Microstructure to Mechanical Performance
- Predict Residual Stress & Spring-back Due to Large Strain Deformation of Metal Alloys
- Apply Finite Element Analysis to High Strain Deformation Processes
- Generates Appropriate Tool Path Using Robotic Motion Control Platform

Critical Competencies

Critical competencies for Agile Sheet Metal Fabrication are those that will likely require new materials, modules, or courses.

Critical Competencies in 2-Year Community College Programs

- Recognize the Impact of Deformation Processes on Mechanical Properties of Metal Alloys
- Demonstrate Ability to Operate Machine Tools
- Write Standard Code for Controlling CNC Machine Operations

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create						3	
	Evaluate							
	Analyze			2				
	Apply							
	Understand	1						
	Remember							

1. Recognize the impact of deformation processes on mechanical properties of metal alloys.
2. Demonstrate ability to operate machine tools.
3. Write standard code for controlling CNC machine operations.

Critical Competencies in 4-Year University Programs

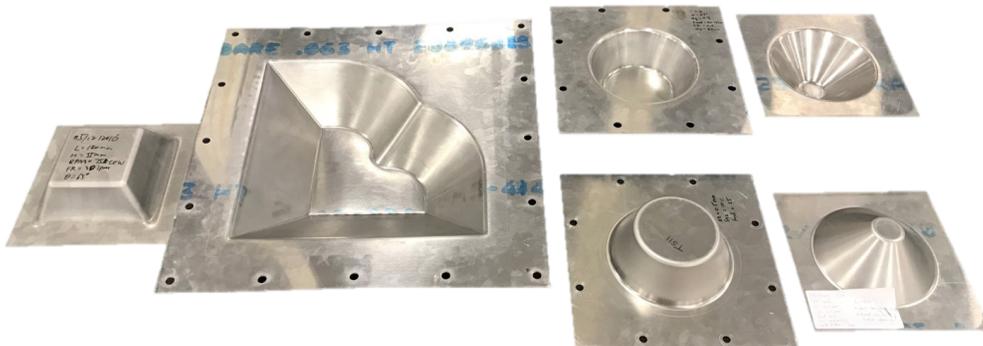
- Assess Shaping & Forming Processes Needed to Produce a Part
- Employ Fundamental Mechanical Metallurgy Concepts
- Assess the Role of Deformation & Strain Path on Microstructure & Property Evolution
- Compare Modeling of Mechanical Behavior with Experiments & Make Improvements

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING							
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation	
THINKING	Create						1	2	3
	Evaluate								
	Analyze						4		
	Apply								
	Understand								
	Remember								

1. Assess shaping and forming processes needed to produce a part.
2. Assess the role of deformation and strain path on microstructure and property evolution needed.
3. Compare modeling of mechanical behavior with experiments and makes improvements.
4. Employ fundamental mechanical metallurgy concepts.



INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING (ICME)

What is Integrated Computational Materials Engineering?

Integrated Computational Materials Engineering (ICME) defines a set of computational processes for working with many new manufacturing technologies by integrating materials information, captured in computational tools, with engineering product performance analysis and manufacturing process simulation. With ICME, sophisticated computational databases and tools are used to simulate design and performance, allowing for simulation-based identification of failures in materials, construction, and performance before costly use of materials to test and build. This new approach requires different skills and different workflow design; however, the tradeoff is considerable savings in time, materials, and cost. ICME has been adopted by Light Weight Innovations for Tomorrow (LIFT) as a cross-cutting approach to manufacturing design and construction, applicable across LIFT's six technology pillars (see <https://lift.technology/pillars/>). LIFT's vision is to provide robust, validated, and industry-ready ICME capability to LIFT partners in order to drive manufacturing innovation.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

ICME Saves Time, Money & Materials

ICME offers the ability to arrive at optimal processing conditions in manufacturing without extensive trial-and-error efforts. ICME is often referred to as a transformational approach to manufacturing because of its outsized capacity to save time and materials, as well as its requirement to change workflow processes and needed employee skills. Although not embraced widely by industry at the moment, ICME could provide a significant return on investment and serve as a powerful differentiator in a competitive marketplace. If you can build models through simulation rather than using actual materials, you can solve many problems that cause failure before actually manufacturing a product. The savings that ICME affords can be maximized when it is combined with other new manufacturing techniques, such as metamorphic manufacturing or what is sometimes referred to as a robotic blacksmithing. Here, the fields of material science and mechanical engineering are combined with powerful computational methods in a process that iteratively “corrects” the design of an actual product as it is forming. However, ICME can also be applied to save time and materials in manufacturing a product in more traditional ways, for instance, in designing and producing a die that is later used to cast a final product. In short, ICME disrupts the traditional approach of “design, build, and bust” to test a physical product or manufacturing process by accomplishing all of these tasks through simulation using computational tools. Also, manufacturers that choose to incorporate ICME approaches and have the potential to explore processing techniques in a virtual environment can possibly arrive at an optimal or novel manufacturing practice or product well in advance of their competitors.

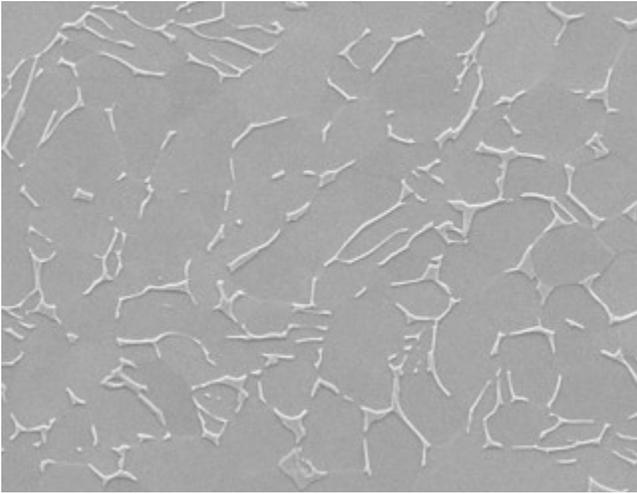
ICME Takes Increased Skill in Designing Simulations & More Teamwork

ICME is about designing and creating simulations, not designing, building a model, examining failure,

and starting again. Simulation software packages are available to assist this design process, and they are not typically expensive compared to the capital investment of physical experiments involving large manufacturing lines. However, it is important for the simulation tools to be validated with empirical measurements as the fundamental characteristics of complex manufacturing processes are being evaluated. In short, ICME requires personnel who are skilled in building or manipulating simulations as well as evaluating the validity of their results. In large manufacturing installations, the design of simulations would take place in manufacturing research and development departments; the designers must know what is feasible and how to build a model to achieve that outcome. Personnel also need to know how to manage information from large databases which are employed in the design and simulation process. For the simulation designer, sophisticated expertise in materials phenomena at several levels (e.g., atomic, granular, and micron level) as well as expertise in the physics involved with assessing each of these properties is essential. Designers need to know how materials change under various conditions (i.e., scales of behavior) and how that affects their properties (e.g., atoms, grains). Skills required to do this include:

- Understanding and manipulating mathematical models,
- Observing and analyzing materials at several levels and scales of behavior, and
- Approximating different scales of behavior as they affect the design process.

These skills allow the designer to get close to building a successful simulation more quickly. In ICME manufacturing settings, the designer must continuously adapt to changing conditions and modify design assumptions, constantly analyzing results using different computational databases. These designers/analysts often have to develop their own tools, employing skills that would be acquired at the M.A. or Ph.D. level in current curricula. Some modeling tools do exist, but must be used with caution, since different databases give different results depending on the materials analyzed.



In the educational context, ICME should be introduced as an approach in community college, university, and workplace settings:

- At the community college level, in addition to core curriculum in materials, introduce expertise in operating simulation models developed by others and moving data from materials/manufacturing databases into simulations.
- At the university level, include sophisticated expertise in materials, thermal calculations, and finite element analysis (FEA).
- For existing workers, emphasize knowledge of ICME concepts, advanced instruction in model-building, and how to develop multi-scale linkages and incorporate experiments in the simulation process.

To secure these skills, changes are required in course materials and educational approaches as well. In existing engineering programs, for instance, senior faculty may need to adopt more computational approaches to design; summer school for educators can assist with this. Likewise, students will need to adapt to the notion that you can model instead of “build and bust,” a change in perspective acquired both through education and experimentation. Also, students from one curriculum need opportunities to team with students from different but related programs so they can understand how multiple experts must work together to build and operate simulations; for example, in combined teams of materials and mechanical engineers. Ideally, “work and learn” settings provide the best opportunities

for students to acquire and apply these skills in multiple environments; for example, in the college lab, university/workplace innovation settings, and the LIFT lab.

Applying ICME techniques in the manufacturing environment requires a sea-change in how workflow is managed in traditional manufacturing environments. Processes that have been performed separately — and often sequentially — by different personnel are now performed simultaneously in the ICME environment. Teamwork is the driving factor here. In large-scale manufacturing, cross communication and workflow may involve several currently separate departments, bringing together, for instance, materials engineers who develop and test new materials with manufacturing research engineers who develop and test manufacturing processes. And it also may require adding missing expertise in simulation model development. Changes such as these will often initiate from below as workers quickly recognize the need to have new skills in the process of model development. However, for change to stick it must be supported by management. Workers and management must be prepared for this cultural shift and increased cross-department cooperation. Companies need to:

- Recognize the need for change,
- Change workflow as required, and
- Hire the necessary experts to develop materials models.

Larger research institutes and companies will need employees who can develop the fundamental framework for application-specific ICME models and have extensive knowledge of mathematical models, data regression, and multi-scale phenomenological modeling. In smaller operations, workers may not be developing simulation models as this is a task suited for larger research and development operations. However, small manufacturing companies may incorporate ICME through applying and manipulating existing simulations, a task that also requires teamwork among skilled workers in different domains.

To sum up, ICME is a game-changer for manufacturing, eliminating the need to “build and bust” through applying computational models to

simulate performance in product development. At the same time, industries traditionally dedicated to physical experiment may balk at this approach, exhibiting an inherent distrust of simulations. As the ICME models are being developed, empirical validation will be required. ICME workers will need to be familiar not only with the capabilities of simulation packages, but also their limitations to accurately represent physical phenomena. A good balance between real world experience and knowledge of fundamental principles will guide productive efforts. To prepare students for the ICME world and adapt current workplaces to the ICME environment, schools and companies need to:

- Know ICME exists and educate their constituents;
- Understand and acquire expertise in materials properties and behaviors; and
- Embrace ICME as a team sport, rather than a set of skills present in an individual employee or single department.



Technology Timeline

Estimated time by which ICME will appear in production environments:

- **2018 & Continuing:** ICME project work is ongoing at LIFT.
- **2018:** ICME is currently being used in production environments. Large growth is expected between 2018 and 2023.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness for ICME, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for ICME are those that are likely already addressed in the two-year or four-year engineering/technology curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold //** Course(s) Where Competency is Likely Addressed

Supporting Competencies in 2-Year Community College Programs

- **Recognize the Relationships among Manufacturing Processes, Material Microstructure, & Material Performance //** Materials Science Course
- **Identify Key Material Properties that Will Be Affected by Various Manufacturing Processes //** Manufacturing Technology Course
- **Demonstrate Proficiency with Standard Manufacturing Process Operations & Identify Primary Processing Parameters //** Manufacturing Technology Course

Supporting Competencies in 4-Year University Programs

- **Describe the Foundational Physics-Based Models for Major Manufacturing Processes //** Manufacturing of Materials Course
- **Design Experiments to Validate Model Predictions //** Experimental Methods Course
- **Express a Mathematical Model of a Manufacturing Process in a Common Programming Language //** Programming Course
- **Relate Metallurgy & Microstructure to Product/Part Quality & Performance //** Materials Science Course

Critical Competencies

Critical competencies for ICME are those that will likely require new materials, modules, or courses. These competencies are listed on the following page, along with information about where or how each could be addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency Could Be Addressed**

Critical Competencies in 2-Year Community College Programs

- **Understand the Foundations of ICME Models as They Are Reflected in Principles Taught in Introductory Physics, Chemistry, & Material Science // All Intro Courses**
- **Manipulate Database Information to Supply & Retrieve Relevant Production Data about Alloys, Processing History, Quality, & Characterization to further Inform the Development of Modeling Tools // Computer Literacy Course**
- **Understand the Role of ICME Modeling in Guiding Process Improvement // Manufacturing Technology Course**

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze							
	Apply							
	Understand							
	Remember							

1. Understand the foundations of ICME models as they are reflected in principles taught in introductory physics, chemistry, & material science.
2. Understand the role of ICME modeling in guiding process improvement.
3. Manipulates database information to supply and retrieve relevant production data about alloys, processing history, quality, and characterization to further inform the development of the modeling tools.

