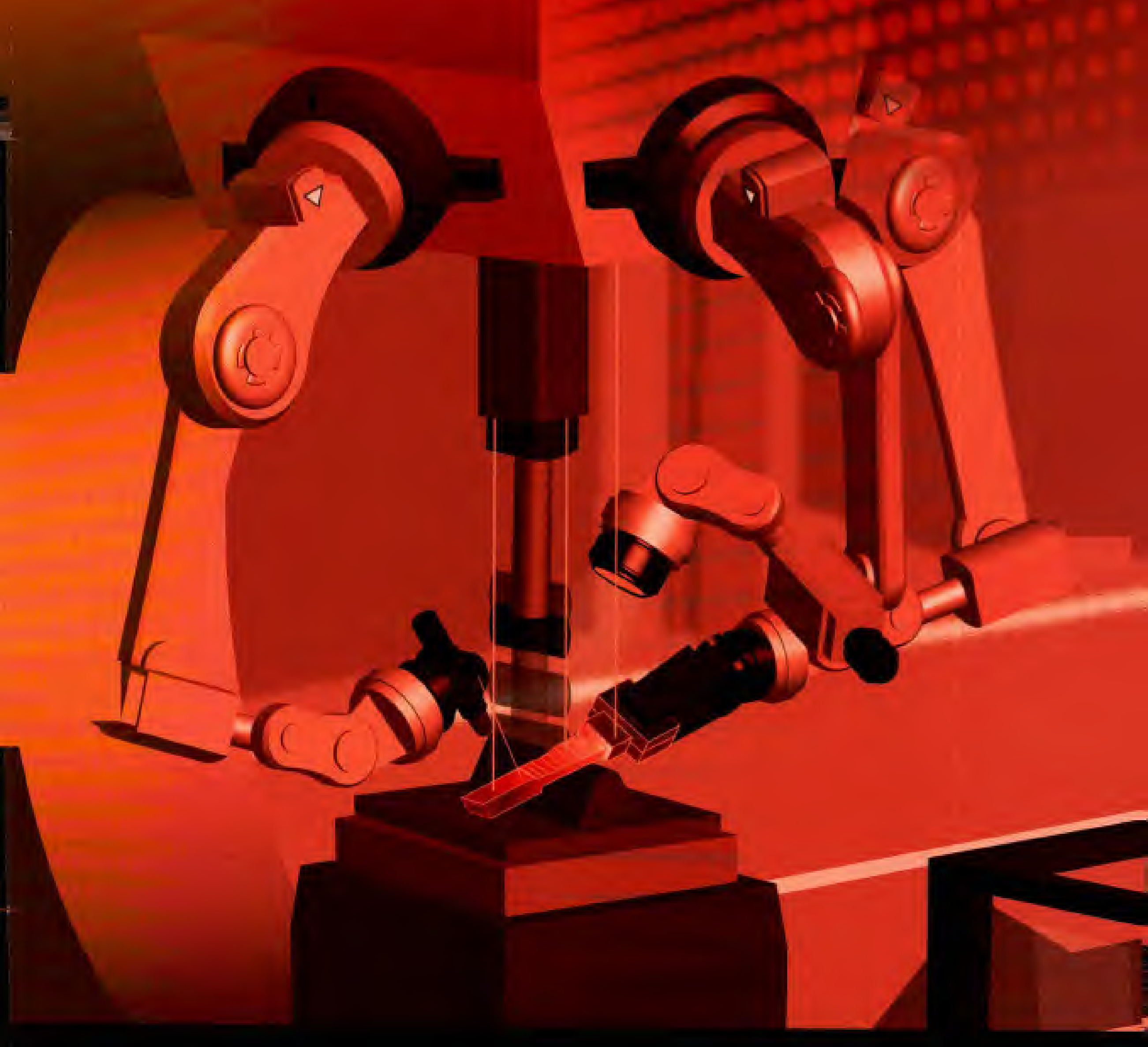
METAMORPHIC MANUFACTURING

Shaping the Future of On-Demand Components



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14. ABSTRACT
Metamorphic manufacturing (MM) can be concisely described as a new, revolutionary approach to manufacturing that relies on closed-loop, numerically controlled, incremental forming to simultaneously achieve complex shapes, specific engineering properties and local microstructures. Metamorphic manufacturing has also been referred to as robotic blacksmithing, with the skill and force of the human blacksmith replaced by robotic systems. Five fundamental elements that provide the basis for the full implementation of metamorphic manufacturing (STARC) are: sensors, thermal control, actuators and forming tools, robotic manipulation systems, and computation

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Metamorphic Manufacturing: Shaping the Future of On-Demand Components

METAMORPHIC MANUFACTURING

Shaping the Future of On-Demand Components

A STUDY ORGANIZED BY

The Minerals, Metals & Materials Society (TMS)

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The Minerals, Metals & Materials Society (TMS)

Promoting the global science and engineering professions concerned with minerals, metals, and materials

The Minerals, Metals & Materials Society (TMS) is a member-driven, international organization dedicated to the science and engineering professions concerned with minerals, metals, and materials. TMS includes more than 13,000 professional and student members from more than 70 countries representing industry, government and academia.

The society's technical focus spans a broad range—from minerals processing and primary metals production to basic research and the advanced applications of materials.

In recent years, TMS has particularly established itself as a leader in advancing integrated computational materials engineering, computational materials science and engineering, multiscale materials modeling and simulation, and materials data infrastructure issues.

To facilitate global knowledge exchange and networking, TMS organizes meetings; develops continuing education courses; publishes conference proceedings, peer-reviewed journals, and textbooks; leads technology studies and reports; and presents a variety of web resources accessed through www.tms.org.

TMS also represents materials science and engineering professions in the accreditation of educational programs and in the registration of professional engineers across the United States.

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TMS is committed to advancing diversity in the minerals, metals, and materials professions, and to promoting an inclusive professional culture that welcomes and engages all who seek to contribute to the field.

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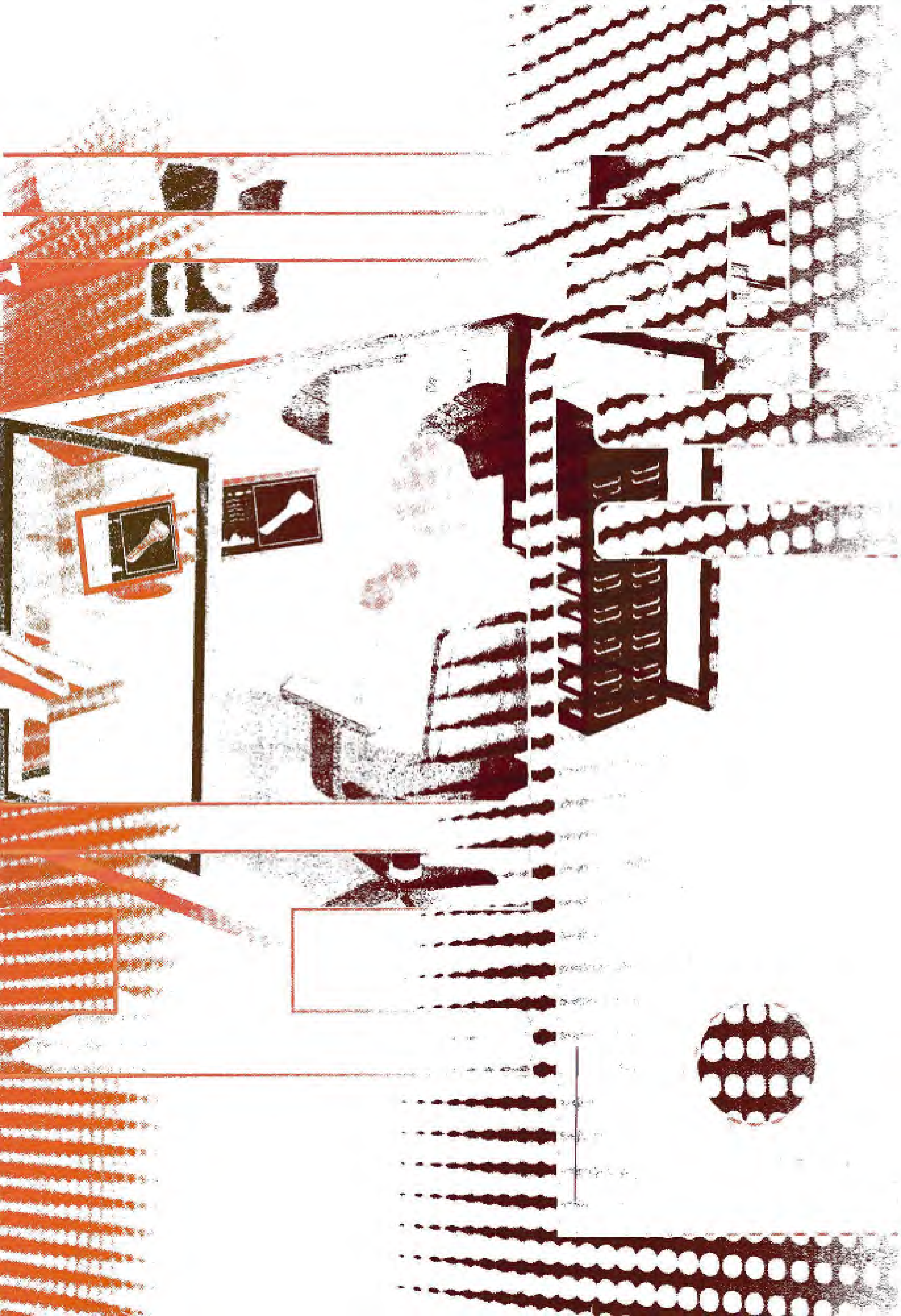

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Acknowledgements

Metamorphic Manufacturing: Shaping the Future of On-Demand Components is a culmination of the efforts of globally recognized technical experts from across academia, industry, and government, who volunteered significant time to this study. Collectively, these experts participated in online meetings and teleconferences, in-person meetings, interviews, writing, editing, and reviewing this document.

The dedication and active involvement of all of these experts has been the major foundation of this effort, and the value of their time and contributions cannot be overstated. We express our sincere gratitude for their hard work and are confident that it will have a lasting impact on the community. The content of this report is reflective of the culmination of their efforts, and in no way represents the specific views of any of the individuals who contributed to this report, or any of their employers and/or affiliated organizations.

Glenn Daehn, *Metamorphic Manufacturing* Committee Chair
George Spanos, *Metamorphic Manufacturing* Project Leader

Lead Study Team

Glenn Daehn, Study Team Chair

Mars G. Fontana Professor of Metallurgical Engineering, The Ohio State University

Glenn S. Daehn is the Mars G. Fontana Professor of Metallurgical Engineering within the Department of Materials Science and Engineering at The Ohio State University. The focus of his work spans from process innovation in creating new manufacturing processes, to providing authentic content and professional development for K-12 STEM teachers, to advancing manufacturing policy with a focus on the role of the 21st-century land grant university. Most of his current process innovation work is in developing impulse-based manufacturing processes for the joining, shaping, and cutting of material. Daehn is also active in a number of manufacturing initiatives, playing a key role in establishing the Lightweight Innovations for Tomorrow Manufacturing USA institute, the Ohio State Center for Design and Manufacturing Excellence, and the Ohio Manufacturing Institute. He also serves on the executive committee for MForesight (Alliance for Manufacturing Foresight). He received his Ph.D. in materials science and engineering from Stanford University and an undergraduate degree from Northwestern University.

John Allison

William F. Hosford Professor of Materials Science and Engineering, University of Michigan

John Allison's major research interests encompass understanding the inter-relationships between processing, alloying, microstructure, and properties in metallic materials, and then incorporating this knowledge into computational tools for use in research, education, and engineering. Within this scope, Allison has dedicated himself to the development of integrated computational materials engineering (ICME) as a discipline. Allison is also the director of the Predictive Integrated Structural Materials Science center, where his research is focused on quantifying the influence of alloying and processing on microstructural evolution and mechanical behavior in magnesium alloys. Prior to his current roles with the University of Michigan, Allison was the senior technical leader of Research and Advanced Engineering for the Ford Motor Company, while also serving as an adjunct professor at the University of Michigan and Wayne State University in Detroit, Michigan. His career in materials science and engineering includes serving as a visiting scholar and scientist for Monash University in Melbourne, Australia and Brown Boveri and Company in Baden Switzerland, respectively, and working for the U.S. Air Force.

Allison has been inducted as a member of the National Academy of Engineering, is a Fellow of both TMS and ASM International, and was the 2002 TMS president. He earned his B.S in mechanical engineering from the U.S. Air Force Academy in Colorado Springs, Colorado, his M.S in metallurgical engineering from The Ohio State University in Columbus, Ohio, and his Ph.D. in metallurgical engineering and materials science and engineering from Carnegie Mellon University in Pittsburgh, Pennsylvania.

Elizabeth Bilitz

Metallurgy Manager, Finkl Steel

In her role as metallurgy manager for Finkl Steel (based in Chicago), Elizabeth Bilitz leads a team of metallurgical engineers to improve process and drive innovation and development. Bilitz is the dean of Finkl's Annual Forging Forum, a program that brings students from the Colorado School of Mines to a Finkl plant to receive in-class instruction that is coordinated with shop floor tours. Bilitz has held progressively responsible roles, ranging from specification and processing metallurgist to estimating and marketing manager and technical product manager. She contributes to the Schmolz + Bickenbach Research and Development Group and assists with the Forging Industry Association's Forging Industry Educational and Research Foundation educational outreach. Bilitz earned her undergraduate and master's degrees from the Illinois Institute of Technology in materials science and engineering, where she was a member of the Material Advantage program.

David Bourne

Principal Scientist, Carnegie Mellon University

David Bourne is one of the founding members of the Robotics Institute at Carnegie Mellon University (CMU). Bourne has spent the past 39 years working in the areas of artificial intelligence, robotics and manufacturing, robotics and medicine, and robotics and education. Bourne is also the director of CMU's Rapid Manufacturing Laboratory, which has built a large flexible manufacturing cell for Westinghouse, the Intelligent Machining Station for the U.S. Air Force, and the Intelligent Bending Workstation for Amada Co. Ltd (a sheet metal machine tool manufacturer). Much of Bourne's current work examines how humans can most effectively participate in a robot-centric society without losing sight of what's important to the human experience. This research has been carried out through collaborative efforts with organizations including Defense Advanced Research Projects Agency. In the area of 3D printing, Bourne is focusing on "additive assembly" which is the process of mixing additive manufacturing with the assembly process inline. Bourne has written more than 80 papers in areas applying artificial intelligence to manufacturing and holds nine patents in related areas. He also co-authored the book Manufacturing Intelligence published by Addison Wesley and directed and produced a PBS short series on the topic of mass customization by applying high technology to manufacturing applications. Bourne earned his Ph.D. in computer science at the University of Pennsylvania in Philadelphia, Pennsylvania.

Jian Cao

Cardiss Collins Professor, Northwestern University

Jian Cao is the Cardiss Collins Professor, director of the Northwestern Initiative for Manufacturing Science and Innovation, and an associate vice president for research (AVPR) at Northwestern University. Her research focus is integrating analytical and numerical simulation methods, control and sensors, and design methodologies to advance manufacturing processes, with current work on incremental forming and additive manufacturing. In her role as an AVPR at Northwestern, Cao fosters collaboration among the physical sciences, engineering, and other disciplines across and beyond the university. She is also a board member of mHUB, Chicago's first innovation center focused on physical product development and manufacturing. Cao is the editor in chief of the *Journal of Materials Processing Technology*. Cao is an elected Fellow of American Association for the Advancement of Science, Society of Manufacturing Engineers (where she also served as president of its North American Manufacturing Research Institute), the International Academy for Production Engineering, and the American Society of Mechanical Engineers (where she served as chair of their Manufacturing Engineering Division). Cao received her Ph.D. and M.S. in mechanical engineering from Massachusetts Institute of Technology in Cambridge, Massachusetts, and her B.S. in materials science and engineering and automatic control from Shanghai JiaoTong University in Shanghai, China.

