A Comprehensive Advanced Materials Joining and Forming Technology Roadmap

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EXECUTIVE SUMMARY

Full report available upon request

Materials joining and forming are essential cross-cutting technologies, contributing around $200 billion in value to US-manufactured products annually. The durable goods manufacturing industry in which welding is a critical enabling technology accounts for 90% of total U.S. durable goods value of production.[1] Nearly all major manufacturing sectors rely on materials joining and forming either for the design and manufacture of their products and/or for the fabrication and maintenance of their manufacturing infrastructure and distribution systems. It's not surprising that in 2012 the Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing[2] identified these technologies as "pivotal in enabling US manufacturing competitiveness, both in terms of differentiation and tradability of goods."

Other countries have recognized the importance of joining and forming technologies to manufacturing competeveness and have been accelerating their investments in research and development in these disciplines, in many cases far out pacing levels of investment here in the U.S. Without increased focus and discipline in advancing existing technical capabilities, the U.S. risks falling behind in the development of innovative joining and forming solutions and a continued decline in manufacturing competitiveness and associated economic clout on the global stage.

This document is the product of a two-year study evaluating the technical gaps and needs in U.S. industry related to materials joining and forming technologies. This project was funded by the National Institute of Standards and Technology (NIST) through the Advanced Manufacturing Technology Consortia (AMTech) program. EWI received one of nineteen AMTech-funded roadmap awards in 2014 to develop a comprehensive national roadmap that documents gaps and needs in industry and identifies relevant technology development initiatives that would address those needs in materials joining and forming. All AMTech projects include technology roadmapping through the development of consortiums engaging manufacturers of all sizes, academia, government entities, trade and professional associations, and other stake holders to determine technology development priorities that will reduce barriers and deploy advancements to improve global competitiveness and grow the manufacturing base of U.S. industry. In addition to a focus on materials joining and forming technology advancements, this roadmapping effort sought to also address workforce development needs to ascertain industry's requirements for a skilled workforce to meet tomorrow's global demands.

Table ii-1. Steering Committee

TECHNICAL FOCUS	NAME	AFFILIATION
Materials Joining	John Lippold	The Ohio State University, Manufacturing & Materials Joining Innovation Center (Ma2JIC)
	Warren Miglietti	The International Institute of Welding (IIW)
	Dennis Harwig	American Welding Society (AWS)
	Chris Conrardy	EWI
Forming	Brad Kuvin	Precision Metalforming Association (PMA)
	Carola Sekreter	Forging Industry Association (FIA)
	Taylan Altan	The Ohio State University, Center for Precision Forming (CPF)
	Prof. Gracious Ngaile	North Carolina State University
	Natalie Lowell and Suzy Marzano (replaced Natalie Lowell in late 2015)	Society for Manufacturing Engineers (SME)

EWI is well-positioned to manage this endeavor as it has worked with more than 2,000 manufacturing companies over the last 30 years through its multi-disciplinary industrial consulting and research and development activities. In addition, EWI has worked closely with a number of world-class research universities, government and non-profit research labs, and other leaders engaged in technology development and deployment in materials joining, forming, and allied manufacturing technologies. In addition to this roadmap, EWI routinely engages in its own internal technology roadmapping efforts to identify technology development priorities needed to serve its industrial client base.

Within EWI, the project was led by Tom McGaughy, EWI Director of Technology, who was the overall principal investigator and coordinated the materials joining portion of the project, and Dr. Hyunok Kim, Director of the EWI Forming Center, who led the forming side of the roadmapping activities.

While this project was led by EWI, critical support and guidance was provided by an external steering committee made up of leading researchers and industry professionals in joining and forming technologies. The steering committee members are identified above in Table ii-1. Since a key activity in the project involved canvassing of industry needs, the makeup of the steering committee was designed to maximize the industrial reach of the canvassing efforts and provide meaningful input to workforce development and training needs. As such, the professional and industry associations represented on the steering committee were able to gather input from their membership and provide relevant industry data obtained during their normal course of business. The research professors on the steering committee provided valuable insight to current academic research priorities, as well as activities at the university level to develop the next generation of professional scientists and engineers that will soon enter the workforce. The contributions of this important group of experts are greatly appreciated as they significantly improved the quality of the roadmap document.