Critical Competencies in 4-Year University Programs

- **Demonstrate Competency in Big Data Analytics & Visualization Techniques // Programming Courses**
- **Utilize Model-Based Simulation Packages to Achieve Predictive Analysis & Optimize Processing of Materials // Graduate Manufacturing Course**
- **Represent Multi-Scale Physics-Based Phenomena in a Computational Framework // Graduate Material Science**

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create					1		
	Evaluate					2		
	Analyze				3			
	Apply							
	Understand							
	Remember							

1. Represent multi-scale physics-based phenomena in a computational framework.
2. Utilize model-based simulation packages to achieve predictive analysis and optimize processing of materials.
3. Demonstrate competency in big data analytics and visualization techniques.

METAMORPHIC MANUFACTURING

What is Metamorphic Manufacturing?

Metamorphic Manufacturing is a metal working process by which a machine bends and squeezes metal into shape at varied temperatures and with varied deformation that can improve the material properties of metal. Often referred to as “robotic blacksmithing,” Metamorphic Manufacturing is a process poised for disruptive growth in deformation processing of lightweight metallic parts. Many of the core elements involved in achieving this malleability within manufacturing processes are beginning to mature; however, the complete vision for Metamorphic Manufacturing has not been fully realized and the technologies have not yet been synthesized into a cohesive whole. Metamorphic Manufacturing is envisioned to allow for agile, rapid, and affordable production of small volumes of high-quality metallic parts, with a low environmental footprint, while reducing the need for expensive tooling and reducing fabrication time.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

Metamorphic Manufacturing revolutionizes the production of lightweight materials because it advances the ability to take advantage of topology optimization to make better shapes, and also allows for better material properties at the micro level. In addition to changing manufacturing materials and processes, Metamorphic Manufacturing will likely also change the lightweight materials manufacturing workplace, where this process is in use, by requiring technicians that are more adept at experimentation, adaptation, and “sensing on the fly.”

Metamorphic Manufacturing promises better shaping and better material properties.

Metamorphic Manufacturing will enable the rapid, agile fabrication of lightweight metallic parts for structural applications by controlled deformation processing and, at the same time, eliminate the need for expensive tooling. Metamorphic Manufacturing takes advantage of topology optimization, a mathematical process for minimizing material use and maximizing part strength, to overcome some of the manufacturing difficulties. According to Glenn Daehn, Fontana Professor of Materials Science Engineering at Ohio State University, it is important in lightweight materials manufacturing that the shape and properties of parts be optimal. There are difficulties associated with manufacturing optimal shapes with optimal properties, however.

Topology optimization is also possible through other manufacturing processes such as CNC (Computer Numerical Control) or subtractive manufacturing where the movement of factory machinery such as lathes and mills are controlled by a computer program, as well as additive manufacturing, or 3D printing. But these other manufacturing processes are less-than-optimal for other reasons: CNC creates a lot of scrap material, and additive manufacturing is time- and energy-intensive.

A knife is a good example of a manufactured part that can benefit from the better shaping and

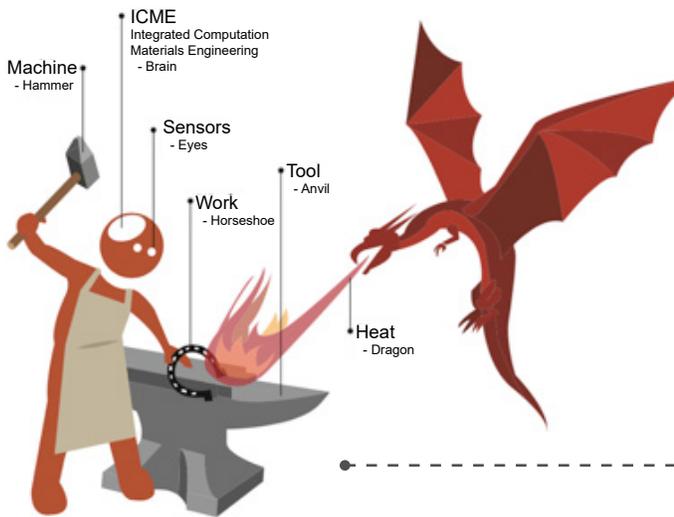
better properties made possible by Metamorphic Manufacturing. With a knife, you need to be able to manufacture a sharp edge which will have a different structure at the micromaterial level than the back edge of the knife. Metamorphic Manufacturing makes it easier to manufacture these kinds of parts.

Furthermore, Metamorphic Manufacturing will allow for parts to be “made-to-order” on an as-needed basis. It will provide new opportunities for small and medium-sized businesses to manufacture parts by this new method with existing machine tools. However, workers will require training to use machine tools for this purpose.

Metamorphic Manufacturing asks technicians to “sense on the fly.”

Technicians engaged in Metamorphic Manufacturing must understand how sophisticated sensing programs control the forming process. On the kinds of skills needed for Metamorphic Manufacturing, Glenn Daehn notes: “When I was young, engineers knew how any process worked, but today’s manufacturing equipment is so complex that it’s not possible to be knowledgeable about every process.” Because of this, both technicians and engineers working in manufacturing today need to be able figure out how to get information from different fields. But even these kinds of skills will not be up to the complexity of advanced manufacturing. The ability of workers to bring together disparate technical information will need to be complemented by artificial intelligence (A.I.) which, in the case of Metamorphic Manufacturing, engages a goal-seeking shaping routine during manufacturing. When the kinds of shaping that can be done by Metamorphic Manufacturing was undertaken by a blacksmith (producing much less complicated shapes), the blacksmith would have gone through a similar goal-seeking routine, checking as he goes how his product measures up to the ideal shape he is after.

In Metamorphic Manufacturing, the A.I. does the goal-seeking thinking, and the technicians and engineers need to be able to shape the A.I. routine



Metamorphic Manufacturing, also called “robotic blacksmithing,” uses robots to do the work that blacksmiths used to do.

and assure its accuracy as the manufacturing process proceeds. One method of checking is closed-loop control, in which the manufacturing machinery does the “checking work” by regularly comparing the actual condition to the desired condition. A.I. is ideal for exerting this kind of control, but both the machines and the humans operating them need to be able to “sense on the fly” how the process is going. To ensure accurate sensing, validation and verification protocols must be present so that components made with these new processes can be certified for safety critical use, for example, in aircraft.

Metamorphic Manufacturing may require a culture change on the production floor. This way of manufacturing represents, to some degree, experimental work. Developing the kinds of skills needed for this work demands different emphasis on the student work to prepare technicians and engineers than educators now generally give. For example, more hands-on labs are likely to be required than can currently fit into many student programs. A challenge with technical education is that it must frequently focus on categorizing things into specific silos of excellence or standards. But with processes like Metamorphic Manufacturing, technicians and engineers need to be able to be a little more adventurous and willing to synthesize their learning as their work processes proceed.

While Metamorphic Manufacturing requires many competencies related to the technical aspects of shaping, some of the most critical competencies will be around skills like “innovation” or “learning to learn.” Students and the incumbent workforce

will need to know how to use machine tools for Metamorphic Manufacturing; they must understand tool path design and have metalworking skills. Technicians and engineers need to know when to ask “does this make sense?” Daehn noted that he has frequently found that some of the best engineers come from a farming background because when you’re a farmer, you need to be able to fix things, and you get very comfortable tackling such challenges. Developing these “hands on” skills will surely present new challenges to educators preparing students to work with processes like Metamorphic Manufacturing.



Technology Timeline

Estimated time by which Metamorphic Manufacturing will appear in production environments:

- **2018:** Some commercial applications and some limited deployment of Metamorphic Manufacturing in production environments.
- **Late 2019:** LIFT technology project on Metamorphic Manufacturing concludes, deployment begins.
- **2028:** Metamorphic Manufacturing should reach full potential and be widely deployed in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

Readiness for Metamorphic Manufacturing requires colleges, universities, and employers to consider the competencies that will be required.

Supporting Competencies

Supporting competencies for Metamorphic Manufacturing are those that are likely already addressed in the curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency is Likely Addressed**

Supporting Competencies in 2-Year Community College Programs

- **Demonstrate General Understanding of Material Mechanical Properties // Materials Science Course**
- **Apply Metal Forging & Forming Processes // Manufacturing Processes Course**
- **Use Tooling Equipment & Demonstrate How to Schedule and Perform Maintenance // Manufacturing Processes or Maintenance Management Courses**
- **Recognize Process & Product Defects that Reduce Quality // Statistical Process Control or Quality Management Courses**

Supporting Competencies in 4-Year University Programs

- **Use Robotics & Computer-Directed Controls in Manufacturing Settings // Robotics & Automation Courses**
- **Employ Data Acquisition Systems, Sensors & Diagnostics for Controlling Manufacturing Processes // Robotics & Automation or Manufacturing Process Control Courses**
- **Use Computer-Aided Design & Computer Programming for Digital Design/Manufacturing // Manufacturing Processes or Computer-Aided Manufacturing Courses**
- **Use Tooling Equipment & Schedule/Perform Maintenance // Manufacturing Processes Course**

Critical Competencies

Critical competencies for Metamorphic Manufacturing are those that will likely require new materials, modules, or courses. These competencies are listed below, along with information about where or how each could be addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency Could Be Addressed**

Critical Competencies in 2-Year Community College Programs

- **Recognize How Metalworking Influences Material Properties // New Materials or Modules in Materials Science Course**
- **Use Robotics & Controls in Manufacturing Processes // New Materials or Modules in Robotics & Automation or Manufacturing Process Control Courses**
- **Employ Data Acquisition Systems, Sensors & Diagnostics for Controlling Manufacturing Processes // New Materials or Modules in Robotics & Automation or Manufacturing Process Control Courses**
- **Use Computer-Aided Design & Apply Computer Programming for Digital Design & Digital Manufacturing // New Materials or Modules in Manufacturing Processes or Computer-Aided Manufacturing Courses**
- **Operate Machine Tools & Develop Tool Paths // New Materials or Modules in Manufacturing Processes Course**

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

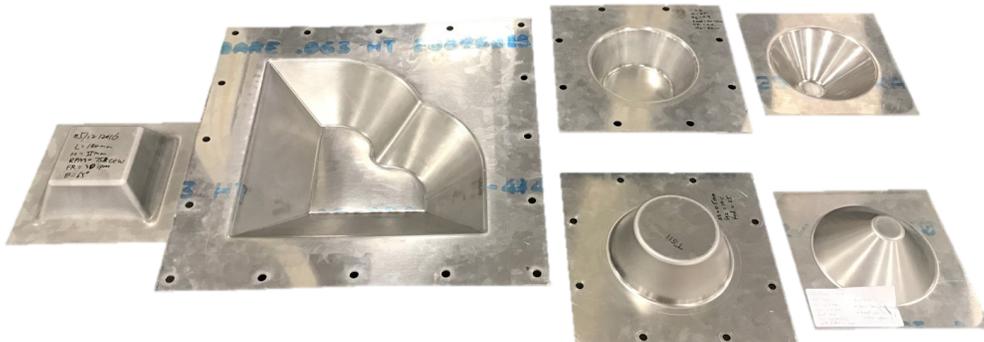
Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create						5	
	Evaluate			2				
	Analyze			3				
	Apply			4				
	Understand	1						
	Remember	1						

1. Recognize how metalworking influences material properties.
2. Use computer-aided design and apply computer programming for digital design and digital manufacturing.
3. Employ data acquisition systems and sensors and diagnostics for controlling manufacturing processes.
4. Use robotics and controls in manufacturing processes.
5. Operate machine tools and develop tool paths.

Critical Competencies in 4-Year University Programs

- **Demonstrate How Materials Processing, Structure, Properties, & Performance Relate to One Another //** New Materials or Modules in Materials Science Course
- **Recommend Metalworking Processes Based On a Fundamental Understanding of Metallurgical & Materials Engineering //** New Materials or Modules in Materials Science Course and/or Manufacturing Processes Course
- **Evaluate Materials Deformation Processing by Modeling & Simulation //** New Materials or Modules in Materials Science Course
- **Design & Recommend Tool Paths //** New Materials or Modules in Materials Science Course
- **Recommend Forging & Forming Processes for Specific Applications //** New Materials or Modules in Manufacturing Processes Course



Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING							
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation	
THINKING	Create						1	4	3
	Evaluate								
	Analyze								
	Apply						2		5
	Understand								
	Remember								

1. Recommend metalworking processes based upon fundamental understanding of metallurgical and materials engineering.
2. Demonstrate how materials processing, structure, properties, and performance relate to one another.
3. Recommend forging and forming processes for specific applications.
4. Design and recommend tool paths.
5. Evaluate Materials deformation processing by modeling and simulation.

FRICION STIR EXTRUSION

What is Friction Stir Extrusion?

Friction Stir Extrusion is one of several friction-stir technologies being developed by Lightweight Innovations for Tomorrow (LIFT) to create more applications for lightweight metals in manufacturing. All these new stir technologies involve generating friction heat to soften metal below the melting process to: weld parts, as commonly done in ship-building; spot weld components, as done in automobile manufacturing; or extrude metals, that is, force metals through a die. Friction Stir Extrusion creates seamless lengths of material with a near net shape. An example of the benefits this process affords is found through an improvement upon a process called hydroforming which engages high pressure fluid to work material into a die, because friction-stir-extruded materials allow for the use of higher-strength aluminum alloys in the hydroforming process. The stir technology makes these alloys more resistant to cracking that can occur during hydroforming and improves their granular structure. This advance means that manufacturers can produce lighter, higher-strength parts with a smooth finish that has the added benefit of being corrosion resistant. The transportation industry will realize the benefits of this technology because it can reduce vehicle mass, promote more efficient builds, and increase component life. Friction Stir Extrusion will also benefit the heat exchanger industry by improving the life of process tubing in marine applications.