Kester Clarke

Forging Industry Educational and Research Foundation (FIERF) Professor, Assistant Professor, Colorado School of Mines

Scientist, Pacific Northwest National Laboratory

In addition to being an assistant professor in the Metallurgical and Materials Engineering Department at Colorado School of Mines (CSM) in Golden, Colorado and serving as the Forging Industry Education and Research Foundation (FIERF) Professor at CSM, Kester Clarke holds a joint appointment as a Scientist at Pacific Northwest National Laboratory. He engages in research on deformation processes in metal alloys with the university's Center for Advanced Non-Ferrous Structural Alloys and Advanced Steel Processing and Products Research Center. His research interests include alloy development, material deformation and fabrication processes, and the use of experimental and modeling methods to examine the effect of material processing history and microstructure on mechanical properties and performance. Clarke's prior experiences include metallurgical engineer for Engel Metallurgical, senior engineer for Caterpillar, and postdoctoral researcher, R&D Engineer, and Scientist at Los Alamos National Laboratory, where he is also currently a visiting scientist.

Clarke has served on the Association for Iron and Steel Technology's (AIST) Board of Directors, is the chair for the TMS Shaping and Forming Committee, and is the past chair of the AIST Metallurgy–Processing, Products and Applications Technology Committee. He received a B.A. in psychology from Indiana University, a B.S. in materials science and engineering from Wayne State University, and M.S. and Ph.D. degrees in metallurgical and materials engineering from CSM.

Johnnie J. DeLoach Jr.

Division Head, Materials, U.S. Naval Surface Warefare Center, Carderock Division

In addition to serving as head of the Materials Division at the Naval Surface Warfare Center, Carderock Division, Johnnie J. DeLoach Jr.'s primary technical concentration includes additive manufacturing, high-strength steels (including castings), materials processing, integrated computational materials engineering, friction stir welding, nondestructive evaluation, and weldability assessment and procedure development for metals used in U.S. Navy ships and submarines. DeLoach is the U.S. National Representative on the Metals and Ceramics Technology and Performance Panel of The Technical Cooperation Program. He has served as chair for the Naval Sea Systems Command Warfare Center Navy Materials Community of Interest, a collaboration intended to enhance synergy, teaming, and expertise in materials and materials-related technologies. In 2013, the Office of Naval Research selected him to manage The Lightweight and Modern Metals Manufacturing Innovation Institute, a U.S. presidential initiative. He is also the government program manager of the Lightweight Innovations for Tomorrow (LIFT) manufacturing institute. DeLoach earned his B.S. in materials science and engineering from Brown University in Providence, Rhode Island and his M.S. in materials science and engineering from Johns Hopkins University in Baltimore, Maryland. He has been inducted as a counselor of the American Welding Society for lifetime contributions to the welding industry.

Ed Herderick

Director, Additive Manufacturing, The Ohio State University Center for Design and Manufacturing Excellence

In his role as director of additive manufacturing at The Ohio State University's Center for Design and Manufacturing Excellence (CDME), Edward D. Herderick is responsible for all of CDME's additive-related activities, including providing industrial education to students, managing user facilities for faculty and partners, and bringing manufacturing innovation to Ohio industry. A primary focus of Herderick's career has been industrialization and implementation of complex materials-intensive manufacturing methods including additive manufacturing, coatings, joining, and inspection techniques.

Prior to his role with CDME, Herderick served in two different positions with General Electric (GE). He initially joined the company as the additive technologies leader for its Corporate Supply Chain and Operations branch and was then promoted to global sales leader for the Inspection Technologies branch, where he led an initiative on inspection and nondestructive testing of additively manufactured metal parts. Prior to GE, Herderick worked as director of research and development at Rapid Prototype + Manufacturing and was director of the additive manufacturing consortium and materials engineer at Edison Welding Institute in Columbus, Ohio. He is currently the industrial editor for *JOM*, published by The Minerals, Metals & Materials Society. Herderick received his Ph.D. from The Ohio State University in materials science and engineering.

John Lewandowski

Arthur P. Armington Professor of Engineering II, Case Western Reserve University

In addition to his duties as Arthur P. Armington Professor of Engineering II, John J. Lewandowski serves as the director of the Advanced Manufacturing and Mechanical Reliability Center (AMMRC) at Case Western Reserve University (CWRU) in Cleveland, Ohio. His research interests are concentrated on processing/structure/property relationships in engineering materials, with a specific focus on deformation processing, fatigue and fracture, advanced engineered materials systems, and additive manufacturing. Prior to joining CWRU, he worked for two years as a North Atlantic Treaty Organization/National Science Foundation (NATO/NSF) postdoctoral fellow at Cambridge University. Lewandowski has served on panels organized by NSF, the U.S. Department of Energy (DOE), and the U.S. National Academy of Sciences/National Research Council, and has chaired the joint TMS/ASM Composites Committee. He is ASM Fellow and Overseas Fellow at Churchill College, University of Cambridge in addition to Visiting Summer Professor at Nanyang Technological University, Singapore. He was also the innovation impact team lead on materials for extreme environments as part of the *Linking Transformational Materials and Processing for an Energy-Efficient and Low Carbon Economy: Creating the Vision and Accelerating Realization* report series project organized by TMS on behalf of the DOE Advanced Manufacturing Office. Lewandowski has published more than 325 papers and co-organized multiple conferences, including one Gordon Conference on Physical Metallurgy. He earned his B.S., M.E., and Ph.D. in metallurgical engineering and materials science at Carnegie Mellon University, where he was a Hertz Foundation fellow.

Tony Schmitz

Professor, University of North Carolina at Charlotte

Tony Schmitz is currently a professor of mechanical engineering and engineering science at the University of North Carolina at Charlotte, where his research interests are machining dynamics, manufacturing process modeling, uncertainty evaluation, and displacement measuring interferometry. Prior to this, he completed a postdoctoral appointment and worked as a mechanical engineer at the National Institute of Standards and Technology, and served as a member of the Department of Mechanical and Aerospace Engineering at the University of Florida. Schmitz has been named to the Society of Manufacturing Engineers College of Fellows and has been awarded a National Science Foundation CAREER award, in addition to serving as an associate editor for the American Society of Mechanical Engineers *Journal of Manufacturing Science and Engineering*. He received his B.S. in mechanical engineering from Temple University in Philadelphia, Pennsylvania, and his M.S. and Ph.D. in mechanical engineering from the University of Florida in Gainesville, Florida.

Howard Sizek
Branch Chief, U.S. Air Force Research Laboratory
Howard Sizek is branch chief in the Propulsion, Structures & Manufacturing Enterprise Branch (RXMS) of the U.S. Air Force Research Laboratory (AFRL) Manufacturing and Industrial Technologies Division. Areas of expertise for the RXMS branch of AFRL include robotics, additive manufacturing, machining, and metal forming. Prior to his work with AFRL, Sizek worked in the nickel alloy metals production industry with Inco Alloys International and Special Metals. His experience with the nickel alloy metal production industry ranged from supervising mechanical testing laboratories and laboratory heat treatment facilities to modeling metal working processes (including open die forging, rolling, and heat treating). He also developed and characterized alloys for high temperature corrosive environments. Sizek has served on the TMS Program and TMS Mechanical Metallurgy Committees, as well as the ASM Database Committee. He earned his Ph.D. in materials science and engineering from Northwestern University, a B.S. in mechanical engineering from Washington University in St Louis, Missouri, and a B.A. in pre-engineering from Illinois College.

A. Erman Tekkaya
Professor, TU Dortmund University, Germany
A. Erman Tekkaya is the director of the Institute for Metal Forming and Lightweight Components (IUL) at the Technische Universität Dortmund in Dortmund/Germany. His research interests cover fundamentals and technology of novel metal forming processes as well as material characterization for modelling the material behavior during plastic deformation. Some of his current research projects are on thermo-mechanical sheet-forming processes, profile bending, hot extrusion, impact extrusion, damage-controlled metal forming, the in-plane torsion test and remote material testing. Tekkaya is a fellow of the International Academy for Production Engineering and a member of the Deutsche Gesellschaft für Materialkunde. He received his BS and MS degrees in mechanical engineering at the Middle East Technical University, Ankara/Turkey. Tekkaya conducted his doctoral research at the Institute of Metal Forming at the University of Stuttgart, Germany and received his degree in 1985. After serving as professor at the Mechanical Engineering Department of the Middle East Technical University, he was the Founding Director of the Center of Excellence in Metal Forming in Ankara. He is the former editor in chief of the *Journal of Materials Processing Technology*, and is currently the chairman of The German Metal Forming Association.

The dedication and active involvement of all of these experts has been the major foundation of this effort, and the value of their time and contributions cannot be overstated. We express our sincere gratitude for their hard work and are confident that it will have a lasting impact on the community. The content of this report is reflective of the culmination of their efforts, and in no way represents the specific views of any of the individuals who contributed to this report, or any of their employers and/or affiliated organizations.

Final Report Review Team

Following the writing and editing of multiple drafts of this final report by the TMS science and engineering staff and the lead study team, an independent review team provided valuable, detailed comments and suggestions for implementation into the final report. These efforts are gratefully acknowledged. Members of this review team are:

- **Richard Fonda**, Section Head, U.S. Naval Research Laboratory; Program Officer, Office of Naval Research
- **Alexis Lewis**, Program Director, The National Science Foundation
- **Tom Mahoney**, Associate Director, MForesight
- **William Mullins**, Program Officer, Office of Naval Research
- **Mohsen Seifi**, Director of Global Additive Manufacturing Programs, ASTM International
- **Chuck Ward**, Chief of Manufacturing and Industrial Technologies Division, Air Force Research Laboratory

Other Key Contributers

This report was sponsored by the Office of Naval Research (Contract # N0014-18-P-2001). The Lightweight Innovations for Tomorrow (LIFT) manufacturing institute, and in particular Alan Taub (Senior Technical Advisor for LIFT), are also gratefully acknowledged for their support of the metamorphic manufacturing technology and this study. The project leader of this study and report was George Spanos, TMS Director of New Initiatives, Science, and Engineering, with support from Michael Rawlings, TMS Science and Engineering Lead, Owen Daly, TMS Technical Communications Specialist, and Justin Scott, TMS Technical Project Lead and *JOM* Principal Editor. The lead study team of volunteer technical experts provided the detailed study inputs and content, which were compiled into this final report format through the efforts of TMS staff and Nexight Group, LLC. Other important TMS staff contributions to this report include those of Matt Baker (Content Senior Manager), Maureen Byko (Editor, *JOM*), Angela Cleri (TMS Technical Intern), Bob Demmler (Graphic Designer), Diana Grady (Customer and Administrative Services Specialist), David Rasel (Media Manager), Lynne Robinson (Marketing and Communications Manager), Marleen Schrader (Accounting and Human Resources Specialist), and Janel Show (Customer and Administrative Services Manager). Nexight staff members who provided invaluable contributions to this effort include Ross Brindle (Chief Executive Officer), Jared Kosters (Technical Project Manager), Jack Holmes (Technical Project Associate), and Changwon Suh (Senior Technical Consultant).

Preface

What is Metamorphic Manufacturing?

New technical ideas provide opportunities to do things differently and, possibly, disruptively. Metamorphic manufacturing (MM) is a new approach to manufacturing that is currently under development. It relies on closed-loop, numerically controlled, incremental forming to achieve simultaneously complex shapes, and specific engineering properties and local microstructures. Following the first two waves of digital manufacturing—computer numerical controlled (CNC) machining and additive manufacturing— MM has been referred to as the third wave of digital manufacturing. It overcomes some of the limitations of both CNC machining and additive manufacturing by combining the incremental thermo-mechanical deformation of a metalsmith with the precision and control of intelligent machines and robotic systems, and thus is also referred to as robotic blacksmithing. This agile manufacturing methodology is especially suited for making small batch, complex, customized parts rapidly, and in a highly economical way. As a possibly disruptive technology, MM has the potential to provide new market opportunities, and could even change the technical hierarchy within companies, regions, and/or countries. Although metamorphic manufacturing has been very briefly summarized here in the Preface, the rest of this report will delve deeply into the background, value, underlying technologies, challenges, and opportunities associated with MM. It will also provide a number of detailed recommendations and actionable tactics to help jump-start the development and growth of this promising new technology.

Who should read this report and why?

This report should be of interest to technical leaders, technical policy leaders, economic policy leaders, and those who are interested in technical development for economic and national security. This report contains detailed information, analyses, and recommendations regarding this potentially disruptive manufacturing technology that will be of high value to scientists and engineers within the materials science and engineering (MSE) and manufacturing communities, as well as to individuals from a number of related disciplines (e.g., robotics, mechanical engineering, computer science), spanning academic, industrial, and governmental sectors. Any federal agencies, private entities, national initiatives (such as Manufacturing USA institutes) or other institutions that support or fund the development or production of manufactured, performance structures or parts will also find this report useful. Many such stakeholders will especially benefit from the assessment of current technical challenges and the recommended action plans provided to further the development of this technology.

Since much of the content in this report relates to shaping the future of advanced manufacturing—particularly within the MSE and manufacturing communities—individuals and organizations who influence the futures of these communities may be able to profit by leveraging the insights from this report. Beyond those experts who can directly contribute to and benefit from this technology, other groups that may be interested in the contents of this report include (1) policymakers at the local, state, and federal level, (2) educators teaching undergraduate and graduate courses on materials engineering, manufacturing, robotics, and/or advanced computation, and (3) department heads and/or deans looking to advance the curriculum around these topical areas. Finally, those who may be engaged in interdisciplinary projects from communities other than MSE and manufacturing, which intersect any of the disciplines mentioned in this report, may also acquire valuable insight from reading it.

How to navigate this report

Readers are encouraged to navigate this report by first examining the Executive Summary to get an overview of the overall structure and highlights of this document and determine which parts might be of most relevance to your expertise, interests, and organizational mission. It is our hope that this report will inspire you to take specific actions consistent with your skills and interests, to support development and eventual widespread implementation of these MM techniques. The Value Proposition section clearly articulates some of the potential advantages of this new technology while the Introduction section provides insight into the current landscape. The Challenges section is meant to prompt you and your colleagues to think critically about the challenges that most impede rapid development of MM and identify the challenges to which you may be able to contribute solutions. In both the Opportunities/Recommendations and Action Plans sections, you will find suggested tactics and actionable next steps to overcome barriers and accelerate development and implementation of this important technology. Hopefully, as you explore these sections, you will begin to focus on the tactical details that resonate most with your interests and expertise, and will prioritize some specific actions that you and your colleagues might undertake.

Call to Action: What action should be taken after reading this report?

A primary goal of this study is thus to stimulate direct action by a wide variety of stakeholders who read this report. Such actions should be centered on furthering the development and adoption of this potentially revolutionary technology. After reading this report, some general next steps could include: (1) identifying specific challenge or tactical recommendation areas that you and your colleagues could address, and from which the most benefit would be gained, (2) sketching out a detailed action plan, and (3) taking concrete steps to initiate this activity. These steps would be different depending on your role and area(s) of interest.