The steering committee played a critical role in the ideation of research and technology development topics that are included in the roadmap. Following identification of pertinent topics, a review and prioritization process was followed to down-select the final topics that appear in the Recommendations section of this summary report. A more detailed discussion of these topics is included in the full report.

In addition to the external steering committee, the roadmap priorities have been reviewed by several leading industry experts and researchers to assist in fine tuning the objectives and high-level approach proposed for each research priority. Therefore, the roadmap identifies the needs and priorities of industry at large. Consideration should be given by all public and private stakeholders on methods and approaches for pursuing these roadmap initiatives to bolster U.S. manufacturing competiveness over the next decade. Successful implementation of the priorities outlined in the roadmap will produce meaningful improvements not only in the ability for U.S. manufacturers to innovate and stay ahead of global competitors, but in the size and prosperity of the manufacturing workforce and the overall U.S. economy for years to come and the ability to maintain a viable defense manufacturing base and enhance national security cannot be overlooked.

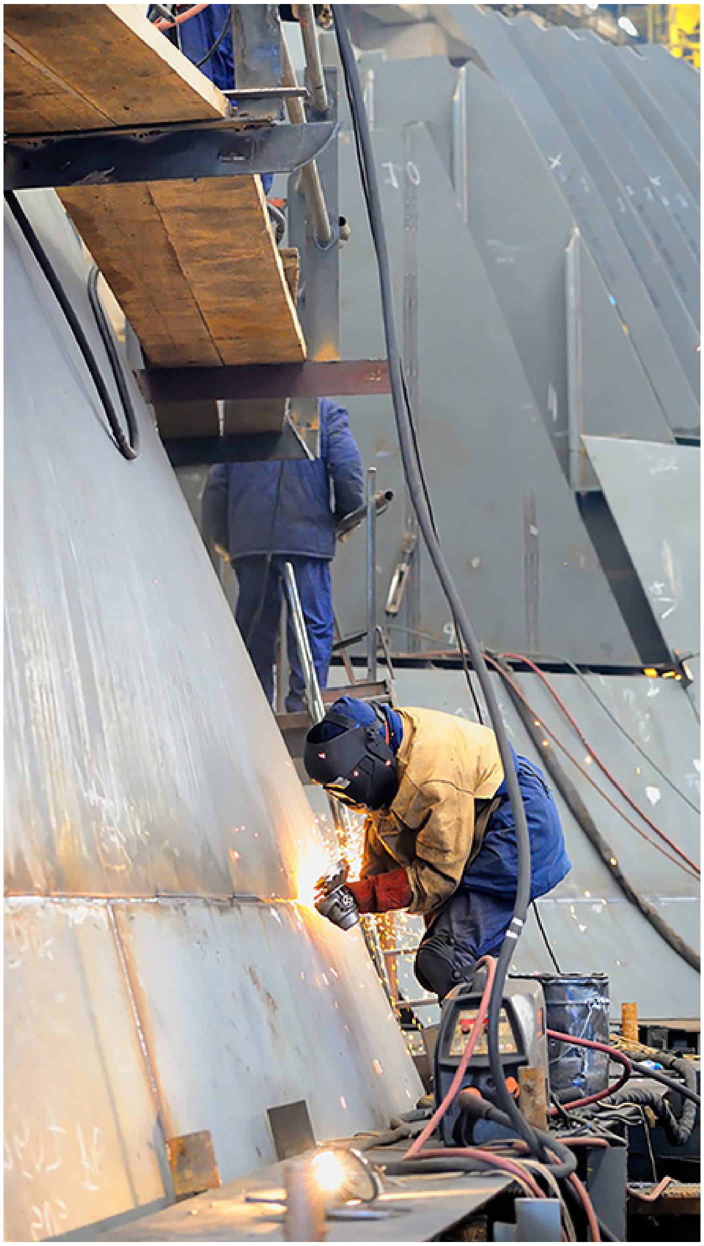
VISION STATEMENT

The vision for this national technology roadmap for materials joining and forming is to identify broad and compelling technology development initiatives that would positively transform these technologies and their application in industry to enhance the global competitiveness of the U.S. manufacturing sectors and the economy at large.