Friction Stir Extrusion Allows Manufacturers to Use Low-Cost Aluminum Alloys to Create Higher-Strength, Lightweight Seamless Tubing that Resists Corrosion

The stirring action involved in the friction-stir extrusion process yields improved formability and a higher strength-to-weight ratio within the formed material. With these properties, manufacturers can use Friction Stir Extrusion to create thinner and lighter tubing that also meets higher strength requirements. Furthermore, the stirring technology produces a higher-grained structure in the formed metal—making it possible for aluminum alloys to have the corrosion resistant, smooth lacquer finish that is naturally obtained by using titanium; a far more expensive material.

The requirement for improved strength and versatility in hydroformed parts is increasing. Hydroformed aluminum tubes are now typically made from alloys that are not high-strength. As noted earlier, a technology like Friction Stir Extrusion that accommodates the use of higher-strength aluminum alloys could provide products with increased strength-to-weight ratio and improved corrosion resistance. Such a technology would also help achieve a substantial decrease in lifecycle cost of hydroformed aluminum components.

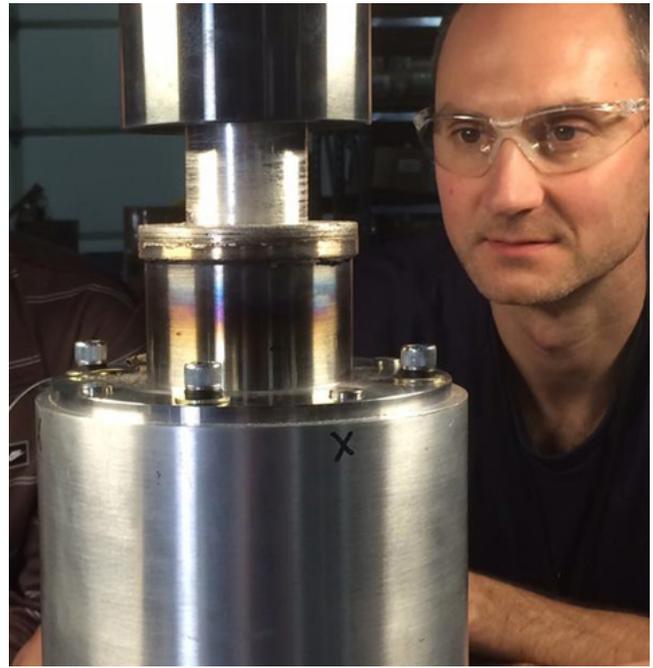
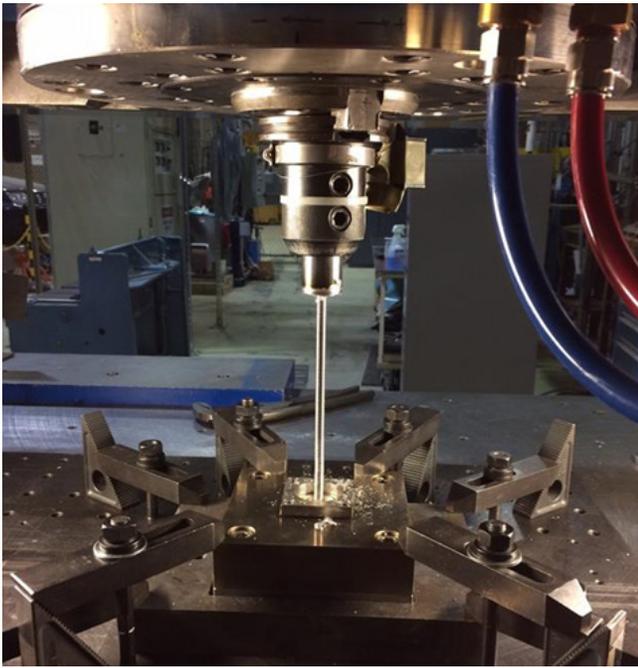
Several industries that currently require high-strength, corrosion-resistant lightweight tubing can benefit from producing components by Friction Stir Extrusion. In the automobile industry, lighter tubing that is more malleable can be used for more functions, with the added value of improving fuel economy and range. Likewise, the benefit of corrosion resistance also means less maintenance and longer life. In marine applications such as Ocean Thermal Energy Conversion (OTEC), where corrosion resistance is paramount, friction-stir-extruded aluminum tubing could replace expensive titanium tubing in heat exchangers.

Friction-stir extrusion processes will require engineers to have or design new “guiding

equations” to control granular structures during the metal forming process, and technicians to apply these new guidelines in a computer-controlled forming process. Because this new technology combines features of friction stir and extrusion metal-forming methods, new equipment and facilities as well as education and additional training of the current workforce is necessary to implement it. In today’s metal forming shops, heat-transfer based processes are not currently used. In the “friction stir” experimental setting, special cameras are used to guide the metal-forming process and evaluate grain-structure during production. Equations to guide the evaluation of grain structure and refinement are not yet available to industry. At present, verification processes are dependent on the experience of an engineer monitoring the process and making corrections through trial and error.

Friction Stir Extrusion processes and the verification equations for assuring process consistency must be designed by engineers. Until a set of such codes is widely available, it is likely to be engineers who train technicians how to guide the processes at manufacturing production sites. Eventually, as more specifications reach industry, technicians will need to know how to monitor machines that computer-control the forming process using coded specifications.

To advance use of Friction Stir Extrusion in design, engineers will need to be well-versed in FEA (finite element analysis), metal deformation concepts, heat transfer processes, and the design of simulations. Technicians who control this technology on the shop floor should have a basic knowledge of statistics for data analysis and understand thermal imaging and thermal sensing data. Educators will need to include instruction on friction stir and extrusion in regular engineering courses. Students also should acquire a basic understanding of heat transfer processes and quality assurance techniques for evaluating the metal forming process. Case studies would help students realize the benefits of this technology. In the workplace, flexibility in adopting new manufacturing techniques to produce parts with high strength-to-weight ratios will be required.



Also, additional skills may be required of workers for certain applications; for instance, workers may need to have knowledge of corrosion testing for marine applications. In summary, the skills listed below have a bearing on developing and using this new technology:

- Application of FEA (finite element analysis),
- Use of CAD engineering drawings,
- Knowledge of heat transfer and its role in simulations,
- General understanding of extrusion processes,
- Use of analytics to monitor processes, and
- Understanding of tools for process optimization.



Technology Timeline

Estimated time by which Friction Stir Extrusion will appear in production environments:

- **Mid 2019:** LIFT technology project on Friction Stir Extrusion concludes, deployment begins.
- **2020 — 2022:** Friction Stir Extrusion should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness for working with Friction Stir Extrusion, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for Friction Stir Extrusion are those that are likely already addressed in the two-year or four-year engineering/technology curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency is Likely Addressed**

Supporting Competencies in 2-Year Community College Programs

- **Understand Aluminum Alloy Properties // Metal Materials Course**
- **Understand Yield & Plastic Phenomenon In Metal Extrusion // Materials Science & Strength of Materials Courses**
- **Develop Quality Control Procedures // Quality Control Course**
- **Understand Heat Generation & Dissipation in Metal Extrusion // Thermodynamics Course**

Supporting Competencies in 4-Year University Programs

- **Develop & Design Tools for Extrusion with Friction Stir Welding Function // Metal Forming Processes Course**
- **Understand Heat Generation & Dissipation in Metal Extrusion // Thermodynamics Courses**
- **Gain Comprehensive Knowledge of Manufacturing Processes // General Manufacturing Processes Course**
- **Understand Metal Phase Transformations // Metal Materials Course**

Critical Competencies

Critical competencies for Friction Stir Extrusion are those that will likely require educators to develop new materials, modules, or courses.

Critical Competencies in 2-Year Community College Programs

- **Employ Features of Extrusion & Friction Stir Welding in New Processes**
- **Understand the Basic Corrosion Process**
- **Practice the Extrusion Hydroforming Process**
- **Apply Knowledge of Mechanical & Metallurgical Properties in Manufacturing Processes**

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create				1			
	Evaluate				1			
	Analyze			2		3		
	Apply			2		3		
	Understand			2		3		
	Remember	4						

1. Practice the extrusion hydroforming process.
2. Employ features of extrusion and friction stir welding in new processes.
3. Apply knowledge of mechanical and metallurgical properties in manufacturing processes.
4. Understand the basic corrosion process.

Critical Competencies in 4-Year University Programs

- Analyze Solid-State Joining Processes
- Analyze Microstructural & Grain Size Characterization
- Understand & Practice Testing Procedures of Joining

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate					1		
	Analyze			2		3		
	Apply			2		3		
	Understand			2		3		
	Remember			2		3		

1. Analyze microstructural and grain size characterization.
2. Analyze solid-state joining processes.
3. Understand and practice testing procedures of joining.

DISTORTION CONTROL

What is Distortion Control?

Distortion Control is the elimination of factors that produce distortion in the product, materials, or process in manufacturing applications. Distortion Control in heavy manufacturing involves controlling factors that cause the following conditions: longitudinal shrinkage, transverse shrinkage, angular distortion, bowing, buckling, twisting, or bending.¹ In manufacturing settings, Distortion Control is a system property and must follow a systems-oriented approach.² Distortion Control in lightweight manufacturing is particularly important because lightweighting often involves joining many different types of materials, making the joining process specific to the properties of each and their changing dimensions and performance in the manufacturing process. Also, joining or welding techniques traditionally used in the manufacture of thick steel, which has been used in shipbuilding, often cause distortion in the lightweighting environment.

Lightweight Innovations For Tomorrow (LIFT, www.lift.technology) has conducted a project focused on developing solutions to prevent distortion resulting from the joining and assembly of lightweight steel structures. The project focuses on the integration and refinement of a suite of tools and recommendations for shop floor workers, designers, and production engineers to use during component material selection, design, production, and assembly stages.

¹ "Challenges in Heavy Manufacturing," Part I, EWI website training

² "Distortion Engineering," B. Clausen, T. Lubben, and R. Rentsch, Stiftung Institut für Werkstofftechnik, Copyright # 2014, ASM International, all rights reserved, asminternational.org.

Better Distortion Control Techniques Save Costs in Lightweight Manufacturing

Lightweight design can involve greater variation in the materials used to produce a product, which also creates greater variation in the processes used to construct a final product and increases the number of factors influencing Distortion Control. As reported by Hunting Ingalls Industries and the University of Michigan in their abstract for LIFT on joining techniques in lightweighting, “Distortion Control for complex structural assemblies in production environments remains largely empirical and experience-based.” This team notes that:

- Effective distortion modeling techniques for complex structures must focus on what contributes to distortion on a structural level because doing so contributes to computational efficiency when designing practical applications;
- Microstructure changes and other behaviors during welding contribute to local through-wall (i.e., a wall that requires venting) self-equilibrating stress states (i.e., residual stress factors) and have little effect on structural distortions that are global structural phenomena; and
- Without effectively separating local from global effects, current distortion modeling methods are too complex to implement for practical applications.

The Hunting Ingalls/University of Michigan team concludes that better distortion prediction and better Distortion Control processes will significantly improve production of first-time quality products, and result in less rework and increased productivity in constructing lightweight structural components. The benefits of these developments are: improved shop-floor operating procedures, simplified distortion-estimation equations that engineers can use to optimize designs for production, and finite-element-based distortion-analysis procedures for

additional engineering design and manufacturing analyses.

A broader way of thinking about Distortion Control is understanding its relationship to dimensional accuracy. Since the 1930s shipyards have been dealing with managing distortion to achieve dimensional accuracy in the joining of heavy, thick parts (e.g., 0.5-inch plate). Today’s problem is how to make the production process friendlier to lightweight product design. Some of the greatest advances in mitigating distortion in lightweight manufacturing have been made by the shipbuilding industry; automotive manufacturers are also making progress on this front.