Due to the necessary integration of multiple technologies that will be required to enable MM, it is clear that experts from MSE, manufacturing, and many other communities must work collaboratively to address many of the challenges and recommendations presented in this report. It will be critical to engage others beyond MSE and manufacturing in this discussion, including experts in the fields of robotics, mechanics of materials, statistics, signal processing, computer science, image analysis, data sciences and informatics, software engineering, physics, chemistry, mechanical engineering, and multidisciplinary design optimization, to name a few. Identifying and establishing effective interdisciplinary collaborations will be a vital part of realizing the full potential of this approach.

The specific recommendations and action plans identified within this report should in no way be viewed as all-inclusive, and the leaders, researchers, and policy makers who read it are encouraged to develop and execute other activities and tactics as well as to address the needs and challenges associated with this emerging technology.

Our desire is that the readers will act promptly on the recommendations of this report. Although much work remains to be done, the potential is great for making both impactful short-term progress and foundational longer-term contributions to accelerate implementation and maintain sustainability of this potentially game-changing manufacturing technology.

Executive Summary

Background and Motivation

Metamorphic manufacturing (MM) can be concisely described as a new, revolutionary approach to manufacturing that relies on closed-loop, numerically controlled, incremental forming to simultaneously achieve complex shapes, specific engineering properties and local microstructures. Metamorphic manufacturing has also been referred to as robotic blacksmithing, with the skill and force of the human blacksmith replaced by robotic systems.[1,2] Metamorphic manufacturing was identified by technical leaders at the Lightweight Innovations for Tomorrow (LIFT) manufacturing institute, and considered to be the third wave of digital manufacturing (i.e., following CNC machining and additive manufacturing).[1,2]

Five fundamental elements that provide the basis for the full implementation of metamorphic manufacturing (and can be represented by the acronym, STARC) are:

S–sensors

T–thermal control

A–actuators and forming tools

R–robotic manipulation systems

C–computation

Metamorphic manufacturing is thus synopsized graphically in Figure 1 (reproduced from Section I). Reduced versions of this vision can also be accomplished without sensing and closed-loop operations, or thermal treatment.

Figure 1. Synopsized illustration of metamorphic manufacturing (MM), including the five fundamental elements represented by the acronym STARC (Sensors; Thermal control; Actuators and forming tools; Robotic manipulation systems; Computation).

A more complete synopsis of MM is provided in the one page summary of key ideas and concepts on the next page (reproduced from Section I).

METAMORPHIC MANUFACTURING

Shaping the Future of On-Demand Components

What it is MM? A new approach to manufacturing that relies on closed-loop, numerically controlled, incremental forming to simultaneously achieve complex shapes, specific engineering properties, and local microstructures. It has also been referred to as "*Robotic Blacksmithing*", and "*The Third Wave of Digital Manufacturing*" (i.e., after CNC machining and additive manufacturing).

Why does MM matter? It is a new, powerful, agile way to make components that attempts to optimize component shape and properties using well-understood concepts from thermal mechanical processing of metals. MM leverages many rapidly emerging foundational technologies (see below) to make something very new. It also offers investment opportunities for technology leaders and researchers in new areas for R&D, technology integration, and manufacturing innovation.

Foundational Constituent Technologies

S - senors	**T** – thermal control	**A** – actuators/forming	**R** - robotic systems	**C** - computation
Real-time monitoring of Dimensions/geometry Thermal properties Mechanical properties Acoustics/ ultrasonics, etc.	Thermal-mechanical processing including control of localized temp., heat treating atmosphere, heating and cooling rates, etc.	Variety of tools for incremental forming: Hammers Presses English wheels Spinning devices, etc.	System of precise robotic arms & manipulators for: workpiece positioning, integration with actuators/tools, reproducibility, etc.	Computational brain at center of MM operation: specify sequencing & tool paths, control robotics, collect sensor data, make real-time decisions, predictive simulations.

Some things we should learn from past, allied work

Human Blacksmiths	CNC Machining	Additive Manufacturing	Related R&D	Standards/Qualification
Shown how a wide variety of shapes can be formed with limited strength, power, reproducibility, dimensional accuracy, temperature control	Demonstrated ability to create parts from code, without storing dies or forms. Represents first wave of digital manufacturing.	Demonstrated creation of complex parts without using tools or dies. Limited control, high embodied energy, and low build rates all limit future capabilities.	R&D in some areas has provided MM foundation, but must be integrated into a cohesive whole. E.g., sensors, thermo-mechanical treatment, incremental forming, robotics, A.I., simulation.	Implementation of any new manufacturing technology is limited by methods for assuring qualification for safety-critical applications. Fundamental work is required here for MM.

What's next? Build awareness of MM and it's value, foster research opportunities and industry projects, establish technology demonstrations, build prototype process suites and/or demonstration facilities, develop computational codes/simulations, develop standards, educate and develop the MM workforce, garner fiscal support/investment for these MM efforts. Read the full report for MM needs, opportunities, and detailed recommendations.

The underlying component technologies of MM have not yet been synthesized into a cohesive whole. When that occurs, it is believed that MM could become a disruptive technology whose realization would provide great strategic, economic, and national security benefits for the United States.[1,2] Considering the potentially disruptive nature of metamorphic manufacturing, the overarching objective of this study and final report is to jump-start the emergence, development, and growth of this new technology.

Study Process

This technology study, *Metamorphic Manufacturing: Shaping the Future of On-Demand Components*, was executed by The Minerals, Metals & Materials Society (TMS) on behalf of the U.S. Office of Naval Research (ONR) and the Lightweight Innovations for Tomorrow (LIFT) manufacturing institute. A team of 12 internationally recognized experts was convened by TMS via online meetings, homework assignments, and two professionally facilitated (by Nexight Group, LLC) two-day in-person workshops, which generated the bulk of the content of this report. Those outputs were distilled into the final study report, which was iteratively edited by the lead study team, TMS science and engineering staff, and an independent final review team of experts (as listed in the Acknowledgements section). TMS staff then completed all copy editing, design, graphics, and production of the final report.

Value Proposition

Since MM is a technology in its infancy, it is critical to first identify and communicate the benefits that MM will provide if adopted. Such value propositions provide the motivation for pursuing and investing in any new technology. The overarching value of MM lies in its ability to achieve both low raw materials loss and tailored material properties while providing for agile manufacturing and economical production of small-batch, complex, customized parts. More specifically, some of the key benefits of MM are provided in Table 1 below (reproduced from Section II), and discussed in detail in Section II of this report.

Table 1. MM Value Proposition and Key Benefits

Value Proposition Categories	Key Benefits
Economical and Environmentally Friendly	Lower material waste
	Little (or no) need for die fabrication and storage
	Reduced energy consumption and carbon footprint
Shape and Property Control	Superior local property control
	Unique, highly complex shapes/geometries
	Larger build envelope
	Optimization of process routes and properties via iteration (possibly aided by machine learning)
Superior Manufacturing Flexibility and Accessibility	Expanded suite of materials options
	Attractive product lines for many small and medium sized businesses
	Small batch production and part design variability capabilities
	Short lead time from concept to production

Conceptual MM Equipment Suite

Building on the five fundamental elements mentioned previously (STARC), it is useful to lay out a conceptual equipment suite or part production line for MM in order to assist the community in developing MM facilities. Although specific MM equipment suites that are actually developed may differ and/or contain additional elements, the conceptual suite illustrated in Figure 11 (reproduced from Section IV) and the related discussion in section IV provide a framework from which interested parties can begin to develop their own MM capabilities, or possibly inspire an entrepreneurial company to develop a system for sale or distribution.

Figure 11. Conceptual metamorphic manufacturing equipment suite (containing the five fundamental elements of metamorphic manufacturing represented by the acronym STARC, and described above).

Challenges and needs for the emergence and growth of MM

Thirty-eight specific technical challenges and needs, which could also be viewed as domains of opportunity for the development and widespread adoption of MM, have been identified. The 11 highest-priority challenges, arranged in six different categories, are shown in Table 2 (reproduced from and discussed in detail in Section V).

Table 2. Key MM Categories and Technology-related Challenges/Needs

Category	Challenges/Needs
Standards and Specifications	Lack of existing standards and specifications to support qualification and certification for MM-based components
	Undeveloped taxonomies, classifications, and terminologies
Design, Modeling and Simulation	Lack of generalized "lightweight" (less computationally intensive) models for evolutionary shape estimation for broad material classes
	Lack of fast, accurate predictive models of material behavior in MM processes
	Secondary processes used to complete parts (e.g., trimming, coating, testing, inspection, finishing) are difficult to assess and incorporate into simulation efforts
Materials Behavior/ Characterization	Lack of comprehensive, quantitative, predictive understanding of processing-structure-property-performance relationships for many potential MM materials
Sensors and Process Control	Insufficient in-situ process monitoring (sensor selection for accurate data collection) and in-process closed-loop feedback control (adjusting process to make "in-spec" parts) capabilities
	Robots not yet integrated into closed-loop controlled thermal-deformation processes such as sample rotation, controlled quench/cooling, and robot arms for localized heating, sensing, and testing capabilities
	Current equipment suites are not optimized or designed to handle MM methods (e.g., presses, robots, sensors, control integration, specific tools); lack industrial internet of things (IoT) integration capabilities (in addition to cyber security solutions)

Value Proposition Assessment	No process- and material-specific value stream maps exist for MM
Workforce/ Culture	Shortage/dearth of skilled, multidisciplinary and multifunctional tradespeople with hands-on expertise in processing science and digital interfaces (e.g., to install, debug, integrate, etc.)

These challenges provided a foundation for consideration of key opportunity areas and broad recommendations for accelerating the development and adoption of metamorphic manufacturing.

Opportunity Areas

Some high-priority opportunity areas related to the challenges and needs were identified, and are summarized in Table 3 (reproduced from Section VI).

Table 3. High-Priority Opportunity Areas
Building MM awareness
Standards and specifications
Modeling and simulations
Technology demonstrations and benchmarking
Sensors and data analytics
Workforce

These opportunity areas were selected with the mindset that that they could be addressed (at least to a high degree) within the next 2-3 years, in order to accelerate the growth and integration of MM technologies in that timeframe. Some more general recommendations within these opportunity areas are considered in Section VI, while detailed action plans and specific tactics are presented and discussed in depth in Section VII of this report.

Action Plans

Recommended Action Plans and detailed Tasks within each Action Plan, which, if accomplished, could strongly contribute to the development, emergence, and growth of this new technology within the next 2-3 years, are summarized in the following list (reproduced from Section VII). The individual tasks are generally ordered in a sequential fashion within a given action plan, although many of them could be executed simultaneously.

Action Plan 1:

Launch integrated computational materials engineering (ICME) benchmarking and modeling efforts for MM-based forming processes

1.1. Establish a lead benchmarking team
1.2. Perform a literature review on candidate materials
1.3. Define key model features and develop process models
1.4. Identify a generalized industry metal-forming example
1.5. Define scope and specifics of detailed benchmark problems/challenges
1.6. Select a data repository to house demonstration problem information
1.7. Execute an ICME benchmarking challenge competition

Action Plan 2:

Build prototype MM process suites and exemplar parts

2.1. Define feature sets for MM processes and exemplar products
2.2. Build prototypes of tools and products

Action Plan 3:

Characterize critical-to-quality (CTQ) property drivers for MM materials

3.1. Identify representative products or classes of products
3.2. Identify key materials system, MM processes, and final product requirements
3.3. Compile and curate MM data

Action Plan 4:

Develop an MM internship

Action Plan 5:

Establish a shared technology demonstration facility

5.1. Establish small MM facility with a technical advisory committee
5.2. Develop a "one design" small MM desktop kit (see also Action Plan 8)
5.3. Establish a large MM shared facility
5.4. Use the facility and assure long term sustainability

Action Plan 6:

Foster small organization-led industry-based projects and R&D opportunities

6.1. Educate small organizations (as opposed to large companies) on MM benefits
6.2. Survey needs and constraints of smaller organizations
6.3. Identify collaborative partnerships
6.4. Disseminate funding agencies' request for proposals from small businesses
6.5. Designate existing demonstration facilities for MM R&D

Action Plan 7:

Formulate and address a set of MM grand challenge problems (GCPs)*

* Numbers in this case represent some potential/example GCPs

7.1. "Forged in Fire"-like competition demonstration
7.2. Submarine hull prototype
7.3. Space vehicle application
7.4. Unmanned transportation platform application
7.5. Medical application(s)

Action Plan 8:

Create a desktop prototype MM machine

For each of the tasks (and for action plans 4 and 8), details such as timeframe, personnel or affiliation types needed to lead or participate, metrics to measure progress, and rough estimates of costs are considered in Section VII of this report.

Final Remarks

More than just educating the community about MM, a major intent of this report is to stimulate many of the scientists, engineers, designers, policy makers, and others who read it to initiate activities that could contribute to accelerating the emergence and growth of this new technology. A first step would be to identify the activities suggested here that most closely align with your areas of interest, expertise, and/or experience, and then take direct action, as there is great potential for MM to become a disruptive technology that could be considered the next wave of digital manufacturing.

1. Introduction, Motivation, and Study Process

Digital manufacturing has enabled the creation of complex parts with high accuracy. While the first two waves of digital manufacturing—CNC machining and additive manufacturing—have driven manufacturing forward, they lack the ability to impart simultaneously low buy-to-fly ratios (reduced raw materials loss) and tailored material properties associated with incremental thermomechanical deformation techniques. Identified by the technical leaders at the Lightweight Innovations for Tomorrow (LIFT) manufacturing institute,[1] metamorphic manufacturing is a new innovation under development that aims to overcome such barriers by combining the incremental thermomechanical deformation of a metalsmith with the precision and control of intelligent machines and robotic systems. Additionally, this agile manufacturing methodology is especially suited for making small-batch, complex, customized parts rapidly, and in a highly economical way.

A very brief definition of metamorphic manufacturing (MM) has been developed by the study team as a useful first description:

> *Metamorphic manufacturing is an approach to manufacturing that relies on closed-loop, numerically controlled, incremental forming to simultaneously achieve complex shapes, specific engineering properties, and local microstructures.*

As metamorphic manufacturing is a type of digital manufacturing that follows the first two waves (CNC machining and additive manufacturing), it has been dubbed the third wave of digital manufacturing. Additionally, the combination of incremental thermomechanical deformation and robotic systems has yielded an alternate description of MM: robotic blacksmithing. While still centered on incremental thermomechanical deformation, MM replaces the human blacksmith with automated systems comprised of five fundamental elements (represented by the acronym, STARC):

S–sensors

T–thermal control

A–actuators and forming tools

R–robotic manipulation systems

C–computation

In MM, sensors, thermal controls, actuators, and forming tools are integrated via closed-loop feedback. Robotic arms and manipulators are critical for workpiece positioning and reproducibility, and are integrated with the actuators and forming tools. Computation encompasses not only the computational "brain" at the center of the MM operation, but many other elements, such as collecting sensor data, artificial intelligence, real-time decision making, and predictive simulations of microstructure and property evolution and control. Collected data can also provide a digital thread that is used to assure quality, provide model validation, and meet evolving standards.

Although the details of this technology will be covered in much more depth in Sections II–IV, the definition of MM and integration of these five fundamental elements are synopsized and captured pictorially in Figure 1.

Figure 1. Synopsized illustration of metamorphic manufacturing (MM), including the five fundamnetalelements represented by the acronym STARC (Sensors; Thermal control; Actuators and forming tools; Robotic manipulation systems; Computation).