SCOPE

This roadmap focuses on materials joining and forming technologies and includes applications across all manufacturing sectors of the economy. Materials joining and forming are broad disciplines that include many specific technologies so some definition of what is covered in this document is useful for context.

Materials joining involve processes that join or bond or otherwise form an indelible joint between two or more materials or "pieces" into a single structural unit. For the purposes of this report, all processes used to join structural or engineered materials are considered except for wood, paper, and cloth. Of primary interest are metals, plastics, ceramics, and advanced composites such as metal-matrix composites (MMCs), ceramic-matrix composites (CMCs), and polymer-matrix composites (PMCs). These are the materials from which the vast majority of engineered and manufactured components are produced. Joining processes include everything except mechanical fasteners such as rivets, bolts, etc. Thus, the joining processes of relevance include all forms of electric arc welding, resistance welding, solid-state welding, brazing, soldering, adhesives, high energy welding processes such as laser, plasma, and electron beam, and hybrid variations of these processes. Some hybrid process combinations include laser-gas metal arc welding and resistance-braze welding.



This roadmap does not include additive manufacturing, also known as 3D printing. While additive manufacturing requires one or more materials joining processes, it is not incorporated into this document as other roadmapping efforts detailing needs in 3D printing have been completed under the AMTech program.

With respect to forming, the roadmap includes all metal forming operations. Some examples include: stamping, punching, deep drawing, crimping, forging, extruding, roll forming, powder forming, and wire drawing. Materials considered include all metals that have the ability to undergo the deformation and plastic flow required of forming operations.

The timeline for this roadmap covers a seven-year period beginning in 2017. Insight into technical needs beyond this period become less certain simply due to the pace at which technology develops along with changing economic and market forces—both on a domestic and global basis—that become much more uncertain on longer timescales.

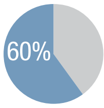
ROADMAP SUMMARY

Motivation for This Roadmap

The roadmap provides the results and recommendations from the Advanced Forming and Materials Joining Technology Roadmap project, funded by the National Institute of Standards and Technology (NIST) through the Advanced Manufacturing Technology Consortia (AMTech) program under contract 70NANB14H050. This project was performed by a consortium led by EWI that included U.S. materials joining and forming organizations from industry, academia, and professional societies. The project team identified and prioritized technology development needs in materials joining and forming technologies and provides a research and development portfolio to impact U.S. manufacturing competitiveness.

This roadmap presents a national perspective on the technical and economic needs of the materials joining and metal forming industries within the U.S. manufacturing economy. While other broad reviews and forward-looking reports on the state of these technologies have been published by various organizations over the years, it is believed that the detailed roadmap report represents the most comprehensive review and assessment carried out to date within the U.S. The roadmap is the culmination of more than two years of industry canvassing across every major manufacturing segment in the U.S. economy, and includes feedback from more than 400 companies that participated in focus group sessions, surveys and interviews. These companies span the spectrum from small, family-run businesses to large, multi-national conglomerates.

Nearly 60 percent of all manufactured goods include some joining and/or forming operations.



The importance of materials joining and forming technologies on the manufacturing base cannot be over-stated. Nearly 60 percent of all manufactured goods include some joining and/or forming operations. These operations are pervasive throughout manufacturers of all size in every sector of the economy. However, outside of the newer emerging manufacturing technologies, such as bio-engineering, ultra-clean room nano-manufacturing, and some advanced energy technologies, the more traditional and mature manufacturing technologies are often viewed within the U.S. as dangerous, dirty and dying, and thus are seen by some to have limited growth potential and minimal value for investment. Many companies have moved these operations overseas to take advantage of lower labor costs, relocating closer to growing markets and/or to tap into a larger labor pool as U.S. workers more frequently shun careers in these fields. Therefore, while the state of materials joining and forming in the U.S. has decayed by some measures over the last two or three decades, they are vibrant in some European, Asian, and South American economies. And, many countries in those regions have proactively invested in these technologies, not only to improve the ability of their manufacturers to engage in joining and forming manufacturing operations, but also to advance the state of the art to enhance the productivity and global competitiveness of their economies.