That being said, Distortion Control in lightweighting applications has remained a top concern for modern shipbuilding: “The trend in both military and commercial shipbuilding is the increased use of thin steel to reduce weight and improve performance. . . . Welding practices developed for thicker plate can result in significant out-of-plane distortion when applied to thin-plate structures.” To fabricate large-scale, lightweight steel structures needed for shipbuilding, distortion must be controlled and minimized during joining and assembly. Distortion of an individual component increases the cost and cycle time of production and the assembly process, and the dimensional geometry and structural integrity of a final assembly is affected by individual distorted components: “Buckling distortion of complex lightweight panels has resulted in a significant negative effect on manufacturing cost and production throughput, limiting the shipbuilders’ ability to produce innovative ship designs.”³

Product design engineers can solve most distortion problems using statistical controls in the manufacturing process; however, designers cannot rely on traditional methods to account for material and product variation during manufacturing. Designers both need to apply statistical controls and understand the physics of different materials when they are combined. They need to solve the problem of designing and combining materials at the piece level, as

³ “Practical welding techniques to minimize distortion in lightweight ship structures,” C. Conrardy, T. D. Huang, D. Harwig, P. Dong, L. Kvidahl, N. Evans, A. Treaster, *Journal of Ship Production*, 22.4 [November 2006], abstract

explained by LIFT-affiliated researcher Pingsha Dong. New manufacturing processes, such as those that incorporate integrated computational materials engineering (ICME), are heavily weighted toward the use of statistical models in product design which may not be able to address entirely the physical complexities involved in Distortion Control for lightweighting. For instance, some computer programs and their corresponding databases are not sophisticated enough to account for the physical interactions of variable joined parts in the manufacturing process. Hence, achieving an effective and buildable design through simulation alone, that is, without constructing a physical prototype, may be problematic.

Another technical problem in mitigating distortion when lightweighting is the tendency to “optimize” design, that is to strive for the most efficient and least costly process and final product. An optimal design might work well on paper, as it were, but ultimately fail as a physical process or product. To solve this problem, more quantitative tools are needed that interrelate optimizing design and manufacturing feasibility, and greater attention needs to be paid to manufacturing feasibility in design creation.

Bring Design & Build Together to Solve Distortion Control

Design engineers need to learn from shop floor technicians what happens to a design once a manufacturing process has been standardized. If designers can't see what happens to a product on the floor, their designs may miss distortion factors. As noted earlier, simulations alone can't account for this. Currently, the automotive industry is doing a better job of bringing design and build departments together; their interest in reducing costs due to failed design has been the driver here. In the ship-building industry, where federal contracts dominate, the motivation for shop floor personnel to be proactive in influencing design has not been there; in short, contracts that calculate payback for time and materials do not reward efficiency. Awarding bonuses for delivering effective products ahead of schedule might correct this problem. Another problem causing inefficiencies and cost-overruns is the consumer attempt to optimize the product after



Technology Timeline

Estimated time by which Distortion Control will appear in production environments:

- **Late 2018:** LIFT technology project on Distortion Control concludes, deployment begins.
- **2023:** Distortion Control technology should begin showing up in production environments.

the final design has been standardized, which can lead to costly re-design; in short, the desire to optimize design must be weighed against the need to standardize processes and parts.

Controlling and minimizing distortion during joining and assembly will require new material handling and processing procedures and work controls (administrative and engineering). Distortion Control needs to be addressed, starting with the engineering design and moving through component production to the assembly process. Process mapping and planning tools may help to identify important variables that, if sufficiently addressed, will help to streamline practices, standardized work procedures, and improve product quality. To address Distortion Control in lightweight design and manufacturing a few key changes are necessary in the workplace:

- Highlight the challenges of light-weighting design and the need to link design and manufacturing performance;
- Recognize that workers from different disciplines will carry different perspectives on the importance of optimization and standardization in design and bring them together if possible; and
- Allow for differences in small-scale manufacturing that emphasize optimization and customization and know the effects of these changes on standard design.

Principles of Distortion Control should be emphasized in regular engineering courses;

Distortion Control must be factored in instruction about engineering design, component production, and the manufacturing assembly process. To prepare the workforce for the new parameters affecting Distortion Control in lightweight design and manufacture, educators and managers should take advantage of these professional opportunities:

- Courses offered by researchers from LIFT, as well as LIFT website materials; and
- Training offered by professional societies such as the American Welding Institute (AWI), the Navy Shipyard Research Program (NSRP), and the Automobile Steel Partnership.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness for achieving Distortion Control in lightweighting, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for mastering Distortion Control are those that are likely already addressed in the two-year or four-year engineering/technology curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency is Likely Addressed**

Supporting Competencies in 2-Year Community College Programs

- **Review Standardized Work Procedures // Metal Material Property and/or Manufacturing Processes Courses**
- **Describe Material & Property Changes During Joining Processes // Welding Processes or Quality Control on Welded Distortion Courses**

Supporting Competencies in 4-Year University Programs

- **Identify Potential Sources of Distortion // Material Property & Manufacturing Process Courses**
- **Relate Assembly Variation to Geometry Changes & Tolerances // Welding Process, Fixturing, Part Distortion Prediction & Simulation Courses**

Critical Competencies

Critical competencies for mastering Distortion Control are those that will likely require educators to develop new materials, modules, or courses.

Critical Competencies in 2-Year Community College Programs

- **Employ Rules-Based Shop Floor Procedures**
- **Analyze Distortion Control in Joining & Assembly**
- **Employ Process Mapping & Planning Tools to Identify & Mitigate Waste**
- **Practice Joining Processes, Data Acquisition, Standard Operating Procedures (SOPs) & Document Work**



Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze				1			
	Apply			2	3			
	Understand							
	Remember				4			

1. Analyze Distortion Control in joining and assembly.
2. Employ rules-based shop floor procedures.
3. Practice joining processes, data acquisition, SOPs and document work.
4. Employ process mapping and planning tools to identify and mitigate waste.

Critical Competencies in 4-Year University Programs

- Develop Quality Control Procedures
- Recommend Joining & Assembly Processes
- Develop Standard Operating & Work Control Documentation Procedures
- Predict Distortion by Modeling & Simulation
- Relate Distortion Sources to Joining & Assembly Processes

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create						1	3
	Evaluate							4
	Analyze						2	
	Apply							5
	Understand							
	Remember							

1. Develop SOPs and work control documentation procedures.
2. Develop quality control procedures.
3. Recommend joining and assembly processes.
4. Relate distortion sources to joining and assembly processes.
5. Predict distortion by modeling and simulation.

REFILL FRICTION-STIR SPOT WELDING

What is Refill Friction-Stir Spot Welding?

Refill Friction-Stir Spot Welding (rFSSW) is a developing technology that builds on the traditional Friction-Stir welding (FSW) process to join metals without changing their surface geometry. FSW is a metal joining process that uses a tool “to join two facing workpieces without melting the workpiece metal.” The heat generated by “friction between the rotating tool and the workpiece metal leads to a softened region near the FSW tool” (Wikipedia). Friction-Stir spot welds (FSSW) have many of the same solid-state benefits of traditional Friction-Stir welds (FSW) but can be localized and therefore be more readily implemented into robotic assembly systems (LIFT, Technology Project Abstract, March 2, 2018). FSSW avoids the use of additional fasteners, such as rivets, to join metal pieces, but currently has limited applications because use of the welding tool leaves an imprint/depression in the joined metals. This imprint effectively changes the surface geometry, thus eliminating potential uses where an un-marred surface is required.

Refill Friction-Stir Spot Welding (rFSSW) is a new technique being explored in a project conducted by LIFT (Lightweight Innovations for Tomorrow) that overcomes the disadvantages of FSW and FSSW described above. rFSSW uses a tool to join parts that softens the metal of both parts at the joint and rotates to stir the parts together. This tooling process eliminates the problem of imprints left by the spot welding tool and effectively restores the surface geometry of the joined metals. Refill Friction-Stir Spot Welding also allows for the development of pins that can meet the material, stress, and geometry characteristics afforded by rivets. This LIFT project is exploring the use of pins to mount aircraft “skin” (the outer surface of most of the wings and fuselage) to the airframe structure.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

Refill Friction-Stir Spot Welding Saves the Costs of Installing Rivets to Join Dissimilar Metals

Refill Friction-Stir Spot Welding (rFSSW) holds great promise because it allows for the joining of dissimilar metal pieces to create a smooth surface without using additional parts, such as rivets. This advance not only saves the time involved with joining another metal to the target pieces, but also saves the expense and weight involved in adding and installing another part to the joined structure. It is anticipated that rFSSW will permit the joining of sheet metal to airframe structures at low cost and with higher throughput.

Conventional Friction-Stir welding (FSW) has been done with titanium using tools made of refractory metals, that is, “metals that are extraordinarily resistant to heat and wear” (Wikipedia). Conventional Friction-Stir spot welding (FSSW) has had the advantage of joining metals without introducing high temperatures or using rivets. Using rivets to join metal components can drastically increase cost, depending on the complexity and stress requirements of the part; both the rivets and installation involve cost increases. FSSW eliminates these costs, however, FSSW also leaves a hole where the drilling tool has stirred out metal to create the joint. The refill process fills in the imprint of the material stirred out. Hence, using rFSSW for joining can potentially compete with rivets because rFSSW does not change the surface geometry of the joined pieces. Once the rFSSW process has been certified for specific applications, it potentially can replace rivet joining saving significant time, money, and weight in industries such as aerospace, which now uses millions of rivets for joining.

Quality Control in Design, Specification Standards, Process Monitoring is a Must

Success with rFSSW requires a workplace culture that adheres to best practices for: design and assembly, specification standards,

process control, standardized work procedures, workflow documentation, and quality. Specific challenges yet to be met in introducing rFSSW in the aerospace industry and in other applications where end-product performance and safety are paramount include:

- Assuring that the extrusion process of producing the refill creates a good bond and doesn't simply fill the hole left by the welding tool;
- Creating a database of process parameters and mechanical properties for joining various lightweight metals, which is a step toward process certification; and
- Achieving certification of the process for specific applications; in the aerospace industry, Federal Aviation Administration (FAA) approval is also required.

Not surprisingly, aerospace leans heavily on time-proven legacy manufacturing processes. Approval of new techniques such as rFSSW takes time, so adoption of rFSSW in this industry is likely several years out.

As a niche technology, rFSSW can be taught in seminars as an add-on to training in traditional spot welding techniques. Since rFSSW is currently far from certification, educators now should concentrate on making students aware of this new process and its differences from conventional welding techniques. Key concepts to be emphasized include:

- Basics of lightweight materials and welding/joining processes;
- Relevant lightweight manufacturing processes;
- Lightweight design concepts and related tools;
- Relationships between material properties and manufacturing processes;
- Awareness of rFSSW as a new tool for incorporating lightweight technologies;
- Differences between rFSSW and

conventional spot welding methods;

- Familiarity with conventional stir welding technology, which is basic to this new method;
- Typical applications of rFSSW for titanium, aluminum, magnesium, and high-strength steel; and
- Performance and validation methods.

Once rFSSW is certified, it could be taught along with a suite of skills that address lightweight-materials joining processes and Friction-Stir welding processes in general. Tool operators would also need to learn quality control specifications.



Technology Timeline

Estimated time by which Refill Friction-Stir Spot Welding will appear in production environments:

- **Late 2018:** LIFT technology project on Refill Friction-Stir Spot Welding concludes, deployment begins.
- **2019 — 2024:** Refill Friction-Stir Spot Welding should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness to employ Refill Friction-Stir Spot Welding in manufacturing settings, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

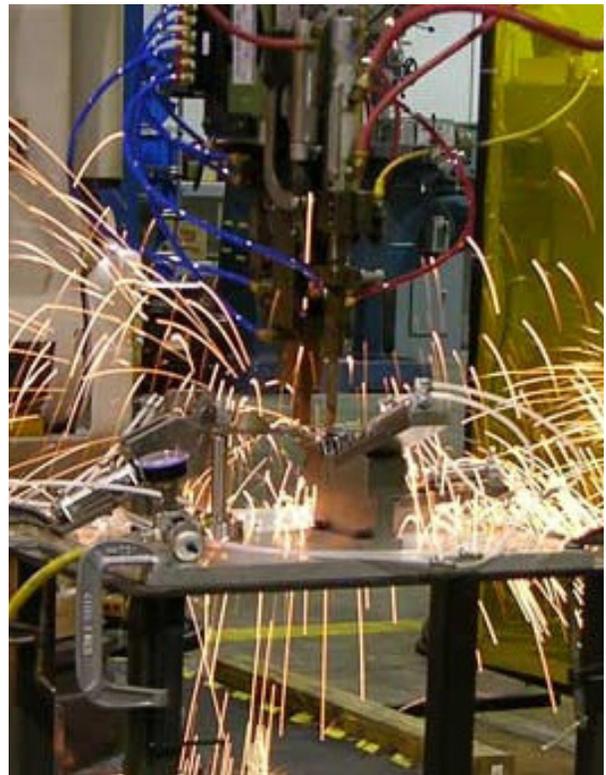
Supporting competencies for Refill Friction-Stir Spot Welding are those that are likely to be already addressed in the curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold** // Course(s) Where Competency is Likely Addressed

Supporting Competencies in 2-Year Community College Programs

- **Review Welding Specifications & Standards** // Develop Modules/Courses, Certificates
- **Practice Weld Quality Inspections & Assessments** // Develop Modules/Courses, Certificates
- **Employ Process Control & Standardized Work Procedures** // Develop Modules/Courses, Certificates

Supporting Competencies in 4-Year University Programs

- **ICME (Integrated Computational Materials Engineering) Modeling of Welding Processes & Properties** // Develop Modules/Courses
- **Practice Weld Quality Inspections & Assessments** // Develop Modules/Courses, Certificates
- **Predict Residual Stresses of Metals/Parts Related to Processing** // Develop Modules/Courses



Critical Competencies

Critical competencies for Refill Friction-Stir Spot Welding are those that will likely require new materials, modules, or courses. These competencies are listed below, along with information about where or how each could be addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency Could Be Addressed**

Critical Competencies in 2-Year Community College Programs

- **Recommend Solid-State Joining & Assembly Processes for Dissimilar Metals //** Manufacturing Courses
- **Demonstrate Ability to Operate Welding Equipment //** Hands-On Welding Courses
- **Apply Spot & Friction-Stir Welding Techniques //** Hands-On Welding Courses
- **Relate Assembly & Process Variations to Distortion Control in Manufacturing //** Manufacturing Courses

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze				1		2	
	Apply							
	Understand							4
	Remember					3		

1. Apply spot and friction-stir welding techniques.
2. Relate assembly and process variations to distortion control in manufacturing.
3. Demonstrate ability to operate welding equipment.
4. Recommend solid-state joining and assembly processes for dissimilar metals.