A more complete synopsis of MM, including the various ideas and elements mentioned previously, is provided in the one page summary on the next page.

A SUMMARY OF KEY IDEAS AND CONCEPTS

METAMORPHIC MANUFACTURING

Shaping the Future of On-Demand Components

What it is MM? A new approach to manufacturing that relies on closed-loop, numerically controlled, incremental forming to simultaneously achieve complex shapes, specific engineering properties, and local microstructures. It has also been referred to as "*Robotic Blacksmithing*", and "*The Third Wave of Digital Manufacturing*" (i.e., after CNC machining and additive manufacturing).

Why does MM matter? It is a new, powerful, agile way to make components that attempts to optimize component shape and properties using well-understood concepts from thermal mechanical processing of metals. MM leverages many rapidly emerging foundational technologies (see below) to make something very new. It also offers investment opportunities for technology leaders and researchers in new areas for R&D, technology integration, and manufacturing innovation.

Foundational Constituent Technologies

S - senors	T – thermal control	A – actuators/forming	R - robotic systems	C - computation
Real time monitoring of: Dimensions/geometry Thermal properties Mechanical properties Acoustics/ ultrasonics, etc.	Thermal-mechanical processing including control of: localized temp., heat treating atmosphere, heating and cooling rates, etc.	Variety of tools for incremental forming: Hammers Presses English wheels Spinning devices, etc.	System of precise robotic arms & manipulators for: workpiece positioning, integration with actuators/tools, reproducibility, etc.	Computational brain at center of MM operation: specify sequencing & tool paths, control robotics, collect sensor data, make real-time decisions, predictive simulations…

Some things we should learn from past, allied work

Human Blacksmiths	CNC Machining	Additive Manufacturing	Related R&D	Standards/Qualification
Shown how a wide variety of shapes can be formed with limited strength, power, reproducibility, dimensional accuracy, temperature control…	Demonstrated ability to create parts from code, without storing dies or forms. Represents first wave of digital manufacturing.	Demonstrated creation of complex parts without using tools or dies. Limited control, high embodied energy, and low build rates all limit future capabilities.	R&D in some areas has provided MM foundation, but must be integrated into a cohesive whole. E.g., sensors, thermo-mechanical treatment, incremental forming, robotics, A.I., simulation…	Implementation of any new manufacturing technology is limited by methods for assuring qualification for safety-critical applications. Fundamental work is required here for MM.

What's next? Build awareness of MM and it's value, foster research opportunities and industry projects, establish technology demonstrations, build prototype process suites and/or demonstration facilities, develop computational codes/simulations, develop standards, educate and develop the MM workforce, garner fiscal support/investment for these MM efforts. Read the full report for MM needs, opportunities, and detailed recommendations.

The integration of robotic systems to guide incremental deformation provides for greatly increased reproducibility, traceability, productivity, and manufacturing agility.[1,2] The as-yet unrealized advantages of metamorphic manufacturing (see Section II for more details of the value proposition) mark it as a potentially disruptive technology, and it's realization could provide great strategic, economic, and national security benefits.[1,2]

While many of the component technologies of metamorphic manufacturing, such as incremental deformation,[2] complex robotic systems,[3] computational modeling (including integrated computational materials engineering [ICME])[4], industrial-scale forging, and in-process simulation[5] are beginning to mature, the full vision of MM has not been realized. That is, the component technologies underlying MM have not yet been synthesized into a cohesive whole. Considering the need for unifying these component technologies and the potentially disruptive nature of MM, the overarching objective of this project is to help jump start the emergence, development, and growth of this transformative technology. The project team aimed to provide a pathway for achieving this objective by addressing the following goals: (1) identify both the value proposition as well as the technical challenges of MM, (2) identify opportunities and develop specific recommendations for promoting the value and addressing the challenges that were identified, and (3) provide actionable tactics to aggressively develop and adopt MM technology over the next three years. Although the focus of this study is on metals, in the future MM might also be demonstrated in educational and R&D environments with other plastically deformable materials (e.g., plastics or clays).

...the component technologies underlying MM have not yet been synthesized into a cohesive whole. Considering the need for unifying the metamorphic manufacturing component technologies and the potentially disruptive nature of MM, the overarching objective of this project is to help jump start the emergence, development, and growth of this transformative technology.

During the development of this study, a team of 12 internationally recognized experts was assembled. This team draws from a wide variety of technical backgrounds and domain expertise. As evident from the Acknowledgements section, the experts' backgrounds span various sub-disciplines including materials science, manufacturing, mechanical engineering, and robotics; with individuals representing academia, industry, and federal agencies. The study team was convened via online meetings, homework assignments, and was twice assembled for two-day, in-person workshops (held in June and October of 2018) to address the objective and goals stated previously. The outputs from the workshops, meetings, and homework assignments were captured and synthesized into this final report. In addition to being iteratively edited by the study team and TMS science and engineering staff, a draft of this report was also reviewed by an independent group of experts, as listed in the Acknowledgements section. Ultimately, it is intended that this report act as an authoritative resource for the community as is it works to implement this potentially groundbreaking technology.

II. Value Proposition of Metamorphic Manufacturing

The performance of any component is governed by its shape or topology and its materials properties. Metamorphic manufacturing offers unique control over both, as well as local control of microstructure and properties. Metamorphic manufacturing is a digital technology similar to CNC machining or additive manufacturing, and like both of these techniques there is no need to store hard tools. Part geometries and production recipes can be sent globally in an instant, and components can be created as quickly as machines are available. Metamorphic manufacturing is a shaping technology, hence in contrast to CNC machining, there is very little material loss in creating machining chips. While the MM "buy-to-fly ratio" can thus approach 100%, some additional machining can still be used if needed for final tolerances or surface finish. Further, as MM is essentially a forging technique, it can be applied effectively to a very wide variety of metals where the best properties are already developed by forging. Thus, as opposed to additive manufacturing, it provides opportunities to use a much wider library of metals, and well-developed thermal-mechanical processing routes can be used to produce locally optimized properties. At its heart, MM is well-controlled open die forging, where machine precision replaces human estimation. As open die forging is the method whereby the technical community produces the largest components, there is also an opportunity to replace the largest closed-die presses (and their dies) with MM systems that can produce very large forged components, such as aircraft bulkheads.

When considering the potential of any early stage technology, it is important to identify the value that the technology will bring to the community if adopted. Some overarching benefits of MM include the ability to impart simultaneously low raw materials loss and tailored material properties, in addition to providing for agile manufacturing that is especially suited for rapid and economical production of small batch, complex, customized parts. Manufacturing value propositions can also be couched in terms of a solution to an existing problem, a more economical (and/or greener) way of manufacturing products, and/or as a vehicle for opening up a new stream of products with enhanced properties and performance. The value proposition serves as a core motivation for pursuing and investing in a new technology. This section thus aims to articulate the value proposition of MM in more detail, according to the specific benefits listed in Table 1.

Table 1. MM Value Proposition and Key Benefits

Value Proposition Categories	Key Benefits
Economical and Environmentally Friendly	Lower material waste
	Little (or no) need for die fabrication and storage
	Reduced energy consumption and carbon footprint
Shape and Property Control	Superior local property control
	Unique, highly complex shapes/geometries
	Larger build envelope
	Optimization of process routes and properties via iteration (possibly aided by machine learning)
Superior Manufacturing Flexibility and Accessibility	Expanded suite of materials options
	Attractive product lines for many small and medium sized businesses
	Small batch production and part design variability capabilities
	Short lead time from concept to production

Economically and Environmentally Friendly

For a manufacturing technology to be disruptive, it should provide some kind of economic advantage over its predecessors. Metamorphic manufacturing achieves this in multiple ways. As will be discussed in greater detail in a subsequent section, MM is centered about the process of incrementally deforming a material to achieve a given shape and set of properties. For most materials, there is little to no change in volume when the material is deformed. This lack of volume change when transforming feedstock into a finished part will drastically reduce the amount of wasted materials, as compared to a process like CNC machining. Moreover, plastically deforming a material can require significantly less energy than the relatively energy intensive processes of additive manufacturing (e.g., see Figure 2). In addition, this die-less manufacturing technique can vastly reduce the equipment capital costs and time to start production of a part. The potential for significant reduction in materials cost, energy cost, and scrap rate makes MM an increasingly intriguing alternative to previous forms of digital manufacturing from both an economic and an environmental perspective.

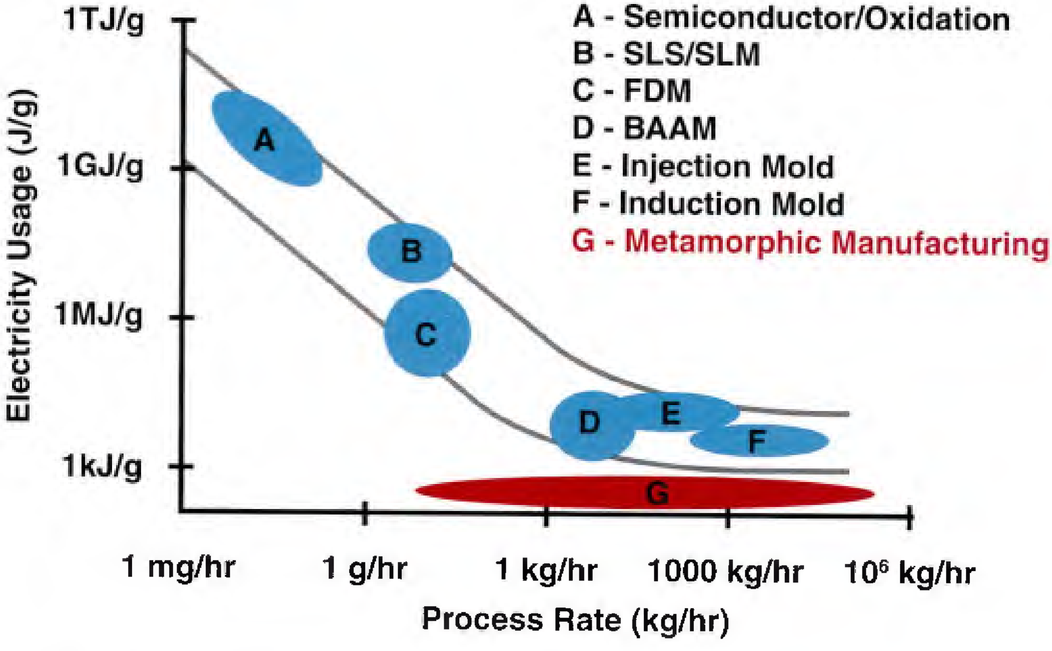

Figure 2: Rough estimates and comparisons of the Electricity Usage vs. Process Rate for various additive and other manufacturing processes (blue) compared to metamorphic manufacturing (red). This graph was produced based on inputs taken from Gutowski et al.[6] , and Glenn Daehn. Acronym definitions: SLS = Selective Laser Sintering, SLM = Selective Laser Melting, FDM = Fused Deposition Modeling, BAAM = Big Area Additive Manufacturing.

Shape and Property Control

One of the most attractive aspects of MM is its potentially unparalleled ability to control both the part geometry and the local properties. Similar to additive manufacturing, metamorphic manufacturing can produce highly complex shapes which are difficult or expensive to CNC machine or die-form; however, unlike additive manufacturing, MM can be utilized to fabricate these complex shapes out of a single piece of material by incrementally deforming, as opposed to building layers upon one another. The prospect of highly complex, monolithic structures could also significantly increase performance as compared to the joining of multiple pieces through welding or brazing, as these joints are often the sites at which the structure fails.

Additionally, combining the process of incremental deformation with localized state control (e.g., heat/quench cycles) allows for various locally tailored properties throughout the material. Given the community's long history of materials property engineering through the introduction of temperature and stress/strain, one could imagine the near endless possibilities of property combinations that could be designed into any given performance part. The ability to consider many combinations and permutations of thermal and mechanical processing again calls to mind the analogy of the robotic blacksmith, where artisan expertise is replaced with well-understood and well-defined processing.

Superior Manufacturing Flexibility and Accessibility

Traditionally, an industrial-scale suite of digital manufacturing equipment requires the workpiece to fit inside a confined work space. Due to the high number of architectural degrees of freedom for the actuators and tools, metamorphic manufacturing techniques can be developed and applied to a piece of material of any size. Moreover, while most preliminary work using MM has been performed on metal, as is the focus of the current study and report, the incremental deformation approach could be applied to shape a wider range of material classes[7] further exhibiting the flexibility of this technology.[7] Lastly, the use of dynamic tooling to create highly complex geometries allows for a significant decrease (if not complete elimination) in the utilization of component-specific manufacturing dies, which are very expensive to construct and store. This die-less manufacturing technique is ideal for rapid prototyping and small batch production, including on-the-fly production of specialty tools for fabricating unique parts, which could significantly lower the barrier to entry for many small- and medium-sized companies to more fully participate in the manufacturing ecosystem. Additionally, the interchangeable nature of the tools enables strategic incorporation of material removal (i.e., CNC machining) and material deposition (i.e., additive manufacturing) techniques into the metamorphic manufacturing process; this allows MM to benefit from the continual improvements of the first two waves of digital manufacturing.

III. Foundational Deformation Technologies Supporting Metamorphic Manufacturing

3.1 General Background

The past 70 years have seen a technological shift to agile and reconfigurable manufacturing which has thus far been dominated by two major waves of innovation: computer numerical controlled (CNC) machining and additive manufacturing. Computer numerical controlled machining was first introduced in the 1950s and became widely used by the 1980s. Modern additive manufacturing first emerged in the 1980s and though it has seen tremendous growth, it is still thought to be in its early stages of development and commercialization.[8] These technologies have introduced innovative contributions to manufacturing, particularly in the use of digital design, automation and robotics in producing parts.

In this regard, digital design and manufacturing is an integrated manufacturing approach centered on computerized systems. The shift to this approach has accelerated due to the rise in automated tools in manufacturing plants, leading to the need to model, simulate, and analyze all of the machines, tooling, and input materials to optimize the manufacturing process. Digital design and manufacturing have evolved and matured largely through the development of CNC machining and additive manufacturing. More specifically, in CNC machining, a part's dimensions are designated by a user through computer-aided design (CAD) software, and then translated into manufacturing directives by computer-aided manufacturing (CAM) software. Directives are then transformed into specific commands which the CNC machine uses to cut away material and produce a desired part, i.e. a "subtractive" type of digital manufacturing. Additive manufacturing is a process which involves adding material sequentially, usually layer upon layer, to make complex 3-D parts from model data, as opposed to subtractive manufacturing or formative manufacturing methodologies.

These technologies have been revolutionary in the manufacturing domain; however, both have some disadvantages. Computer numerical controlled machining, while providing parts with high accuracy, uses only a fraction of the original material in the final product, and offers limited opportunity to improve or modify material microstructure locally.[2] Additive manufacturing, while providing enormous manufacturing design freedom for complex and difficult-to-build geometries, is still relatively expensive, may produce undesirable structural properties if not controlled properly, has build volume limitations, possesses materials qualification issues and often requires major secondary operations to qualify parts.[2] More specifically, since in MM there is no loss of material and the thermomechanical deformation can be localized, the high waste and limited ability to modify local microstructure of CNC machined and/or additively manufactured parts can be eliminated.[9]

To move the development of MM forward, understanding the progress in digital manufacturing thus far is important. Clearly the evolution from the first to the second to the third waves of digital manufacturing did not occur independently, but rather these technologies, or at least their foundations, have been developing somewhat in parallel. Computer numerical controlled machining has advanced over time due to improvements in tool path planning, tool changes, lubrication, closed loop control, and fast precision location mechanisms, many of which have aided the development of additive manufacturing.[1] As digital design and manufacturing technologies continue to develop simultaneously through CNC machining and additive manufacturing methodologies, components such as computer aided design (CAD), computer aided manufacturing (CAM), and the use of robotics can help to drive the development of MM. The first applications in metal forming of numerical control were realized in radial forging (which involves localized compressive forces around the work piece's circumference) in the mid-1980s.