Today, there is a new wave of regulatory, economic and technical forces impacting U.S. manufacturers' ability to meet rapidly changing consumer demands, achieve higher levels of productivity in the face of a dwindling technical labor force, compete against lower-cost global manufacturers, and in some cases, meet new and more stringent government regulatory requirements. Pertinent examples include:

- New CAFE mileage standards in the automotive industry are driving the implementation of advanced ultra-high strength steels and aluminum alloys in frame and chassis construction. These emerging materials create significant technical challenges in joining and forming operations.
- Growing use of high-capacity batteries for increased battery life and higher voltage or current capacity to power electric vehicles, new generation smart phones and tablets, and a myriad of other consumer products, is creating significant challenges in the manufacture of these batteries, where often the critical components determining the safety and cycle life of a battery are the welded terminal connections.

- The demands for greater aircraft fuel efficiency and range are leading to the development of wide-body commercial aircraft made primarily of composites, resulting in a fundamental shift in how aircraft are designed and manufactured.
- The world's demand for fossil-based fuels will not reverse in any significant way until viable and economical alternatives are fully matured. As a result, oil & gas producers need to continue seeking reserves in deeper water and further from coastlines as the "easy" reserves are gradually exhausted. While the growth of on-shore

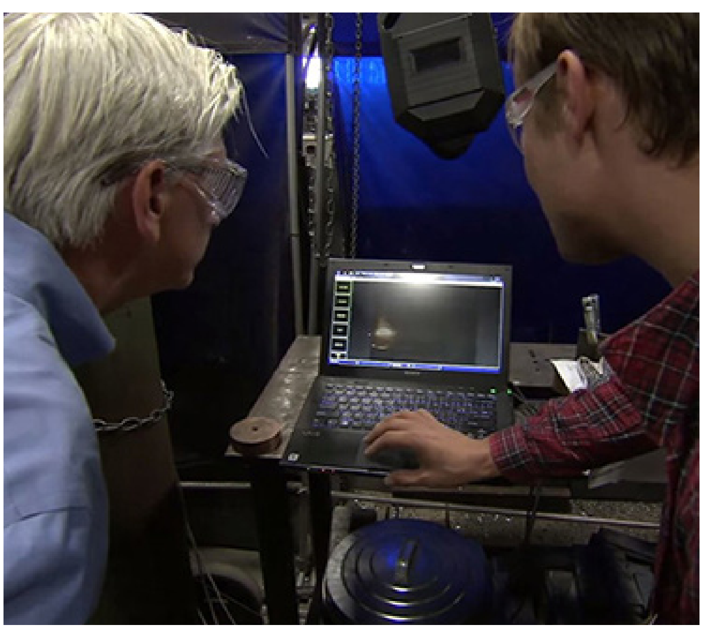
shale production has offered viable alternative sources, the very large scale of the remote deep water reserves will remain an important part of the fossil fuel portfolio for many years. The safety and performance demands for deep water infrastructure are challenging operators to adopt new advanced high strength steels and alloys that can safely operate at the higher temperatures and pressures encountered in these deeper waters. These new materials must also achieve the required safety margins for remote operations where failure of critical components will lead to possibilities for devastating environmental damage. Consideration of the corresponding economic impacts of such failures is also important. These demands are creating new challenges to how this infrastructure is welded and formed (such as large-scale forging operations) while ensuring longer service life.

Many other examples could be listed. Regardless, it is clear that the U.S. needs a renewed focus on advancing materials joining and forming technologies to address the emerging challenges and revive a critical part of the U.S. manufacturing base. Doing so would not only fundamentally improve the global competitiveness of U.S. manufacturers, but would bolster the middle class and reduce the trade balance deficit that has been steadily rising for more than two decades. With the recent growth of the shale energy industry here at home, a primary resource needed for large-scale fabrication intensive manufacturing operations is now readily available. This reduces the cost of energy for some manufacturing operations. Now the focus should turn to advancing the technologies associated with joining and forming and addressing workforce issues to grow the necessary technical labor force to realize a reinvigorated U.S. manufacturing base.