Critical Competencies in 4-Year University Programs

- **Correlate Structure, Processing, Properties, & Performance Relationships in Various Materials Used in Aerospace //** Materials Science & Engineering Courses
- **Develop Solid-State Welding Processes & Parameters //** Welding Metallurgy Courses
- **Assess Advantages/Disadvantages of Various Welding Technologies //** Welding Metallurgy Courses
- **Develop Process Control & Standardized Work Procedures for Manufacturing Processes //** Manufacturing Courses; Develop Certificates
- **Develop Assembly & Welding Specifications & Standards for Component Manufacturability //** Manufacturing Courses; Develop Certificates

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING							
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation	
THINKING	Create					1		2	5
	Evaluate					3			
	Analyze							4	
	Apply								
	Understand								
	Remember								

1. Develop assembly and welding specifications and standards for component manufacturability.
2. Develop solid-state welding processes and parameters.
3. Develop process control and standardized work procedures for manufacturing processes.
4. Correlate structure, processing, properties, and performance relationships for various materials used in aerospace.
5. Assess advantages/disadvantages of welding technologies.

THIN-WALL ALUMINUM DIE CASTING

What is Thin-Wall Aluminum Die Casting?

Thin-Wall Aluminum Die Casting is a new lightweighting technology that allows manufacturers to build lighter and stronger aluminum parts while maintaining energy efficiency in the overall die-casting process. Thin-wall die casting, also called high-pressure die casting (HPDC), ideally can reduce the wall thickness of die castings to less than 3mm in parts with larger mold-fill area and still achieve complete mold fill. The technology is currently in the development stage; problems to be resolved include reducing variability of HPDC castings and increasing the minimum mechanical properties. These limitations currently restrict its use for some structural applications in the automotive and aerospace industries. Current die casting design methods apply the minimum mechanical properties of cast alloys uniformly to the whole casting, which can result in over-design of a casting, especially when a large safety factor is used. Thin-wall die casting can eliminate over-design and costly over-use of materials. This can be achieved by producing statistically accurate custom processes for thin-wall castings that account for mechanical properties at different stages in the design process; doing so can result in greater design efficiency overall.

Lightweight Innovations for Tomorrow (LIFT) has initiated a project to advance Thin-Wall Aluminum Die Casting. The project personnel are developing new process technologies, including super vacuum die casting and shortened heat treatment, as well as integrated computational materials engineering (ICME) tools for 300-series die casting alloys (Al-Si-Cu-Mg based). The aim is to improve the mechanical properties of the die castings and reduce the minimum wall thickness and weight by up to 40% and 20%, respectively. The overall project goal is to reduce the variability in quality and improve the mechanical properties of high-pressure die castings. Project personnel will also explore new design methods for lightweight castings using local mechanical properties predicted by ICME, as opposed to the current method that relies upon minimum properties of cast alloys for specification of casting design.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

Thin-Wall Die Casting Affords Greater Strength with Less Energy Resulting in Overall Cost Savings

Thin wall die casting is important because less material waste and energy is consumed in the casting process. The result is lighter castings with thinner walls that have greater mechanical properties and strength due to refined grain structure. These properties suggest that this process can be used across many industry sectors beyond automotive. In metal die-casting, the energy efficiency of the process affects the manufacturer's competitiveness in the market. In short, if manufacturers melt less, they save energy and cost. Almost all industrial die-casting sectors could benefit from thin-wall technology. In thin-wall die casting, melted metal solidifies at a higher rate resulting in finer grain structure, which means greater strength and the potential for more efficient product design.

In summary, the overall benefits of thin-wall die casting include:

- Reduction of the minimum wall-thickness of parts which reduces weight and melt cost in manufacturing;
- Use of thin-wall, single-unit castings to replace "built-up assemblies" normally constructed of several thin aluminum sheet-metal units, thus reducing cost;
- Possible application of integrated computational materials engineering (ICME) methods to establish test databases for material properties as well as product design methods that can be repeated across the die-casting supplier base, increasing competitiveness of domestic aluminum product manufacturing.

Thin-Wall Die Casting Requires Workers to Have Greater Statistical Knowledge & Employ Tighter Production Process Controls

Thin-wall die casting is a complex process that is "less forgiving" than traditional die-casting. Tighter process control is required for all key components of the product and casting process. This new technology also introduces other key technologies into traditional aluminum die casting, such as vacuum die casting, and it minimizes heat treatment time.

Die-cast designers and operators need greater statistical knowledge about overall control limits and the interaction of multiple variables. Designers will need to place greater focus upon design of the casting process when designing the product or part itself. Particularly important is gating design; that is, the process and statistical variables involved from the time when metal enters a die mold cavity to when the mold is filled. Specifically, they need to accurately assess the maximum time to fill a cavity before the metal "freezes off." Timing of the "in gate" process must be strictly monitored in the production process, and machines must be regulated to deliver the infill at specific rates. In some industries, gating design manuals include new equations for machine infill rates that result in the highest degree of success in casting. In other industries, controlling these variables is still in development and remains a design problem to be solved. Furthermore, new digital tools are needed that predict what mechanical properties are achieved at different thicknesses in product areas; databases to assist prediction are continually being developed through ICME applications in the design/production process.

For both designers and shop operators, greater knowledge of the variables involved in standard high-pressure die casting, or high integrity die-casting, is needed. This knowledge base includes a focus on skills involved in semi-solid metal processing, squeeze casting, and high-vacuum die-casting. The workforce will need to know statistical process control (SPC) and principles

for design of experiments (DOE), as well as understand process problem solving.

High-vacuum thin-wall casting processes create high performance products that can't be achieved by traditional die-casting. Traditional processes produce thicker metals with too much porosity to perform well. High-vacuum casting, by contrast, allows for elongation of the metal flow creating low levels of porosity. At the same time, treatment and handling of the metal in initial and secondary processing becomes critical with these new processes to achieve success. For optimum reliability, laser-engraved bar-coding of a product that is serialized to identify all processing parameters at each stage of production is desirable. This is not currently done in typical die-casting for non-critical applications.

To prepare for wide use of thin-wall die casting, companies need to think of the cast product as the result of an entire process. This may involve a cultural change where cross functional teams are formed that optimize and oversee the entire casting process. Component traceability linking a casting back to the operating conditions during

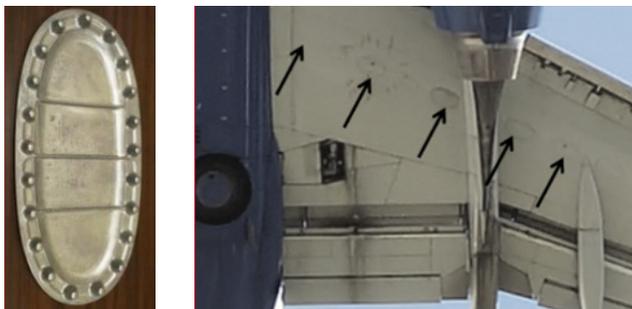
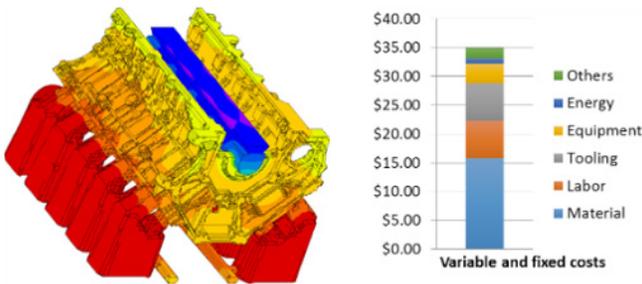
production will be important, and this may require that work process specifications be rewritten.

To summarize, skills needed for thin-wall die casting at both the design engineering and production level include:

- General knowledge of hydraulics, with greater emphasis on technical aspects at the design engineering level;
- Attention to control speeds at the “shot end” of a machine and requirements for monitoring the fill process; and
- Knowledge of instrumentation, sensing devices, and controls (e.g., closed-loop controls) involved in production.

Short courses for designers could be offered to address new techniques for:

- Design of die-casting molds, including configuration of dimensional tolerances and die construction; and
- Introduction to types of die materials, heat treatment for dies, and various die surface treatments that can be applied.



Technology Timeline

Estimated time by which Thin-Wall Aluminum Die-Casting will appear in production environments:

- **Late 2018:** LIFT technology project on Thin-Wall Aluminum Die-Casting concludes, deployment begins.
- **2019 — 2024:** Thin-Wall Aluminum Die-Casting should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness to employ Thin-Wall Aluminum Die Casting in manufacturing settings, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for Thin-Wall Aluminum Die-Casting are those that are likely already to be addressed in the curriculum. These competencies are listed on the following page, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold // Course(s)** Where Competency is Likely Addressed

Supporting Competencies in 2-Year Community College Programs

- **Demonstrate Understanding of Vacuum Die Casting Machine, Both How It Works & How to Troubleshoot // Manufacturing Processes Course**
 - Describe Operation of a Vacuum Die Casting Machine
 - Describe Pre-Process & Post-Process Techniques that Can Improve Accuracy of the Surface Finish of a Die-Cast Part
 - Define the Five Grades of Surface Finish Classifications
- **Demonstrate General Knowledge of General Casting Process, Die Casting Process, & Procedures for Equipment Operation & Maintenance // Manufacturing Processes Course**
 - Compare the Advantages & Disadvantages of Common Types of Casting Processes
- **Demonstrate Knowledge of Principles of Hydraulics & Pneumatics // Standalone Course in a Manufacturing Technology Curriculum**
 - Apply the Bernoulli's Equations & Mathematical Formulas Involved in Solving Fluid Power Problems
- **Apply Knowledge of Instrumentation & Controls // Standalone Course in a Manufacturing Technology Curriculum**
 - Demonstrate the Proper Use of Terms & Symbols Used in the Process Control Industry

Supporting Competencies in 4-Year University Programs

- **Demonstrate Knowledge of Opportunities & Challenges in Design of Lightweight Castings // Manufacturing Processes Course**
- **Show Ability to Design Various Lightweight Casting Parts with Complex Shapes & Functionality, while Maintaining the Appropriate Design Guidelines**
- **Demonstrate Knowledge of Metallurgical & Materials Engineering, Including Heat-Treatment // Engineering Materials Course**
- **Demonstrate Knowledge of ASM & ASTM Standards & Other Common Standards // Manufacturing Processes & Machine & Tool Design Courses**
- **Apply ASTM & ASM Standards During the Design of Thin-Wall Castings Made of Lightweight Materials**

Critical Competencies

Critical competencies for Thin-Wall Aluminum Die Castings are those that will likely require new materials, modules, or courses.

Critical Competencies in 2-Year Community College Programs

- Define Types of Heat Treatments Used with Die Castings
- Demonstrate Knowledge of Die Casting Design
- Identify Factors to Consider When Placing a Parting Line in the Design of a Die Cast Part
- Exhibit Knowledge of Gating Design by Listing the Elements of a Gating System
- Analyze the Effect of Each Element of a Gating System on Overall System Design

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze	1			2			
	Apply	1			2			
	Understand	3	4	5				
	Remember	3	4	5				

1. Identify the factors to consider when placing a parting line in the design of a die cast part.
2. Analyze the effect of each element of a gating system on overall system design.
3. Demonstrate knowledge of die casting design.
4. Exhibit knowledge of gating design by listing the elements of a gating system.
5. Define types of heat treatments used with die castings.