This section provides a historic summary of some innovations in deformation technology leading up to the current status, as relates to the development of metamorphic manufacturing. Particular focus is given here to methodologies based on incremental forming, in which the final part is formed by a large number of small, localized incremental deformations, often while the workpiece is being translated and/or rotated. In sheet forming, for example, research has been performed on robot-assisted incremental sheet forming (RISF) by integrating a three-axis CNC machine, a robotic manipulator, and components of tool path planning into one process[11] ; this technique will be discussed in more detail in a later section. Finally, it is important to remember that while most of the preliminary work supporting MM reported here is applied to metals, this technology can be applied to any material which can be plastically deformed (e.g., plastics[12] and clays).

Particular focus is given here to methodologies based on incremental forming, in which the final part is formed by a large number of small, localized incremental deformations, often while the workpiece is being translated and/or rotated.

3.2 Incremental Deformation and Shaping Strategies

The deformation and shaping strategy used to reshape a part is dependent on the class of component. Many different incremental deformation strategies for a wide variety of components have been developed in parallel. A previous white paper report by technical experts at LIFT on metamorphic manufacturing defined a number of such component classes. An important conclusion of that study is that there are potentially many ways to reshape metals by incremental deformation/forming, and they are largely limited only by our collective creativity. In this vein, examination of the methods artisans have used to produce components can help inspire some creative ways to form next-generation products by incremental deformation mechanisms. The following subsections present some specific examples and strategies for incremental shaping methods, arranged by workpiece shape class.

3.2.1 Sheet Components

Of the many component classes of MM, sheet metal formation through incremental deformation has exhibited the most active research. Incremental sheet forming (ISF) introduced methods of agile formation of sheet components using a single tool or pair of tools to apply the force, and a pre-programmed tool path. The idea of ISF was patented in 1967 before it was technically feasible,[13] but has undergone extensive research and spawned several subcategories since its inception.

Single-point incremental forming (SPIF) is characterized by the forming of metal sheets using a generic CNC tool stylus, with the sheets clamped with a non-workpiece-specific clamping system, and without the use of a partial (or full) die dictating the final shape.[14,15] The process involves continuous local deformations induced by a small tool which moves along a predefined path in a sheet until a final shape is reached.[15] The shear- and bending-based deformation mechanisms allow for extensive formability of the material.[16] The extensive formability is largely due to the mode of deformation, which suppresses the localization limit but approaches the fracture limit.[17] The formability can be further enhanced through a multi-step incremental forming process.[18] Alternatively, a similar method of SPIF was developed in which the forming tool, which acts as a hammer, is controlled by an industrial robot.[19] This process is illustrated in Figure 3, demonstrating that the back surface of the sheet is a free, unsupported surface (i.e., no die) during SPIF. This allows for flexibility of the processes, but introduces challenges in process control and accuracy assurance.[15] Two different manufacturing methodologies have stemmed from SPIF to address these geometric inaccuracies: two point incremental forming and double-sided incremental forming.

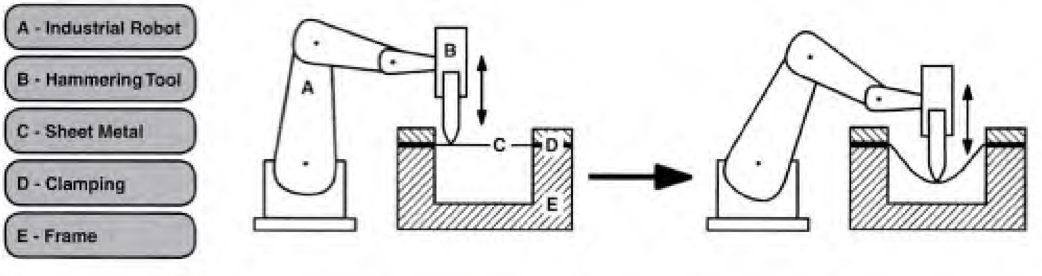

Figure 3: Schematic of Incremental Hammering by an Industrial Robot[19]. (reprinted with permission from publisher)

Two-point incremental forming (TPIF) was developed at around the same time as SPIF and allows for improved process control at the expense of requiring additional tooling.[20] Two-point incremental forming uses a full or partial die on the opposite side of the forming tool to support either the whole part or significant portions of the geometry (Figure 4(b)).[21,22] While TPIF has been applied industrially as a prototyping machine,[23] the need to not only improve geometric accuracy relative to SPIF, but also retain tooling flexibility, drove the development of double-sided incremental forming (DSIF).

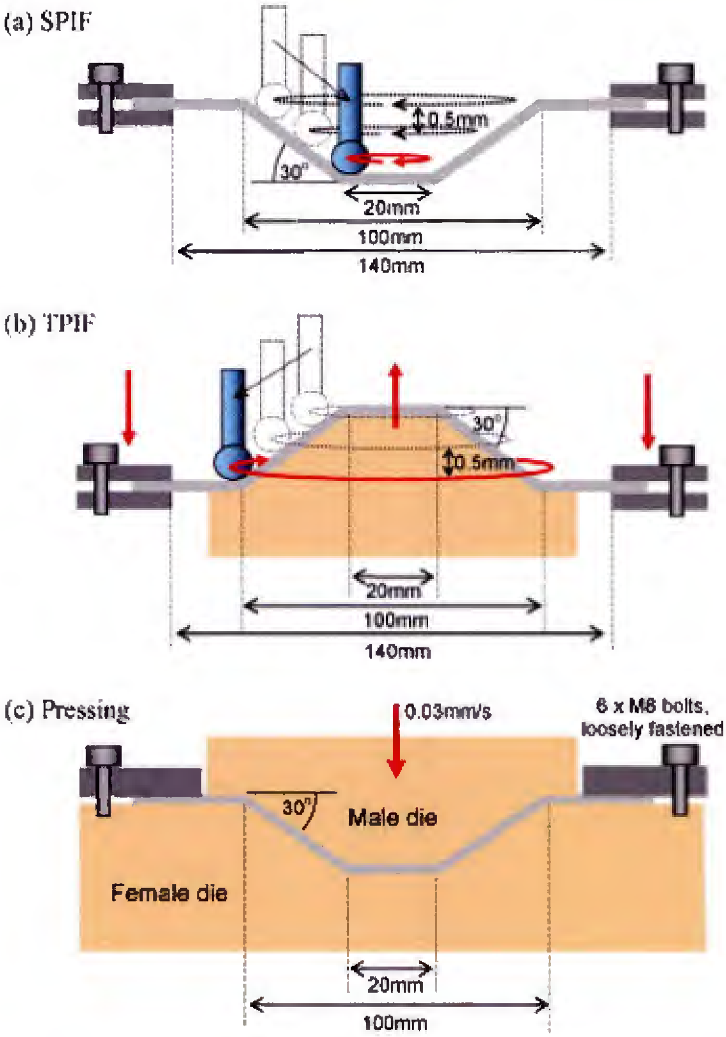

Figure 4. Schematics of (a) SPIF, (b) TPIF, and (c) pressing[22] (reprinted with permission from publisher).

Double-sided incremental forming (DSIF) operates similarly to SPIF (Figure 4(a)) but uses two tools, one on each side of the sheet, to form the desired shape. The positioning of the bottom tool with respect to the top tool influences the geometry of the final product, and several configurations and methods have been explored.[24] One example of this DSIF process is a machine in which one tool acts as a supporting tool while the other forms the sheet (see Figure 5), based upon a predefined gap between the two tools.[23] Alternatively, the two tools can be exchanged to swap their roles as forming or supporting tools, depending on local geometry.[25] Another configuration utilizes two tools mounted on a lathe to squeeze the sheet metal and thereby induce local deformation.[26] Several attempts have also been made to connect both tools in the system with a C-frame with a preset gap, positioning them in such a way to squeeze the sheet metal piece between them.[27–29] However, one of the drawbacks to SPIF, TPIF, and DSIF is that only small areas can be deformed by the tool(s), leading to slow forming rates.

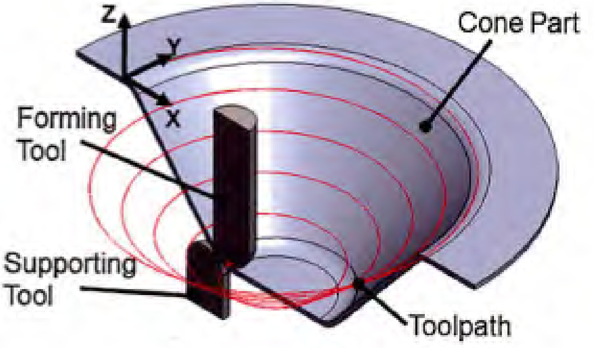

Figure 5. Cross-section schematic Illustrating DSIF [30] (reprinted with permission from publisher).

Electromagnetic forming is a sheet metal forming approach that uses electromagnetic actuators to increase forming rates and enables deformation across large areas.[31,32] This forming technique has been proposed as a potentially foundational technology for metamorphic manufacturing,[1,2] and some researchers have been working to advance this technique.[31–34] Electromagnetic forming utilizes electromagnetic actuators to generate a pulsed magnetic field that applies a force to tubular or sheet metal workpieces made of a highly electrically conductive material, eliminating mechanical contact and the need for a working medium.[31–33]

A challenge with TPIF and SPIF is that there is no existing strategy for tool path generation. For this reason, part production holds significant dependence on the experience of the individual craftsman. Some studies have been conducted on automated processes to eliminate this source of human error. One example of this approach consists of a handling robot and a C-frame press with a top and bottom tool.[35] A neural network is programmed to produce tool paths from expert craftsmen for the production of individualized components, which are relayed to the robot for execution. A concept was developed to generate tool path strategies for the introduced automated processes involved. Subsequent work has been conducted to identify automatically features in a CAD file, and to generate the forming sequence and tool paths for best geometry accuracy for DSIF.[25] Furthermore, process control to take machine and tool compliance into account is needed for better geometry accuracy.[36]

Besides metals, incremental sheet forming has been used for manufacturing polymer parts at room temperature. The shear and bending dominant forming mechanism of ISF permits high formability of materials enabling the manufacturing of several complex shapes made of thermoplastics.[37]

3.2.2 Axisymmetric and Non-axisymmetric Components

Metal spinning is a process that was originally limited to producing only axisymmetric shapes, and for each product it required a dedicated mandrel (against which the material could be shaped). It was determined that this process has three well-defined areas of contact between the mandrel and product, leading to the new idea of replacing the solid mandrel with three adjustable rollers. Controlling these rollers could allow for the formation of both axisymmetric and non-axisymmetric parts.[38] Allwood's group in Cambridge spearheaded this new approach with the design and manufacture of a seven-axis machine used for flexible non-symmetric spinning of parts.[39]

3.2.3 Components Based on Closed or Open Profiles

The incremental tube forming (ITF) process was developed for bending tubes of high-strength materials.[40] This process involves incremental tube spinning and continuous tube bending occurring simultaneously to manufacture tubes with variable diameters, variable wall thicknesses, and freely definable bending curvatures.[40] Figure 6a outlines the process principle of ITF and Figure 6b shows examples of several bent tubes of different radii formed using this process.

The recently developed incremental profile forming process is probably one of the most impressive examples of MM.[41] Using an 8-degree-of-freedom actuator system, profiles can be made in a huge variety of shapes.

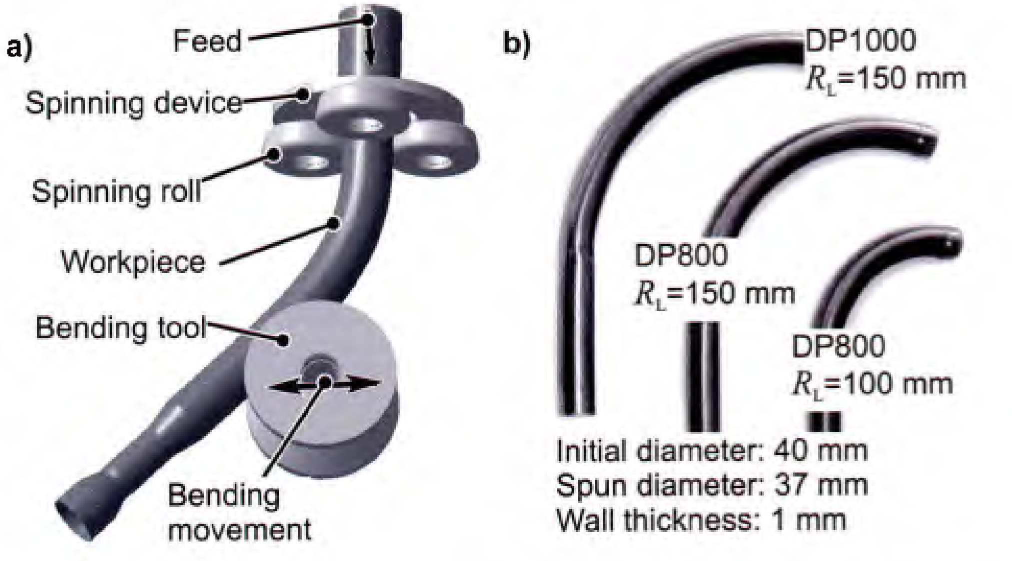

Figure 6. Incremental tube forming: a) process principle, b) application examples[40] (reprinted with permission from publisher).

3.2.4 Bar-based Components

Bar-based components can be fabricated by many different incremental processes such as rolling, incremental hammering,[10] pressing, and rotary swaging. In rotary swaging, the cross-section of tubular or solid bar stock is incrementally deformed to adjust the diameter and change the shape amongst round, square, and hexagonal-profiles.[42] A number of publications have also outlined a simple approach of working a shape from one end of a bar to another under computer control. When combined with the heat of a forge and a twisting motion, this end-to-end shaping can be used to form twisted shapes, such as turbine blades, as illustrated in Figure 7.[42] While most of the incremental forming techniques discussed are cold-working techniques, incremental forging is one of the few to actually include a thermomechanical component.[42]

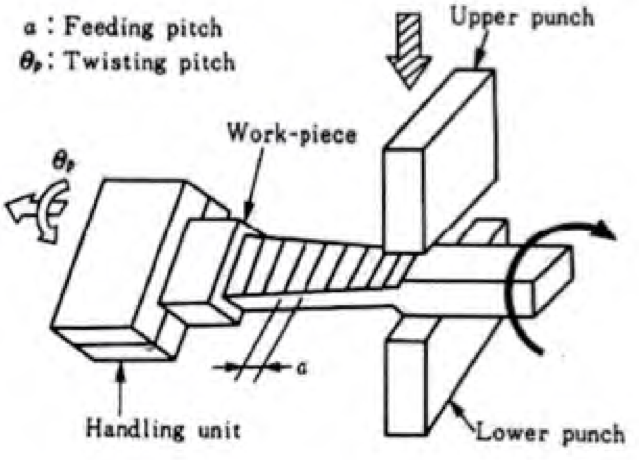

Figure 7. Incremental forging with twisting[42] (reprinted with permission from publisher).