Roadmap Process

This roadmap was developed using input received from a broad industry canvassing effort that included industry focus group sessions held around the country and numerous online surveys seeking feedback on gaps and needs in materials joining and forming operations in manufacturing. These engagements were targeted to reach technicians, engineers, and managers in manufacturing companies of all sizes and in all major economic sectors. In addition, the canvassing included leading academic, government, and non-profit researchers working in the field of materials joining and forming. In total, more than 400 organizations participated in this two-year industry canvassing effort. Some companies participated in multiple focus group sessions. The canvassing activities were designed to understand current limitations in joining and forming applications for today's manufacturing requirements and identify key gaps and needs that, if addressed, would have significant positive impact on U.S. manufacturing competitiveness with respect to joining and forming operations.

Individuals participating in the canvassing activities suggested technology development topics that should be considered for the roadmap. In addition, numerous staff at EWI and within the organizations represented on the project steering committee, and other interested individuals and researchers aware of this effort, proposed technology development topics for consideration. In all, nearly 70 topics were submitted addressing most of the widely-used joining and forming technologies.



The data gathered from this broad industry canvassing program along with the collection of technology development topics submitted was analyzed with the valuable guidance and professional insight of the steering committee (members shown in Table ii-1). Using their input, the project team prioritized, ranked, and then down selected approximately 20 topics for final consideration. Two industry forums were then convened to provide industry an opportunity to consider this set of down-selected topics and then refine and finalize the technology development priorities. At the conclusion of this process, seven technology development priorities were selected.

In addition to technical gaps and needs impacting joining and forming, workforce development needs was a required element of the program. This proved to be particularly relevant as expanding the available pool of manufacturing labor while also improving their skills was found by a wide margin to be the most significant factor that would enhance U.S. manufacturing competitiveness.

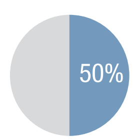
Overview of Current Gaps and Needs

While the volume of joining and forming operations has declined in the U.S. over the past two or three decades, significant advancements have been made in metals forming and materials joining technologies that have reduced manufacturing costs, increased performance, and improved quality and reliability of many of our manufactured products. However, these improvements have not been significant enough to retard the offshoring of many of these operations. Growing use of automation has partially offset a shrinking skilled labor force and increased quality while reducing costs. Development and maturation of new joining processes such as friction stir welding and laser-based brazing have dramatically improved the ability to produce products with a wider array of metal alloys that enhance performance of aircraft, spacecraft, watercraft, and automobiles. The advancement of micro-joining processes has revolutionized the electronics and medical device industries. Advanced brazing techniques allow use of specialized ceramics, metal matrix composites, and difficult-to-weld alloys that improve performance and reliability of critical components such as jet engines, allowing them to operate more efficiently at higher temperatures and pressures.

Regardless, many technical and business challenges impacting U.S. industry remain, and new ones are emerging on the horizon. Today, the U.S. is experiencing a materials revolution on a scale not seen in several decades. New ultra-high strength steels, aluminum alloys, and polymeric and composite materials are being developed to produce dramatic improvements in the performance in the transportation infrastructure. New materials used in the construction of buildings ranging from homes to high-rise commercial office space to advanced clean-room-style automated factories are designed to improve energy efficiency and withstand natural forces from earthquakes and severe weather events. The advancement of additive manufacturing, also known as 3D printing, is opening the door to manufacturing hybrid-material or multi-material products that allow the combination of a variety of metals or plastics in a single component or structure to take advantage of the economics and engineering performance of each material.

The increasing use of advanced materials creates significant challenges to the ability to join and form these materials, particularly with hybrid or mixed-material systems. In some cases, methods of joining have not been fully developed for advanced materials and industry is forced to use older, less efficient methods such as mechanical fastening or in some cases simply not being able to take advantage of these new materials until joining technology catches up. Likewise, difficulties exist in the forming of ultra-high strength steels and certain aluminum alloys now gaining greater use in the automotive industry. Current metal forming technology can often result in high scrap and re-work rates that impede broader application of these emerging materials. In addition, the cost of operating and maintaining metal forming equipment is sometimes prohibitive when used on these more advanced materials.

Aside from the technical gaps and needs that must be addressed to give industry the tools necessary to succeed in an increasingly complex manufacturing environment, the greatest obstacle facing U.S. manufacturers today is a dwindling skilled labor force. This issue was identified as the single most important hurdle impeding U.S. global competiveness—its significance far outpaced the technical challenges that were identified throughout the industry canvassing activities. In all but one of the industry focus group meetings organized during this project, it was agreed that an insufficient number of trained and qualified workers is the single most important issue impacting global competiveness.