Critical Competencies in 4-Year University Programs

- Describe Design of Die-Casting Molds & of Dies, Including Both Processes & Equipment Used // Add to Manufacturing Processes Course
- Apply Knowledge of Dimensioning, Tolerances, & Materials Properties in the Design of Molds & Dies for Thin Wall Die Casting
- Describe Microstructural & Property Modeling Using ICME Principles & Methods // Covered Briefly in Engineering Materials Course & in Detail in Technical Elective Course
- Model & Analyze the Target & Resulting Microstructure & Mechanical Properties of Thin Wall Castings Using ICME
- Display Knowledge of Die-Casting, Including Use of Computer Aided Design (CAD) for Design // Manufacturing Processes Course
- Apply Knowledge of CAD in Design of Molds & Dies for Thin Wall Die Castings
- Display Knowledge of Materials Science, Especially the Properties of Lightweight Metal & How They Will Contribute in Die-Casting Process // Engineering Materials & Manufacturing Processes Course

Thinking & Doing Competency Map for 4-Year University Critical Competencies

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze	1		2	3			
	Apply	1		2	3			
	Understand	4			5	6		
	Remember	4			5	6		
		4			7			

1. Apply knowledge of dimensioning, tolerances, and materials properties in the design of molds and dies for thin wall die casting.
2. Model and analyze target and/or resulting microstructure and mechanical properties of thin wall castings using ICME.
3. Apply the knowledge of CAD in the design of molds and dies for thin wall die castings.
4. Display knowledge of materials science, especially the properties of lightweight metal and how they will contribute in the die-casting process.
5. Describe design of die-casting molds and of dies, including both processes and equipment used.
6. Describe microstructural and property modeling using ICME principles and methods.
7. Display knowledge of die-casting, including use of computer aided design (CAD) for design.

JOINING TITANIUM TO STEEL

What is Joining Titanium to Steel?

The ability to join dissimilar materials, such as titanium and steel, has gained attention recently as manufacturers strive to design and produce lightweight components that can meet the performance, reliability, and cost standards of the automotive, aviation, aerospace and defense industries. To lower production cost, titanium and its alloys are often welded to steel to achieve high performance and cost-efficiency. However, reliable titanium/steel joints can be difficult to produce due to poor compatibility and the formation of hard and brittle characteristics in the joint. Developing advanced computational methods that accurately predict material and joint properties of titanium-to-steel joints will significantly impact lightweight component design for transportation industries. Eliminating more complex joints will lead to more efficient designs, reduced weight, and reduced production time and cost.

Lightweight Innovations for Tomorrow (LIFT) is developing, validating, and implementing methods employing integrated computational materials engineering (ICME) to model and predict joint performance of welded titanium/steel. Once validated, the models will be verified on industrial-partner selected applications to ensure they accurately predict the required component performance, including lifecycle and corrosion resistance.

Multi-Material Combinations of Non-Compatible Metals, Like Titanium & Steel, Are Needed to Make Ever Lighter, Stronger Products

Reliable joining of titanium to steel could mean lighter, stronger, more reliable, and less costly parts. The lightweighting industry is currently reaching its limits for effective weight reduction in manufacturing, and novel joining methods for producing multi-material assemblies are needed to yield further weight reduction adventures.

Critical parts like power trains and engines currently have a limited number of components that can be reduced by lightweighting, if the parts are to remain strong, stiff, and reliable throughout their heavy use. Ideally, combinations like titanium and steel, which can reduce weight without sacrificing strength or adding cost, could allow for lightweighting of parts currently restricted to steel. In general, eliminating more complex joints by adopting new methods for joining dissimilar metals will lead to more efficient designs, reduced weight, and reduced production time and cost.

Joining dissimilar materials is in general more difficult than joining the same material (or alloys with minor differences in composition), and the number of applicable and successful joining techniques are few. However, in most cases dissimilar materials can be successfully joined using an appropriate method, with properly adapted processing conditions. Joining Titanium to Steel is particularly important for the transportation industry because steel is the most commonly used metal in the industry and titanium can offer superior mechanical characteristics over steel, and at reduced weight.

Joining Titanium to Steel is also important because both metals have good strength. Steel is widely available, but it is heavy; titanium also is widely available, and it is strong and light, but it is currently very expensive. Because of its expense, titanium today is mostly used in specialized products which often are smaller and require less product to manufacture. Designers

are reluctant to use titanium when other materials are available and can meet specifications. Hence, the limited use of titanium also contributes to its current expense. At the same time, titanium's lighter weight and resistance to corrosion make it an ideal product for marine applications and other applications that require reduced weight and corrosion resistance. Joining steel to titanium could reduce the expense of the metal, without sacrificing its advantages and open the possibility of a host of new applications in the aerospace, automotive and medical industries, among others. The challenge is to join these metals in such a way that performance requirements are met.

At present, effective joining of titanium to steel for critical applications has not been developed. New joining technologies have been achieved in the lab, but these techniques would need to be reliable at production scale to produce reliable consumer products. The typical joining methods for titanium-to-titanium include welding, brazing, soldering, and mechanical joining. As noted, titanium can be welded; however, effectively joining titanium to other metals by welding remains a problem to be solved. Joining titanium to other metals by soldering or brazing (both employ a filler material) has been demonstrated, but with a limited array of other metals and, again, mostly in the test phase. Titanium can also be joined to dissimilar metals by mechanical methods, such as riveting and bolting. However, galvanic corrosion sometimes occurs at the joint site. In short, the problem of effectively Joining Titanium to Steel, the technology in focus here, remains (see "Joining Titanium," Total Materia website, <http://www.totalmateria.com/Article136.htm>).

The LIFT researchers who are investigating ways of Joining Titanium to Steel are developing advanced computational methods that will accurately predict the corresponding material and joint properties. This capability will significantly impact use of this technology for lightweight component design in the automotive, aerospace, and other transportation industries.

Designers & Technicians Will Have to Think Outside the Box to Adapt to New Methods for Joining Titanium to Steel

Industries need to focus on the importance of joining dissimilar materials starting with engineering design and moving through production process planning. Design labs will need to adapt to new approaches for component design, and shop floors will need to adopt new production and assembly methods. The technology for Joining Titanium to Steel is still in the experimental stages now, and so it is difficult to determine the cultural and material changes that will need to take place to accommodate it in the workplace. Most industries at present see only the difficulties of Joining Titanium to Steel and so have not yet imagined the possibilities of new products that could be produced from this multi-material combination. It remains clear that wide-spread use of titanium will never reduce its price to compete with steel; only combined with steel could this possibly be achieved. Once this new technology is developed and on the shop floor, the standard methods for joining dissimilar materials will have to be totally reworked to account for such factors as recycling of different metals, continuous tracking in the manufacturing process, and achieving acute precision.

For many, titanium use is considered impractical because of the handling techniques deemed necessary to achieve product purity; a must in the aerospace industry. Industries today envision “white coat only” handling of titanium and are aware that it can be dangerous to work with at certain temperatures. However, the pristine environmental conditions necessary for current applications may not be required for future ones. Also, averting dangers due to temperature can be accommodated as it is for handling many other metals. At present, only one grade of titanium, a very pure form, is produced using a triple melt process. For industries like ship building, a single melt form of the product, which has some impurities that are not critical for these applications, may be

sufficient. In short, the possibility of broadening the use of titanium itself and as a joined object will open up many new opportunities for use beyond aerospace and other specialized markets, and this, in turn, will drive the need for a variety of titanium grades to be produced.

To prepare students and workers to apply joining techniques for dissimilar metals, like titanium and steel, instruction on the interactions and strengths of dissimilar materials when combined should be integrated within regular engineering courses. Case studies would help students realize the importance of using dissimilar materials and their associated joining methods in engineering design and manufacturing process planning. For community colleges or technical programs, students should be introduced to the properties of metals, the instructors should compare the weight and strength advantages of different metals, and the students should understand various ways of joining metals such as welding, adhesion, and mechanical joining. Introduction to the challenges of multi-material welding is also important. At the four-year level, students should learn about materials manufacturing processes, standard and new techniques for joining and welding, different approaches to multi-material joining, and how materials behave at the joint interface. Use of data to analyze and predict performance of these new joining processes is still in development but may soon be a topic that also requires attention for student and worker training.



Technology Timeline

Estimated time by which Joining Titanium to Steel will appear in production environments:

- **Mid 2019:** LIFT technology project on Joining Titanium to Steel concludes, deployment begins.
- **2021:** Joining Titanium to Steel should begin to appear in production environments.

KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness for Joining Titanium to Steel, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for Joining Titanium to Steel are those that are likely to be already addressed in the curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold** // Course(s) Where Competency is Likely Addressed

Supporting Competencies in 2-Year Community College Programs

- **Demonstrate Knowledge of the Basics of Multi-Material Joining Processes** // Materials & Welding Courses
- **Practice a Variety of Welding Operations** // General Welding Course
- **Apply Knowledge to Analyze Advanced Welding Processes** // Welding Course

Supporting Competencies in 4-Year University Programs

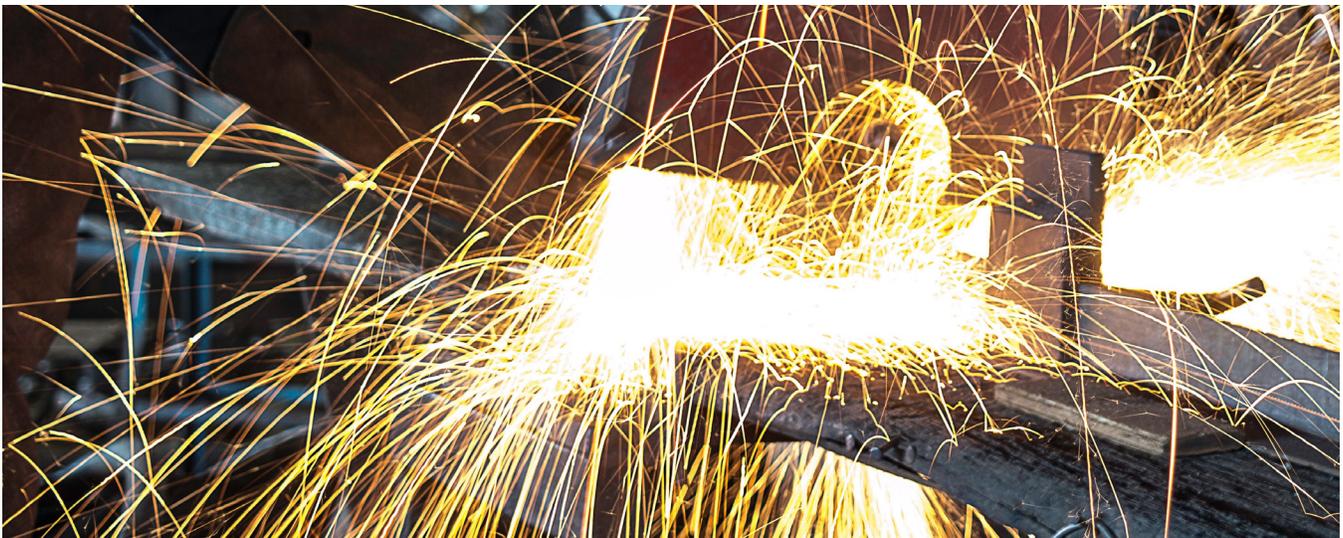
- **Demonstrate Knowledge of the Microstructure of Non-Ferrous & Ferrous Materials** // Metal Materials Course
- **Exhibit Comprehensive Knowledge of Material Properties** // Metal Materials or Engineering Materials Course
- **Compare & Analyze Advantages & Disadvantages of Different Types of Welding Processes** // Manufacturing Processes Course

Critical Competencies

Critical competencies for Joining Titanium to Steel are those that will likely require new materials, modules, or courses.

Critical Competencies in 2-Year Community College Programs

- **Describe & Apply Joining Methods for Dissimilar Materials**
- **Describe & Apply Testing Procedures for the Quality of Multi-Material Welds**
- **Describe & Analyze the Physical Properties of Welds**



Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze		1			2		
	Apply							
	Understand	3						
	Remember							

1. Describe and analyze the physical properties of welds.
2. Describe and apply testing procedures for the quality of multi-material welds.
3. Describe and apply joining methods for dissimilar materials.

Critical Competencies in 4-Year University Programs

- Demonstrate Comprehensive & Deep Knowledge of Joining Process
- Analyze Welding Defects & Methods of Quality Control
- Practice & Demonstrate How to Perform Advanced Welding Processes
- Apply Knowledge to Design Products with Dissimilar Materials & Their Joints

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create			1				
	Evaluate						2	
	Analyze							
	Apply				4			
	Understand	3						
	Remember							

1. Apply knowledge to design products with dissimilar materials and their joints.
2. Analyze welding defects and method of quality control.
3. Demonstrate comprehensive and deep knowledge of joining process.
4. Practice and demonstrate how to perform advanced welding processes.

INORGANICALLY- BONDED SAND MOLDS

What are Inorganically-Bonded Sand Molds?

Inorganically-Bonded Sand Molds contain inorganic materials used to bind sand for building molds for metal casting. Inorganic binders reduce some of the problems caused by organic binders, such as coal, because they produce few or no off-gases in the molding process and reduce the possibility of resulting defects in the mold. Also, because no organic binders are used, mold sand can be reclaimed and used again. Because inorganic binders reduce mold defects, parts that require high safety tolerances can be produced using Inorganically-Bonded Sand Molds. Inorganically-Bonded Sand Molds can also be produced and replicated using 3-D printing, reducing the need for expensive metal dies and allowing for more flexible, less costly mold designs. To increase the suitability of this new technology for manufacturing, Lightweight Innovations For Tomorrow (LIFT) has developed a project to economically produce thin-wall, lightweight iron castings from inorganically-bonded, recyclable sand molds that are 3D printed.