3.2.5 Bulk Components

While bulk components represent a shape class which has probably experienced less attention from the incremental deformation community, some discussion exists in the literature regarding bulk[42] and sheet-bulk incremental deformation.[43] In regards to sheet-bulk incremental deformation, a two-stage forming process has been developed to achieve local thickening of the sheets.[44] In the first stage, the targeted portion of the sheet is drawn into a die cavity, and in the second stage, the deformed section is compressed with a flat die while the flange is clamped, resulting in a localized increase in sheet thickness.[44] Advanced applications include the incremental manufacturing of monolithic and composite gears by sheet indentation.[45] A similar approach was developed for the formation of square cups. In this process, both flanges were clamped and the process was repeated a second time at a 90-degree angle shift.[46]

Another interesting, but different approach which might be applicable was demonstrated by Colegrove and co-workers,[47] in which the improvement in metallurgical properties of a deposited weld metal by local rolling was emphasized. Extensions of this approach might develop both properties and shape.

3.3 Robotic Deformation Systems

3.3.1 Incremental Forging

The concept of incremental forging was introduced around 1989,[48] and it has seen great developments in recent years. When initially introduced, incremental forging was used primarily in the production of flat, basic shapes.[48] However, researchers at Aachen University's Institute of Metal Forming have been investigating a new manufacturing approach to incrementally forge parts with complex workpieces. Their production is realized through superimposed manipulator displacements during the forging stroke,[49] as seen in Figure 8b. Other researchers have employed incremental forging techniques of additional parts with complex geometries, such as helical tubes.[50]

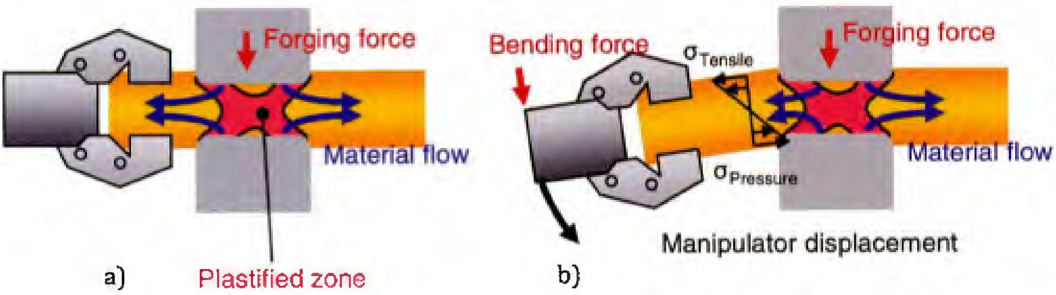

Figure 8: Depiction of (a) conventional open-die forging and (b) open-die forging with superimposed manipulator displacements[49] (reprinted with permission from publisher).

Incremental forging has been aided by the development of finite element analysis software, allowing various forming processes to be simulated, informing the design of incremental forging process programs.[50,51] The development of robots that can withstand extremely high temperatures and grip parts of various geometry and weight has allowed incremental forging to be applied in both research and industrial settings.[52,53] Clearly, the components of incremental forging could directly contribute to metamorphic manufacturing, as both technologies are examples of systems that perform incremental thermomechanical deformation.

3.3.2. Robotic sheet metal bending

Robotic Deformation Systems: Amada Robotic Bending Machines

Japanese sheet metal fabrication machine manufacturer Amada Co. Ltd. has released a robotic sheet metal bending machine that is capable of automatically positioning and bending large and highly-complex parts efficiently and accurately.[54] The automatic process program for the machines, developed by the Carnegie Mellon Robotics Institute, can automatically determine, based off of a CAD design for a new part: the operation sequence, the tools and robot grippers needed, the tool layout, the grasp positions, the gage, and the robot motion plans for making the part.3 This system is highly flexible and adaptable, as the machine has four different part grippers, which are automatically changed based on the part program.[54]

Additionally, accuracy is insured by various in-process sensors. A back-gauge potentiometer checks and compensates for any placement deviations, and L-shift capabilities impart the robot with the ability to gauge a wide range of part geometries. The machine is also equipped with high-speed, probe-style bend sensors to measure and adjust the bend angle by measuring and compensating for any material springback or material thickness variation.[54] Although the bending process executed by this machine is not representative of incremental deformation, some of its features could prove extremely valuable if applied to metamorphic manufacturing. Namely, the machine's flexibility, automatic process program, and in-process sensors could be utilized in a different robotic deformation system.

3.4 Localized Thermal Processing

In conjunction with localized deformation during incremental forging processes to control properties locally across a component, the use of rapid, localized thermal processes also has the potential to enable exceptional control of the material microstructure (and thereby properties) and residual stress development (which can be used to improve component performance). These local thermal processes must be integrated into the incremental forging manipulations discussed previously to maximize potential property gains, and advances in robotic control and finite element analysis are two key technologies that will enable this integration.

Rapid thermal processes are facilitated by relatively mature technologies such as induction, laser, plasma, and flame heat treating, as well as gas or liquid cooling sprays. It is important that these processes can be performed at an appropriate time scale for a given component processing pathway. There are many examples of rapid thermal processing enabling improved performance in steels alone, with some examples including induction surface hardening of steel components,[55] rapid tempering of steels,[56] and recent improved kinetic understanding used to develop rapid processes to facilitate implementation of 3rd generation advanced high-strength steels.[57] Although the heating and cooling technologies are well-developed, the processing-microstructure-property relationship understanding that is critical to facilitate this type of processing are not well developed for short-time thermal processes. This is partially due to the challenge in measurement of rapid, kinetically controlled processes in real time, and partially because most thermal processes in broad industrial use involve thermal cycles on the order of hours rather than seconds. Further understanding of microstructure evolution and kinetics during rapid thermal processes is required to fully exploit this type of processing. An additional challenge, but also a great opportunity as well, is to incorporate simultaneously localized thermal processing and deformation in order to further expand the available processing landscape.

IV. Fundamental MM Elements and Conceptual Equipment Suite

The five fundamental elements mentioned in the Introduction (Section I) and represented by the acronym STARC are considered in more detail here, as is a conceptual equipment suite or part production line for MM in order to assist the community in developing its own metamorphic manufacturing capabilities.

4.1 Fundamental Elements of MM (STARC)

Based upon the ongoing technological developments described in Sections I and III, the study team was charged with identifying what they viewed to be the core, fundamental elements that are essential to metamorphic manufacturing. The five fundamental elements identified (represented by the acronym, STARC) provide a framework for an MM equipment suite, and also help identify the challenges associated with integrating such elements. Note that while specific suites of metamorphic manufacturing equipment may include additional elements, these five are meant to comprise the essential components which fully actualized metamorphic manufacturing production suites will require.

S–Sensors

All forms of digital manufacturing require sensors to ensure real time monitoring, analysis, and control of dimensional and, often, thermal properties. For MM, additional sensors are required to account for the dynamic nature of incremental deformation and the robotic manipulation system. A comprehensive suite of sensors which constitute a vision system for geometric measurements, object detection, material state measurements, and machine distortion checking is likely to be part of all advanced adaptations of MM. This sensor system could include, but is not limited to: optical, infrared, and x-ray imaging devices including thermal cameras and lasers; load cells; hardness testers; torque, speed and vibration measurement devices; coordinate measuring machines; and acoustic and ultrasonic testers. In particular, sensors could also measure the material state through ultrasonic estimations of modulus to assess texture, or x-ray diffraction to measure residual stress or texture. Moreover, this sensor system will likely be incorporated in an iterative feedback loop with an environmental control system to accurately predict the desired final geometry and material condition.

T–Thermal Control

Thermal-mechanical processing and controlled-atmosphere heat treating form the foundation for processing high-performance metals. In order to take advantage of our wealth of materials engineering knowledge, a precision environmental control system for modifying metal shape, microstructure, aesthetics, and other performance-based features must be established. For high quality manufacturing, this system could control a variety of elements, including localized temperature, heating and cooling rates, oxidation, carburization, nitriding, and perhaps even galvanization, plasma spraying, and coatings. As previously stated, this system should be coupled with the suite of sensors described previously to obtain a comprehensive picture of the part's evolution. In addition, these thermal/environmental controls should also be aware of any actuators or tools being employed to ensure the desired properties are being achieved.

A–Actuators and Forming Tools

The actuators and forming tools are critical components in MM because they provide the plastic deformation that transitions a raw material through the various intermediate states needed to achieve a final, desired product. There could be various tooling components for forming, state control and aesthetics, and even material deposition. These components could include hydraulic presses, high-speed hammers, rollers, pincer actions, peening impulses, and so on. Beyond the reshaping concept, milling/CNC machining components, additive or waterjet material deposition heads, electrodes for welding and surface finishing capabilities (burnishing and coatings) could be added to the suite. The tools and actuators required may be specific to a family of components and should be removable and exchangeable in between projects; this allows an MM equipment suite to produce a wide variety of structures while also being cost effective and taking up minimal space.

R–Robotics

Due to the dynamism required to incrementally deform 3-D structures, the workpiece must be precisely positioned in the deformation tool, but allowed some freedom of motion during forming if needed. This is most effectively achieved by a system of precision robotic mechanical arms and manipulators. This robotic manipulation system will provide excellent precision, reproducibility and traceability throughout the deformation process. Ideally, the dimensional positioning of the workpiece by this robotic manipulation system would be driven by the CAD/CAM software and fully integrated with both the material state (e.g., temperature) controls and the actuators and tools being utilized to obtain a particular shape or property. Moreover, by including robotics to switch between various actuators and tools, one could achieve fully automated manufacturing capabilities leading to continuous, uninterrupted productivity.

C–Computation

A computational "brain" must sit at the center of the MM operation. For straightforward open-loop operations it would simply specify sequencing and tool paths. In more advanced operations it would collect sensor data for quality assurance. In the most advanced operations it would make real-time decisions on modifying the operational plan to optimize component shape and properties, and use artificial intelligence (AI) routines to learn and improve the approach with each operation, much like a human blacksmith might. Given the vast automation and interconnectedness of the four fundamental elements described previously, the need for a digital framework or "thread" integrating all manufacturing activities is apparent. The development of digital libraries of materials[4] and manufacturing data, toolboxes, and design methodologies would allow for CAD/CAM modeling that successfully incorporates centuries of human knowledge of materials manipulation and design. Combining this knowledge with cutting edge computational tools such as those employed in integrated computational materials engineering (ICME),[4,58,59] hierarchical and multi-scale modeling can provide local microstructure and property control, while Artificial Intelligence (AI) and machine learning (ML) techniques can inform users when new materials are needed or new, previously unexplored design paths become available.

With proper software integration, this framework would be vital in communicating path planning strategies, tracking, decision-making, process design, data flow, and lifecycle design to all the necessary MM elements. A continuous, iterative feedback loop between physical operations and digital libraries and designs would lead to real-time product optimization throughout the production process. Moreover, the uniformity in data and metadata formatting necessary to achieve such synergy in manufacturing would allow pre- and post-production data to be processed and shared more readily within a company or community.

The concept of integrating a network of physical objects—such as tools and robotics—with sensors, software, and network connectivity so objects can collect and exchange data in real time is encapsulated in the Internet of Things (IoT)[60] and is already being applied to the manufacturing sector. Additionally, data collection provides a simple path to assuring component quality. Further reading about the concepts and techniques mentioned here is recommended for anyone looking to build a digital thread throughout a MM equipment suite.

4.2 Integrated MM Production Cycle and Equipment Suite

Figure 10 illustrates the production lifecycle of an MM project. A "digital twin" as referred to in the outer ring in Figure 10, has been described as "a digital model of a particular asset that includes design specifications and engineering models describing its geometry, materials, components and behavior…."[61]

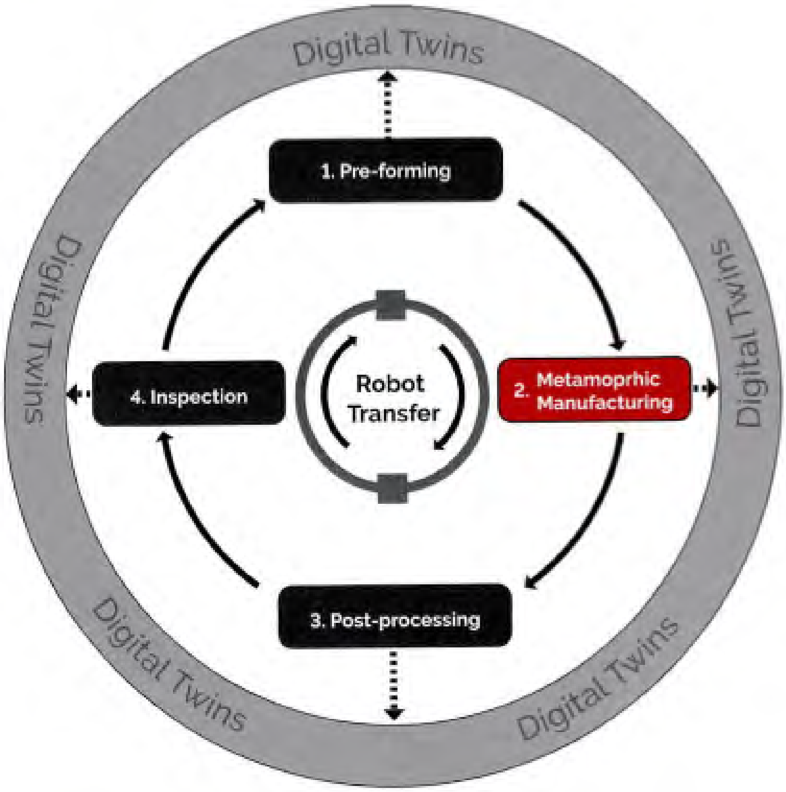

Figure 10. Schematic of MM production lifecycle.

A hypothetical MM equipment suite (corresponding to item 2 in Figure 10) fully incorporating the five fundamental STARC elements listed in subsection 4.1 is illustrated on the next page in Figure 11.

Figure 11. Conceptual metamorphic manufacturing equipment suite (containing the five fundamental elements of metamorphic manufacturing represented by the acronym STARC).

Linking the STARC elements (parenthetical letters in the following text) to the illustration in Figure 11, the top right side of Fig. 11 shows a thermal component (T), as a heated starting block of metal is being removed from a furnace for transport by a robot (R) to the central MM forming station in the upper left of the figure. This station contains robotic arms (R) that control the movement of the hot workpiece, as well as position sensors (S), and some lasers (represented in green) which could be used for position/dimension sensing (S) and/or additional local heating (T). This station also contains a vertical, actuated (A) forming tool that provides the force for incremental deformation on the workpiece. On the lower left of the figure is a robot which is taking a piece from the MM forming station to either finishing operations, or another MM work station. The computer station (C) in the center schematically illustrates the central "brain" controlling the various components of the MM equipment suite/part production line.

Although Figure 11 gives some indication of the key pieces of equipment required and how they interact, full integration of these components is not easily represented in such a simple figure. Additionally, specific MM equipment suites that are actually developed may differ and/or contain additional or fewer elements. Nevertheless, this conceptual suite provides a framework from which interested parties can begin to develop their own MM capabilities, or possibly inspire a company to develop a system for sale or distribution.