In many companies, more than 50 percent of their technical work force is age 50 or older.

There are several factors linked to the workforce skills issue. First, the majority of the technical work force (consisting of engineers, scientists, technicians, and skilled trades and machine operator positions) is currently at mid- or late-stage career. In many companies, more than 50 percent of their technical work force is age 50 or older. The number of new graduates coming out of university, community college, and vocational school over most of the last two decades has been inadequate to maintain a reliable pipeline of technical workers to meet the growing retirement rate of the baby boomer generation. Over this period, the number of university students in the U.S. entering traditional manufacturing-related engineering and scientific degree programs has

been on the decline. This is compounded by a common societal perception that manufacturing puts workers in an environment that is dark, dirty, and dangerous. And, the perception exists—partly due to the loss of manufacturing jobs over the years to offshoring initiatives—that jobs in manufacturing are disappearing or dying. Consequently, it has become common for young students with an aptitude for science and math to gravitate towards newer technology fields such as bio-medical, bio-engineering, or the various information technology, computer science, and even financial analysis fields. Workforce expansion needs are broadly spread across the full spectrum from professional degreed technical positions to technicians and the skilled trades. In several companies it was noted that the shortage of trained skilled trade workers is more acute than for the degreed professional workers. Professional degreed workforce needs have often been met at least to some degree through immigration channels whereas the skilled trade workforce tends to more frequently consist of a local or regional labor pool and may be more difficult to augment without adequate local vocational or STEM training resources and a sufficient talent supply for those programs.

In addition to ensuring an adequate pipeline of newly graduated workers to enter the labor force, there is a growing need for further technical training of the existing incumbent workforce. Technology is advancing faster than ever and minimum skill levels to perform properly on the job continue to increase. Thus, frequent augmentation of skills in the existing labor force is an expanding need. While larger employers may have adequate resources to either coordinate their own internal training programs or fund staff training at established workforce development centers, smaller employers often lack the internal staff and resources to provide appropriate training for their workers. Consequently, small and medium-sized manufacturers risk falling behind. Additionally, companies that do invest in training programs for their staff often find their competitors eagerly offering employment opportunities at higher wages to these workers to take advantage of their new skills. This has created undesirable competition for labor that can be a disincentive to employers who proactively provide training programs.

Addressing workforce needs is a critical priority that will require collaboration and commitment from industry, academia, and vocational training institutions and government entities.

Recommendations

The data obtained from the extensive industry canvassing efforts along with the careful assessment of the steering committee and other project and industry stakeholders has led to a series of recommendations listed below. Successful accomplishment of these recommended actions would measurably advance the state of the art in materials joining and forming technologies, and provide U.S. manufacturers with critical capabilities that address today's and tomorrow's challenges while enhancing U.S. competiveness. Details of each priority listed below are given in the detailed roadmap report available from EWI. The technical priorities identified in this project are listed below in no particular order:

- Workforce skills development encompassing the emerging and incumbent labor force, and including technician, skilled trades and professional staff.
- Development of advanced weld distortion control methods.
- Development of next-generation prediction tools: automata materials exploration and optimization for joining processes.
- Development of advanced high-productivity fusion processes.
- Development of joining processes for hybrid materials and mixed metals.
- Implementation of advanced measurement, prediction, and control technologies in forming processes.
- Development of practical warm/hot forming technology for aluminum, titanium, nickel alloys, and steels.
- Development of advanced technologies for lightweight forgings.

U.S. manufacturers would gain differentiating capabilities if progress can be made on these priorities and technology advancements delivered to the manufacturing floor. These advancements would reduce waste, scrap and rework, increase productivity of joining and forming operations, and create abilities to manufacture products with material combinations currently not feasible with existing technology. The growth of hybrid and mixed material systems will greatly enhance performance, durability and quality of products on a level that does not exist today. If the U.S. leads the development of these technical advancements, U.S. manufacturers will reduce or eliminate current gaps on cost of production and create opportunities to be first to market with goods that would be difficult to manufacture elsewhere where these new capabilities do not exist.

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