CHANGING TECHNOLOGY, CHANGING WORKFORCE

Inorganically-Bonded Sand Molds Can Produce Complex Parts Economically & Cleanly

Sand molds made with inorganic binders are economical and eco-friendly because the sand can be reused multiple times, and they reduce waste, dirt, odors, and fumes. At present, the casting industry is viewed by many as old, dirty technology. Traditional heavy metal casting with dies employs large machines that cost upwards of \$75K apiece; in fact, it is expensive and dirty. Casting molds must be shaken off the resulting pattern creating dust and grime, and the resulting casting often requires removal of excess material. The introduction of 3-D printing technology and the use of inorganic binders in sand molds has changed that. And although these new processes may not be suitable for producing thousands of parts at speed, as found with a casting die, they can afford customization of parts without the need to invest in expensive dies. As technology advances, it may be possible to print molds at the production line speed, which would allow mass customization of complex cast metal parts.

Inorganically-Bonded Sand Molds can be used to produce more organic shapes and complex surface profiles with new lightweight metal alloys in molds that eliminate the need for draft tolerances, fillets, and radial corners. Draft tolerances are the slight angles produced on a vertical wall that allow the resulting product to be removed from a mold without disturbing the mold or damaging the pattern or product. Because Inorganically-Bonded Sand Molds can be removed from the part in aqueous media and the mold can be inexpensively reproduced, draft tolerances aren't needed. Likewise, fillets, or "the rounding-out of internal corners of the pattern," as well as radii, "added to round-out the external edges of the pattern," are not needed to reduce the possibility of hot-tears and ease pattern removal from the mold (Kay, Ian M., "Casting Facts: Patternmaking 'Tricks' for Better Casting," Engineering Casting Solutions, Winter 2002: 48-49). In short, printing the sand molds and cores allows for greater design freedom and complexity in the final parts produced.

Computer-aided design and 3D printing allow for using the maximum potential of Inorganically-Bonded Sand Molds to produce highly unusual and customized products. Sophisticated software programs can help an engineer design molds for parts that use less metal and have organic shapes that derive their strength from unique pattern angles. Such organic shapes cannot be made without damage in molds that must be pounded or shaken off. Likewise, traditional sand-molds and heavy metal dies cannot be produced with the facility and environmental cleanliness that is afforded by 3D printing of Inorganically-Bonded Sand Molds. Furthermore, 3D printing of sand molds allows for a much higher degree of complexity in cast metal parts without the need for generating a starting pattern (thus dramatically reducing the processing steps). A current challenge of this new technology is to produce the printed molds and resulting patterns at line-speed, since 3D printing is a slower technology than high-speed stamping.

Teamwork Is Essential for the Design & Use of Inorganically-Bonded Sand Molds

Design engineers and technicians must work together to assure that the organic designs made possible with Inorganically-Bonded Sand Molds meet manufacturing requirements. Design engineers will need to become familiar with computer databases that direct design parameters for extruded geometric shapes. They no longer will have to design drafts, fillets, or radii to produce castings, since this technology is well-suited to the use of new metal alloys that can be thin-casted and thus avoid the risk of uneven solidification of the metal melt. Creating designs for thin-wall casting of new light-weight alloys will require mechanical engineers to be supported by the work of metallurgists who understand the capabilities of these new alloys. At the same time, the heavy reliance of many mechanical engineering programs on computer-aided design, without the benefit of building test models, may require designers in industry to have close collaboration with shop floor technicians who understand better

the physical limitations of some manufacturing processes.

Workforce changes are inevitable with this new technology. Rather than employing primarily artisan mold-makers, tool and die shops will need CAD designers who use simulation tools to design molds in three dimensions (accounting for warping / distortion) to achieve high dimensional accuracy. Simulation tools will also be used to evaluate mold-filling and flow lines to assist with the mold design. Inorganically-Bonded Sand Molds can allow for a virtually tool-less foundry where all the molds are printed and designed with the assistance of simulation software.

Technicians who work on the shop floor may find themselves elevated to the position of creating entry-level gating designs for the flow of molten metal into these sophisticated molds. Therefore, they will need a general knowledge of metallurgy, training on software, and introduction to new 3D manufacturing processes that are projected to replace the heating, welding, and rolling techniques taught in traditional metal casting. CNC (computer numerical control) machining techniques used to remove unwanted metal left in traditional casting will need to be replaced by software for gating design and monitoring of the casting process with the object of producing a perfect result from the get-go.



Technology Timeline

Estimated time by which Inorganically-Bonded Sand Molds will appear in production environments:

- **Early 2019:** LIFT technology project on Inorganically-Bonded Sand Molds concludes, deployment begins.
- **2020 — 2022:** Inorganically-Bonded Sand Molds should begin to appear in production environments.

Students introduced to this new casting method will need to understand the capabilities and limitations of design and simulation software tools, as well as the basics of metallurgy and fluid flow. As noted above, the technician in an advanced foundry may be doing much more simulation work in the future, such as mold flow analysis to design gating and evaluating the progression of the solidification front. The role of the engineer will shift to design and modeling of the part (such as topology optimization), rather than mold flow simulations.



KNOWLEDGE, SKILLS, AND ABILITIES

To assure worker readiness for Inorganically-Bonded Sand Molds, colleges, universities, and employers need to address the specific competencies that will be required.

Supporting Competencies

Supporting competencies for working with Inorganically-Bonded Sand Molds are those that are likely already addressed in the two-year or four-year engineering/technology curriculum. These competencies are listed below, along with information about where or how each is addressed, as follows: • **Supporting Competency in Bold // Course(s) Where Competency is Likely Addressed**

Supporting Competencies in 2-Year Community College Programs

- **Recognize the Impact of Heat Transfer Principles on Casting Processes // Heat Transfer Course**
- **Relate Metallurgy & Microstructure to Part Quality & Performance // Materials Science Course**
- **Identify Appropriate Manufacturing Approaches for Desired Components // Manufacturing Technology Course**

Supporting Competencies in 4-Year University Programs

- **Recognize the Impact of Heat Transfer Principles on Casting Processes // Heat Transfer Course**
- **Relate Metallurgy & Microstructure to Part Quality & Performance // Materials Science Course**
- **Explain Solidification Front Characteristics for a Casting Process // Materials Science & Thermodynamics Course**

Critical Competencies

Critical competencies for working with Inorganically-Bonded Sand Molds are those that will likely require educators to develop new materials, modules, or courses.

Critical Competencies in 2-Year Community College Programs

- **Demonstrate Proficiency with Mold Flow Simulation Software**
- **Describe the Role of a Solidification Front in Casting Processes**
- **Utilize Additive Manufacturing to Print a Complex Part**

Thinking & Doing Competency Map for 2-Year Community Colleges Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze							
	Apply							
	Understand	1		2	3			
	Remember							

1. Describe the role of a solidification front in casting processes.
2. Utilize additive manufacturing to print a complex part.
3. Demonstrate proficiency with mold flow simulation software.

Critical Competencies in 4-Year University Programs

- Demonstrate Mastery of Mold Flow Simulation Software for Casting
- Evaluate Various Additive Manufacturing Routes for Complex Parts
- Employ Simulation Software to Optimize Component Shape for Desired Performance (Topology Optimization)

Thinking & Doing Competency Map for 4-Year University Critical Competencies

Please refer to the Thinking and Doing section above for more information about how to use the Thinking/Doing Competency Map.

		DOING						
		Recognition	Handling	Basic Operation	Competent Operation	Expert Operation	Planning	Evaluation
THINKING	Create							
	Evaluate							
	Analyze							
	Apply							
	Understand				1	2	3	
	Remember							

1. Demonstrate mastery of mold flow simulation software for casting.
2. Employ simulation software to optimize component shape for desired performance (topology optimization).
3. Evaluate various additive manufacturing routes for complex parts.

Chapter 4: Resources

The EET understands that the recommendations called for in this report will require significant resources and work to implement. To aid in these efforts, the EET has compiled this section of existing resources that can be leveraged to in curriculum and program development.

LIFT RESOURCES

LIFT has made over 40 investments in education and workforce development to develop an educated, skilled workforce ready to implement lightweight technologies in advanced manufacturing. Through partnerships than 150 education and workforce development organizations, these LIFT investments have aimed to address the “skills gap” at all levels and have impacted more than 200,000 students and teachers.

The EET has compiled a snapshot of these investments below, and the full portfolio can be found at <https://lift.technology/education-workforce-development/>.

High Bay- The LIFT High Bay is the nation’s premier lightweighting applied research and development facility. Featuring full-scale equipment installed for both LIFT and IACMI (The Composites Institute), the facility is uniquely positioned to help revolutionize manufacturing through lightweight innovation and education. The LIFT High Bay features 100,000 square feet of equipment directly related to the technologies reviewed by the EET, including: one of the world’s largest linear friction welders, a robotic blacksmithing cell, tilt pour casting, an extrusion press capable of producing up to 400” sections, a state-of-the-art metrology lab, and a hydroforming press. Learn more: www.lift.technology/lift-facilities/lift-high-bay/.

Learning Lab- The LIFT Learning Lab is being designed as a state-of-the-art interactive learning facility, located in the LIFT High Bay, with curated resources that will create an immersive learning environment, designed to provide students with introductory advanced manufacturing skills in an industry research and development setting. The Lab will feature: a flexible learning space, a computer and virtual reality lab, a fundamental skills development lab, a robotics lab, a materials science and project fabrication lab, a CNC (computer numerical control) operations training center, and a welding technician training center. Learn more: <https://lift.technology/education-workforce-development/>.

Learning Hub- The LIFT/IACMI Learning Hub is a joint education and workforce development initiative between LIFT and IACMI (The Manufacturing USA Composites Institute), providing the first nationally relevant, open source and scalable online library of lightweighting and composites related educational materials for use by educators and students at all levels. The Learning Hub currently features more than 2,450 resources providing educational tools related to lightweight metals and composite materials for any age group, topic or duration. Since the Learning Hub was launched, over 2,000 visitors have searched the site for materials. Learn more: www.liflearninghub.com/.

IGNITE: Mastering Manufacturing- LIFT, along with the America Makes and DMDII institutes,, developed a foundational competency model for the “multi-skilled technician” needed in today’s workplace. That competency model has been translated to an educational and curriculum pathway targeted at the high school level, in partnership with Amatrol, The Ohio State University, ASM Education Foundation, and the Past Foundation, that recognizes the next generation

manufacturing technical workforce must, in fact, be a workforce of high skilled technicians – individuals with the knowledge, skills and abilities who understand materials science and can optimize manufacturing technologies, processes, and systems. Learn more: www.lift.technology/ignite.

Operation Next- Operation Next is designed to (1) address critical national skills shortages, and (2) translate and enhance separating military personnel's skills, resulting in receipt of nationally portable, industry recognized, and highly marketable credentials by bringing market leaders in manufacturing training together in a full- service online learning platform that soldiers can access before leaving the service, accelerating their transition into civilian manufacturing careers. The hybrid training program combines self-directed virtual learning with hands-on lab work and gives soldiers foundational knowledge, practical real-world skills, and national industry credentials with immediate value in the labor market. The program begins and ends while the student is still on active duty so he/she is immediately prepared for employment upon separation. Learn more: <http://www.opnextjobs.com/>.

MakerMinded- MakerMinded impassions students about advanced manufacturing and equips them with the skills and mindsets needed in the innovation economy. It directly links students to a diverse range of national and local STEM and advanced manufacturing programs, including manufacturing facility tours, gaming activities and project-based learning. MakerMinded also drives a sense of competition, as students and schools receive points for each completed activity, which are tallied on a real-time online leader board, with the top schools being celebrated at year-end recognition events. MakerMinded is active in Tennessee, Kentucky, Indiana, West Virginia, Ohio, Michigan, and Idaho. Learn more: <http://makerminded.com/>.

Virtual Welding and Non-Destructive Evaluation Modules- LIFT sponsored the creation of new online training modules related to lightweighting, in collaboration with EWI and 180Skills, to allow LIFT members access to high-quality training for new lightweighting technologies without excessive cost or the need for workers to travel. Two modules are available: 7 student contact hours on Nondestructive Evaluation for Lightweighting Material; and 4.3 student contact hours on Fundamentals of Arc Welding for Lightweighting Materials. More information is available at www.LIFT.Technology.

Lightweighting Professional Certificate Program- In partnership with LIFT, Case Western Reserve University developed specialized programming for working professionals to increase their knowledge of lightweight metals and other advanced manufacturing technologies. The certificate program includes three modules on Polymers, Additive Manufacturing, and Advanced Materials. Additional information is available at www.case.edu/cps/.