The conceptual illustration in Figure 11 (and it's accompanying description) can also be used as a framework for the prototypes and demonstration facilities discussed in Action Plans 2 and 5 in Section VII of this report, as well as for companies or other organizations that might wish to develop a full-scale MM production system for sale/distribution, and/or part production. Since the conceptualization, research, and development of this new technology is being led in the United States, final commercialization within the U.S. is also important, in order to take advantage of the potentially great benefits of MM for the U.S. economy, society, and national security. In this regard, examples of the types of U.S. machine providers or other organizations that might undertake development of a full-scale MM production system include Haas Automation, Cincinnati Inc., and/or Oak Ridge National Laboratory (ORNL). For an example in a similar domain (additive manufacturing), Cincinnati Inc. collaborated with ORNL on a BAAM (Big Area Additive Manufacturing) industrial sized system installed at ORNL, which has been operating with great success.[62,63] Additionally, companies such as Coal Ironworks[64] could be candidates for providing many of the components needed for assembling smaller, simpler MM demonstration units relatively soon (see Section VII), as they now offer hydraulic metal forming presses, induction forges, and tools/dies that can be applied to MM.

V. Challenges and Needs

Based on their expertise, experience, and knowledge of the current state-of-the-art of the various MM-related foundational technologies, the study team was asked to identify what they viewed to be the most significant technology-specific challenges preventing the emergence, development, growth and adoption of MM technologies. These challenges then provided a basis from which the team could develop specific recommendations and action plans to address these areas (see Sections VI and VII). It is emphasized that it is not necessary that *all* of these challenges/needs must be addressed to start implementing MM, but the team was nevertheless asked to brainstorm any possible challenges they could identify for fully addressing the many aspects of MM.

A prioritized list of the key technical challenge categories for full development of metamorphic manufacturing is thus presented in the first column of Table 2. Alternatively, these could also be viewed as domains of opportunity for the development and widespread adoption of MM. Moreover, the most significant challenges which need to be overcome within each of these categories are provided in the second column of Table 2. Beyond those presented in Table 2, a full list of all categories and challenges identified is presented in Appendix A.

Table 2. Key MM Categories and Technology-related Challenges/Needs

Category	Challenges/Needs
Standards and Specifications	Lack of existing standards and specifications to support qualification and certification for MM-based components
	Undeveloped taxonomies, classifications, and terminologies
Design, Modeling and Simulation	Lack of generalized "lightweight" (less computationally intensive) models for evolutionary shape estimation for broad material classes
	Lack of fast, accurate predictive models of material behavior in MM processes
	Secondary processes used to complete parts (e.g., trimming, coating, testing, inspection, finishing) are difficult to assess and incorporate into simulation efforts
Materials Behavior/ Characterization	Lack of comprehensive, quantitative, predictive understanding of processing-structure-property-performance relationships for many potential MM materials
Sensors and Process Control	Insufficient in-situ process monitoring (sensor selection for accurate data collection) and in-process closed-loop feedback control (adjusting process to make "in-spec" parts) capabilities
	Robots not yet integrated into closed-loop controlled thermal-deformation processes such as sample rotation, controlled quench/cooling, and robot arms for localized heating, sensing, and testing capabilities
	Current equipment suites are not optimized or designed to handle MM methods (e.g., presses, robots, sensors, control integration, specific tools); lack industrial internet of things (IoT) integration capabilities (in addition to cyber security solutions)
Value Proposition Assessment	No process- and material-specific value stream maps exist for MM
Workforce/ Culture	Shortage/dearth of skilled, multidisciplinary and multifunctional tradespeople with hands-on expertise in processing science and digital interfaces (e.g., to install, debug, integrate, etc.)

Standards and Specifications

For any emerging technology area to be developed in a reasonable timeframe and widely adopted, consensus-based and industry-driven standards are needed to streamline communication and collaboration across the community. Such standards are particularly vital for manufacturing technologies since the industry, as a whole, is required to conform to specifications and safety standards in addition to achieving repeatability and reliability. For MM, a comprehensive list of essential terminologies and taxonomies needs to be developed for various part and materials classes to help formalize and guide this rising technology. Similarly, a repository of standards for MM-based components and products must be established and, due to the iterative nature of MM designs, these standards will have to be in model-enabled formats to ensure the desired parameters are met. Moreover, the formulation of specifications and standards for MM data processes and outputs are needed in order to optimize interoperability and data sharing across various design/equipment suites, companies, and the greater community.

Design, Modeling, and Simulation

As MM offers a potentially revolutionary way of manufacturing complex 3-D components, it comes with the need to develop revolutionary ways of designing said components that will undoubtedly require integration with various modeling and simulation techniques. Growing efforts and expertise in integrated computational materials engineering (ICME) across industry, academia and national laboratories can be applied to accomplish this task.[4,59] Due to the dynamic nature of the incremental deformation manufacturing approach, structural design interfaces need to be created which leverage models and simulations that can quickly and accurately predict a number of local parameters (e.g., force, shape, failure mechanism, microstructure, local interfacial contacts, etc.), and then utilize both these predictions and measured data to incrementally improve the design throughout the manufacturing process. To achieve such design interfaces, the underlying models need to be based on equations that accurately predict the materials' behavior at various steps in the MM process (i.e., model verification and validation[65]). Moreover, often the effects of post-forming and secondary processing to complete the manufacture of parts/components (e.g., trimming, coatings, inspections, finishing) are not incorporated into predictive simulations, but need to be. With such accurate predictive models/simulations and real-time experimental data, fast algorithms/systems are required in MM to translate external shape change into localized strains and stresses and to estimate local temperatures.

To assist with evolutionary shape estimation, generalized "lightweight" models for broad material classes will also be needed. These lightweight models should be fast, lower-accuracy ways to quickly assess and inform the shape of the final product. By combining these lightweight models with the previously mentioned, more rigorous models and simulations, a hierarchical modeling system could be developed with stepwise refinement that predicts both material shape and properties.

Materials Behavior/Characterization

While there exists a robust catalog of known mechanical behaviors for many classes of materials (especially metals), currently, there is not a comprehensive, quantitative, predictive understanding of processing-structure-property-performance (PSPP) relationships for all possible MM materials. These gaps in fundamental understanding mean that some of the materials properties of importance for MM processing, such as mechanical springback, may be either unknown or misunderstood and thus unpredictable. As the PSPP relationship suggests, to understand a material's properties one starts with understanding its processing and structure. The continuous, path-dependent processing nature of incremental deformation will require much greater use of in situ characterization techniques, since traditionally structural characterization is performed on fully processed samples. Furthermore, the constantly evolving processing of MM leads to continuous microstructural evolution in non-traditional feedstock, with the effects of such processing needing to be understood from both a local and global perspective within the material. While there are many characterization methods available, there is a need to be able to capture the high strain rate and complex strain states associated with incremental forming[5] at relatively small local length scales and speed. In this vein, a particular challenge is capturing effects of path-dependent structural evolution in order to predict the mechanical behavior throughout a material.

Sensors and Process Control

The integration of numerous sensors needed throughout a MM equipment suite with the requisite processing controls represents another challenge. First, one needs to know what mechanical behaviors to expect from certain materials in order to select appropriate sensors to capture relevant data. The sensors selected should not only measure a given property with accuracy, but should be able to do so rapidly in a production environment. In addition, any ambiguity associated with the material's behavior, for example, kinematic hardening behavior, or lubrication condition, should be considered in advance as it could further complicate the process of designing a part to meet certain specifications (particularly since material behavior is evolving each time it is incrementally deformed).

Once adequate sensors are selected, the process of integrating them with the other fundamental elements of MM (in particular, robotics) into a closed-loop controlled deformation process is quite demanding, from both a hardware and software point of view. To maximize their range of motion, various sensors measuring spatial dimensions, temperature, heating/cooling rate, and numerous mechanical properties will need to be embedded unobtrusively in the manufacturing system, likely in the robotic arms, which is only recently becoming a possibility.[66]

Other challenges include: (1) developing open and seamless software integration protocols across a network of independently designed sensors, robots, tools, and environmental controls, and (2) enabling that network to utilize collective data to facilitate real time iteration in the design and manufacturing process. Some related issues that will need to be addressed include potential physical space limitations, and controlling surface quality with MM-scale tooling while at the same time accounting for tool degradations. The volume of data collected from the various components of the MM network could also result in longer processing times, which will have to be accounted for during execution and incorporation of real-time analyses. Finally, significant financial support will need to be acquired for the costs and labor associated with adaptation of existing equipment and facilities for MM, as most current equipment suites are not designed or optimized for the hardware and software integrations necessary for a robust MM platform.

Value Proposition Assessment

As mentioned in Section II, there is a strong value proposition for MM. One of the distinct advantages of MM is its ability to fabricate complex structures without the use of forming dies, making it conceivably ideal for prototyping and niche applications. However, to date, other than a study of incremental forming on life-cycle energy utilization,[67] there has not been a comprehensive, quantitative study or mapping of the process- and material-specific value stream for MM, making it difficult to access the full impact of this value proposition. A more thorough value assessment of the various economic benefits of MM is needed (perhaps in terms of a cost-benefit analysis as compared to other forms of digital manufacturing), especially for potential niche production/part market capitalization. More quantitative assessments of the environmental benefits of MM, such as energy usage, CO_2 emissions and material waste, are also needed. Any such assessments would not only quantify the value of this technology but also identify the best first use cases, in terms of materials, shapes, and component sizes, to be used for developmental benchmarks.

> *To achieve widespread metamorphic manufacturing adoption, the manufacturing workforce will need to acquire new multidisciplinary, multifunctional knowledge and skills. The next-generation MM manufacturer should show some level of proficiency/understanding in a variety of complementary disciplines, within domains such as materials science and engineering, manufacturing processes, robotics, software engineering, and data science.*

Workforce and Culture

To achieve widespread metamorphic manufacturing adoption, the manufacturing workforce will need to acquire new multidisciplinary, multifunctional knowledge and skills. The next-generation MM manufacturer should show some level of proficiency/understanding in a variety of complementary disciplines, within domains such as materials science and engineering, manufacturing processes, robotics, software engineering, and data science. As manufacturing, and the greater global economy, become increasingly reliant on computation, some future manufacturers may require the ability to install and troubleshoot code in addition to a wide range of more hands-on technological skill sets. To prepare the next-generation workforce, university and community college faculty and departments should consider emphasizing cross-disciplinary educational opportunities for students as well as faculty candidates with multidisciplinary backgrounds. Moreover, companies and enterprises looking to adopt MM technology, as well as professional societies, need to provide continuing educational opportunities for current and future workers, either through internal courses within companies, or by providing the platform and resources for professionals to attend external training. To help accelerate the cultural shift surrounding the requisite skills needed for the MM workforce, it is imperative that current MM innovators and operators involved with developing this technology (i.e., many of the readers of this study) transfer their collective knowledge and experiences into community accessible best practices that will serve as a blueprint for the next generation.

VI. Opportunity Areas and Overarching Recommendations

Building upon the value proposition, foundational technologies, fundamental STARC elements, conceptual equipment suite, and especially the challenges and needs (Sections II–V), the team of experts next determined some key opportunity areas and recommendations to help accelerate the growth and integration of transformative metamorphic manufacturing technologies within the next 2–3 years. These high-priority opportunity areas are summarized in Table 3, and the related, general recommendations are considered below the table. Based on these prioritized opportunity areas and recommendations, a number of highly detailed action plans were then developed (see Section VII).

Table 3. High-Priority Opportunity Areas
Building MM awareness
Standards and specifications
Modeling and simulations
Technology demonstrations and benchmarking
Sensors and data analytics
Workforce

Building MM Awareness

Since metamorphic manufacturing is in its infant stages, particularly in terms of synthesizing the underlying component technologies into an implementable manufacturing framework, an important first step will be to build much greater community awareness, public excitement, and stakeholder buy-in of this potentially disruptive manufacturing technology. This can be done in a number of ways. In the shorter term (18 months or less), beyond wide dissemination of this report, this could involve presentations on MM, review-type publications of the foundational underpinnings, value, and/or future vision for MM, and crowd-sourcing ideas for new products and processes that might be produced by such robotic blacksmithing (a moniker for MM[1,2]). One example of a crowd-sourcing idea could be a student competition to develop thought-provoking proposals or possible use cases for MM in futuristic areas such as in-space manufacturing, metal origami, or even in Hollywood science-fiction movies. In the medium term (1–2 years) public-facing challenges or contests could be executed to develop novel MM applications while generating interest and excitement; a first attempt at this was carried out by LIFT and the Ohio State University, with a robotic blacksmithing student competition and prize.[1,2] Some other examples could include a contest to create uniquely shaped parts by incremental deformation techniques using desktop-sized equipment, an architectural contest to create prototypes, or a competition to reshape a scrap piece of metal using MM. In building public awareness, it will also be important to widely communicate the value proposition of MM (see Section II). Some of the awareness building efforts mentioned here might also result in ideas for entirely new ways to implement MM and/or unique new products that might be formed by this technology.

Standards and Specifications

Achieving repeatability and reliability in a manufacturing process is an inevitable part of implementation and adoption of an emerging technology. As the proper robots, machines, sensors, and other hardware are being integrated to implement metamorphic manufacturing, developing specialized computational codes for predictive models, individual MM hardware components, and integration among and between hardware components and models is imperative. The development of standards is crucial in order to enable standardized ways to consistently communicate the subject matter to the broad manufacturing, materials, robotics, and computer science communities involved, and to leverage efforts and data of different individuals, groups, and organizations. Developing new and utilizing existing standards and specifications wherever possible is an enabler to achieve this goal. Additionally, qualification/certification requirements and regulatory frameworks that might apply to MM present opportunity areas, and need to be determined.

Determination of critical-to-quality (CTQ) drivers is also important. CTQs, or CTQ trees, can be defined as the key measurable characteristics of a product or process whose performance standards or specification limits must be met in order to satisfy the customer; they thus align design efforts with customer requirements.[68] Particularly in the case of MM, these might include efforts such as evaluation of property distributions and performance needs, and quantifying available datasets related to different materials' response to deformation, thermal processing and the resulting microstructures and physical or mechanical properties.

Since metamorphic manufacturing is in its infant stages, particularly in terms of synthesizing the underlying component technologies into an implementable manufacturing framework, an important first step will be to build much greater community awareness, public excitement, and stakeholder buy-in of this potentially disruptive manufacturing technology.

Modeling and Simulation

Robust, accurate, and efficient predictive models and simulations that simulate MM forming processes are vital for accelerating metamorphic manufacturing development and implementation. The growing discipline of ICME is a core technology,[58,59] and approaches for its implementation have been defined.[4,59] Predictive models should include and integrate into the agile manufacturing product development cycle more specific models involving forming techniques (particularly those associated with incremental deformation), thermal processing, microstructural evolution, tool-workpiece interface behavior, and robotics/machine operations. These models require access to appropriate databases due to the rich modeling and experimental datasets already developed in these areas. These datasets must include material data related to the incremental cyclic nature of deformation of the material during MM. Less rigorous, less computationally intensive, faster, lightweight MM models with in situ process monitoring and controls can be developed to learn and to improve the more robust models. These lightweight models will also provide for real-time compensation and feedback, and can perhaps strongly leverage machine learning methodologies[69,70] in order to benefit from a large amount of existing data and make the models more reliable/accurate over time.

Such computational modeling and simulation are critical to the integrated product development cycle during agile manufacturing of complex parts, as well as to the design of new products and platforms.[4] The computational models discussed here are a key component of many of the action plans and tasks presented in Section VII.