Foundations for Manufacturing Careers- LIFT and Ohio TechNet, in collaboration with Lorain Community College, Work Advance and additional educational and industry partners, developed a Foundations for Manufacturing Careers program. Foundations for Manufacturing Careers addresses the skills needed to operate today's manufacturing equipment, as well as the greatest entry-level need of manufacturing employers – employability skills – by providing participants with a career-oriented pathway toward high-demand occupations. Individuals can participate in one of two ways: Manufacturing Readiness Program and a Foundations for Manufacturing Career Course. Learn more at: www.LIFT.Technology.

Robotic Blacksmithing Competition –LIFT partnered with The Ohio State University Center for Design and Manufacturing Excellence (CDME) to hold a Robotic Blacksmithing competition in which high school and college students from around the country can participate, innovate and earn cash prizes. The competition recruited teams to submit solutions to a challenge related to robotic blacksmithing to incrementally re-shape material to create components – instead of removing it, like Computer Numeric Control (CNC) machining or adding material, as in additive manufacturing. The first competition was held during the 2016-2017 school year. Results from the competition are available at www.LIFT.Technology.

Kentucky Fame Teacher Externship Program- LIFT supported Kentucky FAME in the development of an externship program that places teachers onsite in a manufacturing environment for one-week immersive experiences. Teachers have the opportunity to observe and interact with manufacturers and have an outside the classroom business experience. Through this program, teachers learn to work together to create ideas connecting their course standards with industry reinforcing the theme of their academy across subject areas. More information is available at <http://kyfame.com/teacher-externship-program/>.

APLU RESOURCES

APLU: *Ready for Jobs, Careers, and a Lifetime Report*- <http://www.aplu.org/library/ready-for-jobs-careers-and-a-lifetime/file>

APLU: *Aligning Technology & Talent Development Report*

Report 1: <http://www.aplu.org/library/aligning-technology-and-talent-development/File>

Report 2: <http://www.aplu.org/library/report-2-aligning-technology-and-talent-development/File>

Report 3: <http://www.aplu.org/library/report-3-aligning-technology-and-talent-development/file>

LIFT, APLU, and NCMS: *Engineering Work-and-Learn: Imperatives for Innovation*-
<http://www.aplu.org/WorkAndLearn>

LIGHTWEIGHTING-RELATED PROFESSIONAL SOCIETIES

The EET recommended partnering with professional societies and industry associations at multiple points throughout this report. While not an inclusive listing, the following section outlines several professional societies most closely related to the LIFT technology projects reviewed in this report.

American Society for Engineering Education- <https://www.asee.org/>

American Society of Mechanical Engineers- <https://www.asme.org/>

American Welding Society-<https://www.aws.org>

ASM International the Materials Information Society- <https://www.asminternational.org/>

ASM Materials Education Foundation- <https://www.asmfoundation.org/>

National Academy of Engineering- <https://www.nae.edu/>

North American Die Casting Association- <https://www.diecasting.org/>

SAE International-<https://www.sae.org>

Society for the Advancement of Material and Process Engineering-
<https://www.nasampe.org/>

Science Direct Materials Science and Materials Engineering-
<https://www.sciencedirect.com/referencework/9780128035818/materials-science-and-materials-engineering>

Society of Manufacturing Engineers (SME)- <https://www.sme.org>

The American Institute of Aeronautics and Astronautics- <https://www.aiaa.org/>

The Minerals, Metals, and Materials Society- <https://www.tms.org/>

EXPERT EDUCATOR TEAM MEMBERS



Fazleena Badurdeen, University of Kentucky

Fazleena Badurdeen is an Associate Professor in the Department of Mechanical Engineering and also affiliated to the Institute for Sustainable Manufacturing, at the University of Kentucky, USA. She is also the Director of Graduate Studies for the Manufacturing Systems Engineering Program. Professor Badurdeen received her Ph.D. in Integrated (Industrial and Mechanical) Engineering and MS in Industrial Engineering both from Ohio University, Athens, OH. She also holds an MBA from the Postgraduate Institute of Management, Sri Lanka and BS in Engineering from the University of Peradeniya, Sri Lanka.



Amy Clarke, Colorado School of Mines

Amy Clarke is an Associate Professor and Metallurgical and Materials Engineering Site Director in the Center for Advanced Non-Ferrous Structural Alloys. Professor Clarke received both her Ph.D. and MS in Metallurgical and Materials Engineering from the Colorado School of Mines and her BS from Michigan Technological Engineering. Her research areas include innovative materials synthesis and processing through the use of novel tools and unique probes to control the microstructure and properties of energy, defense and industrially important materials, resulting in enhanced performance and reliability.



Mel Cossette, MatEdU

Mel Cossette is the Executive Director/Principal Investigator for the National Resource Center for Materials Technology Education (MatEdU) and Project: Technician Education in Additive Manufacturing & Materials (TEAMM) funded by National Science Foundation's Advanced Technological Education Program housed at Edmonds Community College in Lynnwood, WA. Mel has over 25+ years of experience in manufacturing education, has developed technician training programs for industry and educational institutions, serves on numerous committees and national boards and worked in various industries prior to holding administrative positions in the community and technical college system.



Chad Duty, University of Tennessee

Chad Duty is an Associate Professor of Mechanical, Aerospace and Biomedical Engineering at the University of Tennessee. Professor Duty received his Ph.D. from Georgia Tech and his BSME from Virginia Tech. His areas of research include additive manufacturing of polymer and composite structures, focusing on anisotropic mechanical behavior, new material development, melt flow characterization, and optimizing process-structure-property relationships.



Muhammad Jahan, Miami (Ohio) University

Muhammad Jahan is an Assistance Professor of Mechanical and Manufacturing Engineering at the Miami University. He received his Ph.D. in Mechanical Engineering from the National University of Singapore and his B.S. in Mechanical Engineering from Bangladesh University of Engineering Technology. Professor Jahan also completed Postdoctoral research in Mechanical Engineering at the University of Arkansas. His research areas include Micro and nano-machining processes; conventional and non-conventional manufacturing processes; SPM based nano-machining and nano-patterning; Laser machining/welding and surface modification.



Gene Liao, Wayne State University

Gene Liao is a Professor of Engineering Technology, Electric-drive Vehicle Engineering at Wayne State University. Professor Liao received his Doctor of Engineering from the University of Michigan, a Mechanical Engineer Professional Degree from Columbia University, a M.S. in Mechanical Engineering from the University of Texas at Arlington, and a B.S. in Mechanical Engineering from the National Central University in Taiwan. His research areas include the areas of Mechanical Design, Multi-body Dynamics, Hybrid Vehicle Powertrain, and CAE applications in products development and manufacturing and he has over 15 years of industrial practice prior to joining faculty at Wayne State University.



Kapil Madathil, Clemson University

Kapil Madathil is an Assistant Professor of Civil Engineering and Industrial Engineering at Clemson University. He is also Deputy Director of the Risk Engineering and System Analytics Center. Professor Madathil earned a Ph.D. in Industrial Engineering and a M.S. in Industrial Engineering both from Clemson University, and a Bachelor of Technology in Mechanical Engineering from Vellore Institute of Technology. His area of expertise is in applying the knowledge base of human factors engineering to the design and operation of sustainable human-computer systems that involve rich interactions among people and technology.



Kelly Zeleznik, Lorain County Comm College

Kelly Zelesnik is currently the Dean of the Engineering, Business and Information Technologies Division and the Nord Advanced Technologies Center at Lorain County Community College. She has a M.S. in Engineering Management from eh Gordon Institute of Tufts University and a B.S. in Electrical Engineering from Cleveland State University. She serves as Chair Emerita, United States Fab Lab Network (USFLN) and co-principal investigator for the NSF funded Weld-Ed ATE. She has recently completed an NSF funded Digital Fab Lab Learning Community grant with Fox Valley Technical College.



Rebecca Taylor, National Center for Manufacturing Sciences

Rebecca R. Taylor is currently the Senior Vice President for the National Center for Manufacturing Sciences (NCMS), the largest not for profit research and development consortium in North America focused on Manufacturing. NCMS consists of more than 300 member corporations working toward the goal of improving the manufacturing competitiveness of the nation. In this capacity she is responsible for the operation of the organization's government efforts, for liaison with Members of Congress and the Administration, oversight of all government programs, as well as overall management of the Washington, DC and Bremerton, WA offices until August 1991, Ms. Taylor served as an International Trade Analyst for the US Department of Commerce. In this position she served as a principal in the machine tool trade negotiations with the governments of Japan and Taiwan, representing the Bureau of Export Administration during the trade talks. In addition, she was the Bureau's representative to the interagency working group on the Intelligent Manufacturing Systems program for multi-lateral R&D cooperation.



Jim Woodell, Association for Public and Land Grant Universities

James K. Woodell (Jim) is Vice President for Economic Development and Community Engagement at APLU. He works closely with member institutions to develop tools and resources to enhance their regional engagement and economic development efforts. He serves as the lead staff member for APLU's Commission on Innovation, Competitiveness and Economic Prosperity (CICEP), and the Association's Council on Engagement and Outreach (CEO), advancing APLU's economic and community engagement agenda. Jim earned a Ph.D. in higher education at Penn State University, a Master of Education degree from Harvard University and a BS in Public Communications (TV, Radio, and Film) from Syracuse University.



Emily DeRocco, Lightweight Innovations for Tomorrow

Emily DeRocco is Vice President of Education and Workforce Development for Lightweight Innovations for Tomorrow. Emily DeRocco also leads a Washington, D.C.-based consulting practice linking education, workforce and economic development assets for competitive advantage.

In addition to her reform work with state and local officials, during the past 5 years, she has served as an officer and director of education and workforce for LIFT, the Detroit-based manufacturing innovation institute, a member of the Manufacturing USA network; as director of the National Network of Business & Industry Associations for Business Roundtable; and as a member of several higher education institutions' boards. In 2016, she was appointed to a 3-year term on the Australian Naval Shipbuilding Advisory Board, by the Australian Minister of Defense Industry.

DeRocco is the past president of The Manufacturing Institute where she focused on building an educated and skilled manufacturing workforce. In 2001, she was nominated by President Bush and confirmed by the U.S. Senate as the Assistant Secretary of Labor responsible for managing a \$10 billion investment in the nation's workforce and using talent development strategies to drive

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Shalin Jyotishi, Association for Public and Land Grant Universities

Shalin R. Jyotishi is the Associate in Economic Development & Community Engagement at the Association of Public and Land-grant Universities (APLU) where he works with leaders from public research universities to advance university-based innovation, entrepreneurship and technology-based economic development; talent and workforce development; and public service, outreach and community engagement. Shalin's interest centers on the intersection of economic development and science, technology and innovation policy. Prior to arriving at APLU, he held positions with the Science, Engineering and Technology Policy program at the American Academy of Arts & Sciences. Concurrently, he held a research appointment at the University of Michigan, contributing to the 2nd edition of the widely used book, *Beyond Sputnik: U.S. Science Policy in the 21st Century* (Forthcoming MIT Press). He has also served as a consultant to science and innovation organizations including the American Association for the Advancement of Science (AAAS) and Innovation Associates.



Jacqui Mieksztyn, Lightweight Innovations for Tomorrow

Jacqui Mieksztyn is an Education and Workforce Development Program Manager for Lightweight Innovations for Tomorrow. She also serves as the Director of Business Strategy at Thomas P. Miller & Associates where she delivers workforce development solutions nationally. Having spent 9+ years in public administration, Jacqui has held leadership positions with the Michigan Economic Development Corporation and the State of Michigan Workforce Development Agency and where she led strategies to develop, attract, and retain talent to support Michigan's growing industry sectors. She has a Master of Arts in Organizational Communication from Western Michigan University and a Bachelor of Arts in Communication from Michigan State University.

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Lightweight Innovations for Tomorrow (LIFT), operated by the American Lightweight Materials Manufacturing Innovation Institute (ALMMII), is a public-private partnership to develop and deploy advanced lightweight materials manufacturing technologies and implement education and training programs to prepare the workforce. ALMMII was selected through a competitive process led by the U.S.

Department of Defense. ALMMII is one of the founding members of Manufacturing USA, a federal initiative to create regional hubs to accelerate the development and adoption of cutting-edge manufacturing technologies. Learn more at www.LIFT.Technology.



The Association of Public and Land-grant Universities (APLU) is a research, policy, and advocacy organization representing 237 public research universities, land-grant institutions, state university systems, and affiliated organizations. Founded in 1887, APLU is North America's oldest higher education association with member institutions in all 50 U.S. states, the District of Columbia, four U.S. territories, Canada, and

Mexico. Annually, member campuses enroll 4.7 million undergraduates and 1.3 million graduate students, award 1.1 million degrees, employ 1.3 million faculty and staff, and conduct \$41 billion in university-based research. Learn more at www.APLU.org.



National Center for Manufacturing Sciences (NCMS) is a cross-industry technology development consortium, dedicated to improving the strength and competitiveness of American manufacturing. As a member-based organization, NCMS leverages its network of industry, government, and higher education partners to develop, demonstrate, and deploy

innovative technologies, leveraging the advantages of collaboration across sectors to increase efficiency and optimize performance. NCMS is committed to helping meet U.S. manufacturers' demand for skilled workers through its ongoing support for workforce development, training, and STEM education. Learn more at www.NCMS.org.



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