Technology Demonstrations and Benchmarking

Successfully mapping the value stream for metamorphic manufacturing is vital, and one way to do this is to establish demonstration projects for specific applications. Examples of such applications from the aerospace industry might include aluminum stringers, or titanium bulkheads. These demonstration projects could be undertaken within existing government (plus industry) supported manufacturing institutes, large industrial companies, or other types of manufacturing-related consortia or organizations. New user facilities should be established to demonstrate new MM technologies and test novel MM applications. One example of a business model for such facilities is the Manufacturing USA network of manufacturing innovation institutes.[71] These new MM user facilities could identify, leverage, and/or share tools, expertise, and R&D resources. More specifically, they could develop new MM robots, computational tools, machines, and other MM infrastructure elements and capabilities. For more detailed tactical suggestions concerning technology demonstrations and demonstration facilities, see Action Plans 2 and 5 in Section VII.

In order to properly benchmark MM capabilities, a comprehensive list of MM hardware and software tools and equipment should be developed, perhaps after conducting a study on the process needs for a few use cases (i.e., example components). Metamorphic manufacturing taxonomies should also be developed, including terms, technologies, specific MM approaches, etc. Finally, detailed benchmarking activities related to incremental deformation and/or other aspects of metamorphic manufacturing should be launched, similar to prior benchmark activities such as the 2012 Sandia Fracture Challenge,[72,73] the Additive Manufacturing Benchmarks 2018 event,[74] and the benchmark session at the 11th International Conference and Workshop on Numerical Simulation and 3D Sheet Metal Forming (NUMISHEET 2018).[75] The latter was particularly relevant to the present technology in that numerical simulations of sheet formed parts were compared with experimental results from industry and academia.[75] See also Action Plan 1 in Section VII, which includes detailed activities for an ICME benchmark initiative for metamorphic manufacturing.

Sensors and Data Analytics

As mentioned in early sections of this report (e.g., Section IV), sensors are one of the foundational technological elements supporting metamorphic manufacturing. They are vital to MM-related aspects such as vision systems (optical and infrared) for robots, geometric measurements, object detection, thermal signatures and machine distortion, as well as other nondestructive methods for measurements of material properties, load, etc. Sensors are critical in the operations of the robots and machines to be used in metamorphic manufacturing, and will support in-situ feedback and adjustments during MM, in order to ultimately provide for agile and efficient manufacturing of complex final shapes. Some examples of specific activities for development of MM sensor systems could include: develop a specific NDE toolkit to interrogate MM-based parts, examine the applicability of existing tools (e.g., phased array ultrasound for material defects), and design process-specific tools (e.g., ultrasound-based sensing of the local modulus, embedded miniaturized pressure sensors in tools for measuring contact pressure and sliding).

The data that is produced from sensors, modeling, characterization, and testing supporting MM will not only be central to the full development of this technology, but will be both voluminous and disparate. Whenever possible, the plethora of important existing data should also be made accessible to the broader community, in order to be utilized for MM modeling and technology development. Newly developed MM data will need to be curated, stored, managed, and shared in order to accelerate the full development and implementation of this technology. Other efforts for building infrastructures for materials data[76–78] and other relevant data types should be leveraged wherever possible. There are good examples of such requisite data infrastructures in other science and engineering communities as well, as earth[79] and life sciences.[80]

Workforce

As discussed in Section V, in order to support the development, application, and sustainability of MM, there is a great need to educate, cultivate, and maintain a skilled, multidisciplinary MM workforce. One recommendation is to develop new content and/or entirely new courses at universities, centered about key MM supporting technologies, as well as their integration. These technologies include (but are not limited to) the fundamental STARC elements discussed earlier—sensors, thermal control, actuators and forming tools, robotic manipulation systems, and computation—as well as incremental deformation, data management and sharing, machine operations, and materials processing. Similarly, MM short courses for existing professionals should be developed and provided by professional societies, manufacturing institutes, and/or industrial companies/consortia. Finally, team-based multidisciplinary internships/fellowships in metamorphic manufacturing could not only help develop the MM workforce, but would contribute to pollination of knowledge and personnel across not only disciplines, but among industry, university, and national laboratory sector affiliations as well (see Section VII, Action Plan 4).

VII. Action Plans

Taking into consideration the value proposition, foundational technologies, challenges, opportunity areas, and recommendations for metamorphic manufacturing (Sections II–VI), eight high-priority action plans were developed. The intent of these action plans is to help scientists, engineers, and other stakeholders interested in MM (i.e., the readers of this report) accelerate the development, emergence, and growth of this potentially game-changing technology. Detailed tasks/activities were suggested for each action plan, and issues considered for each task include timeframe, personnel or affiliation types needed to lead or participate, metrics to measure progress, and rough estimates of cost. These action plans are summarized below (in no specific order of priority), and the related key tasks beneath each action plan are generally ordered in a sequential fashion, although many of them could be executed simultaneously (i.e., in parallel) within that action plan.

Action Plan 1:

Launch integrated computational materials engineering (ICME) benchmarking and modeling efforts for MM-based forming processes

1.1. Establish a lead benchmarking team
1.2. Perform a literature review on candidate materials
1.3. Define key model features and develop process models
1.4. Identify a generalized industry metal-forming example
1.5. Define scope and specifics of detailed benchmark problems/challenges
1.6. Select a data repository to house demonstration problem information
1.7. Execute an ICME benchmarking challenge competition

Action Plan 2:

Build prototype MM process suites and exemplar parts

2.1. Define feature sets for MM processes and exemplar products
2.2. Build prototypes of tools and products

Action Plan 3:

Characterize critical-to-quality (CTQ) property drivers for MM materials

3.1. Identify representative products or classes of products
3.2. Identify key materials system, MM processes, and final product requirements
3.3. Compile and curate MM data

Action Plan 4:

Develop an MM internship

Action Plan 5:

Establish a shared technology demonstration facility

5.1. Establish small MM facility with a technical advisory committee
5.2. Develop a "one design" small MM desktop kit (see also Action Plan 8)
5.3. Establish a large MM shared facility
5.4. Use the facility and assure long term sustainability

Action Plan 6:

Foster small organization-led industry-based projects and R&D opportunities

6.1. Educate small organizations (as opposed to large companies) on MM benefits
6.2. Survey needs and constraints of smaller organizations
6.3. Identify collaborative partnerships
6.4. Disseminate funding agencies' request for proposals from small businesses
6.5. Designate existing demonstration facilities for MM R&D

Action Plan 7:

Formulate and address a set of MM grand challenge problems (GCPs)*

* Numbers in this case represent some potential/example GCPs

7.1. "Forged in Fire"-like competition demonstration
7.2. Submarine hull prototype
7.3. Space vehicle application
7.4. Unmanned transportation platform application
7.5. Medical application(s)

Action Plan 8:

Create a desktop prototype MM machine

These action plans are all designed to achieve the same outcome: to help jump start the development, emergence, and growth of this potentially disruptive technology, and make quantifiable progress within the next 3 years. Some of the tasks, enablers, and implementation pathways amongst these action plans are also interrelated, or dovetail with one another.

Action Plan 1:
Launch integrated computational materials engineering (ICME) benchmarking and modeling efforts for MM-based forming processes

Task 1.1–Establish a lead benchmarking team

The first activity would be to convene an ICME-MM technical benchmark team that would likely include scientists and engineers from universities and national laboratories, as well as from original equipment manufacturers (OEMs) and other vendors from industry. This team would be composed of detailed practitioners from a variety of disciplines, who develop and/or work directly with the models, hardware, and other tools related to MM. This is in contrast to the team members in Task 1.4, who would have a higher-level perspective. This technical benchmark team is envisioned to include 10–15 people. The lead organization that assembles and helps guide such a benchmark team could be either a professional society, a public-private R&D organization such as LIFT, a group within a national laboratory, or in some cases an organizing body established to lead a relevant conference series.[72,74,75] The technical benchmark team and coordination organization that lead this task would provide some oversight for the remainder of the tasks (1.2-1.7) in this action plan.

Task 1.2–Perform a literature review on candidate materials

Adequate MM benchmarking will require a detailed literature review and a more detailed gap analysis on some candidate materials. The types of questions that might be answered in such a gap analysis include: What aluminum, titanium, or steel alloys might be most amenable to MM? What are the strain rate targets for such alloys? What type of and how much pertinent data is already available for these alloys? Another candidate material consideration is that property distribution of MM production pieces might often need to meet or exceed those of most current alloys. Other considerations that could be investigated for specific candidate materials include the availability/applicability of existing models (this would overlap with Task 1.3), as well as what existing programs or areas of interest at industrial companies, government agencies, or academic research groups could be leveraged to support and accelerate pursuit of MM for specific alloy candidates. A metric of progress would be publication of the results of this literature review and gap analysis, and personnel to accomplish this task could be two or three people from the same groups in Tasks 1.1 and 1.3, working in collaboration.

Task 1.3–Define key model features and develop process models

This task would be considerably more robust and time consuming than some of the other tasks in this action plan, due to the need for process model development. The technical benchmark team could guide an effort to define some of the key model features, and identify and/or help to develop appropriate models for MM. Development of new models, though, would require the efforts of other researchers within universities, national laboratories, and/or industry. This could involve, for example, building subroutines into temperature histories to examine property solutions. To assess the level of maturity of ICME-MM models, robust model verification and validation (V&V) is an imperative.[65,81–85] ICME-MM models can provide valuable contributions at many levels of maturity as long as the limitations are well quantified and documented. These ICME-MM models will involve high-fidelity data (involving parameters including shape, temperature, strain, machine accuracy, metallurgical properties, mechanical properties, etc.) as model inputs and for model validation, as well as valuable model output data. This effort might even include gathering manual blacksmithing data to improve the simulations.

Although many existing models will be of great utility, new computational models will need to be developed. In addition to members of the technical benchmark team in task 1.1, personnel involved in this task could include other scientists and engineers identified by the benchmark team and others, each possessing key types of modeling expertise, including (but not limited to): forming simulation, microstructural evolution, computational model V&V, robotics, manufacturing, etc. Particularly for the development of at least some of the requisite new models, estimated costs for this task are on the order of $2M and could take 2–3 years.

Task 1.4–Identify a generalized industry metal forming example

A goal of this activity would be to help launch an ICME benchmarking challenge (see also Tasks 1.5 and 1.7). The ICME-MM benchmark team and lead coordinating organization would guide this effort, which might be similar to prior benchmark activities and challenges mentioned in Section VI.[72–75] First, leveraging Task 1.2, one or two candidate metal-forming parts would be identified that are of interest to industry, and for which the models, hardware, and data developed in this action plan could be leveraged and generalized to other MM metals, parts, or problems. Examples of the types of parts that might be considered are: (1) incrementally formed Al-2024 sheet-based shapes (for focus on Task 1.5 parameters such as formability, shape, strength, fatigue, computational time, total process time, and cost), or (2) incrementally forged Ni-Al-Cu propellers (for focusing on parameters such as shape, microstructure, strength, corrosion, computational time, total process time, and cost), or 3) a titanium exo-skelliton that would require similar features, but would need to be tailored to individual physiology. This activity requires access to appropriate databases for material properties, processing parameters, etc. as well as estimates of production costs.

In addition to engaging personnel from Original Equipment Manufacturers (OEMs) for this task, engaging Department of Defense partner(s) may be useful, as agile manufacturing has a strong pull from the US national security enterprise. A small team of approximately five stakeholders should be assembled. These individuals should possess a high-level perspective in order to identify two or three candidate parts (i.e., material, geometry, and required properties and performance) that could impact future products and/or mitigate manufacturing challenges. Members of this team could be chosen by the lead technical benchmark team (Task 1.1). The background information gathering, meetings, documentation, and any other work from this high-level team should take no more than two to three months, at an estimated cost of approximately $20K–$30K. The team could also disseminate their final results to the relevant communities in the form of a publication or presentation that outlines the suggested metal-forming candidates, and how and why they would be highly impactful in the development of MM.

Task 1.5–Define scope and specifics of detailed benchmark challenges

Executing MM benchmarking challenges for comparison and enhancement of MM models from different groups via application to the same physical problem/test would be of great value in developing accurate ICME-MM models. Similar benchmarking challenges have been executed for models of ductile fracture , additive manufacturing, and sheet forming.[72-75] For this task, the technical benchmark team (see Task 1.1) would define the scope and specifics of one or two key benchmark problems or challenges, based on the metal-forming parts identified in task 1.4, as well as consideration of the materials and models identified in Tasks 1.2 and 1.3. Some experiments and/or preliminary modeling would be needed in order to fully define the specifics of the benchmark problems, and the models and experiments from Tasks 1.2 and 1.3 could be leveraged here. Probably the largest time limiter before being able to execute this task is development of any new requisite ICME-MM models in Task 1.3, which could take as long as three years.

Once some of these models are available, if the specific analyses needed have not been done previously (by the benchmark technical team members or other researchers), the benchmark team members may need to conduct some final tests or analyses in their own laboratories, for a given challenge. This activity might take between six and twelve months to complete. Specifics might include the material(s), material properties, test type, test geometries, and/or type of test result.[65] The test conditions and parameters must be very tightly constrained so that different modelers can directly compare their final results and modeling methodologies, and to facilitate the elucidation of key modeling challenges[65] for ICME application to MM.

Task 1.6–Select a data repository to house demonstration problem information

Many of the suggestions for this task are adapted from the recommendations of the previously referenced V&V study.[65] The ICME-MM benchmark challenge event (Task 1.7) is expected to produce robust modeling and experimental data sets that are quite valuable to the MM community, since they will have all been generated for the same, very specific problem(s), and thus could be utilized further by many other researchers beyond those participating in the benchmarking event, to test their ICME-MM models and/or help develop new MM models, equipment, or data. It is thus critical that this rich data set is not lost, and is made available for the community to access and share. All of the ICME-MM benchmark metadata, experimental data, and modeling inputs and outputs should be housed in an existing repository, perhaps at one of the organizations involved in this effort, or a repository developed specifically for this data. Such a repository should be planned for and/or set up in advance of Task 1.7. The results of the ICME-MM benchmark challenge and location of the repository can then be published in a journal(s) with large readership by the relevant communities, in order to provide for much greater impact toward accelerating the implementation of metamorphic manufacturing.

Task 1.7–Execute ICME benchmarking challenge or competition

This task description is mostly taken from a similar one that has been outlined in a different TMS study, for benchmarking challenges related to the verification and validation (V&V) of models associated with the mechanics of materials.[65] After completion of Tasks 1.4–1.6, the first ICME-MM benchmark challenge competition will then be ready to launch. An example of an appropriate coordinating venue at which to launch this competition would be the World Congress on Integrated Computational Materials Engineering,[86,87] which is held every two years (i.e., in odd years). In that case, the ICME World Congress in 2021 could be the venue of choice. The ICME-MM benchmark lead team (see Task 1.1) will have to coordinate with the organization holding the conference, as well as any volunteer conference organizing team. Couched in terms of how TMS operates a specialty conference, the best way to do this would be for members of the ICME-MM lead benchmark team to contact the organization that puts on the conference about 2 years in advance, and offer for some of these team members to become volunteer members of the conference organizing team that year. About one year in advance of the date that the ICME-MM benchmark challenge is held, the final presentations are made, and the modelling results are subsequently judged (i.e., at the conference or workshop), targeted communications would have to be disseminated to the relevant communities concerning entering the competition as well as attending (and/or presenting at) this final event. To launch the effort at a large gathering such as a conference, workshop, or summit, the appropriate launch venue should thus be determined about 2 years in advance, to allow sufficient planning time. The funding support required for such a benchmark event should be similar to that of any large workshop, or small specialty conference, and costs are typically covered by some combination of attendee registration fees, federal agency support, and industrial sponsorship.[65]

Action Plan 2:
Build prototype MM process suites and exemplar parts

Before building a MM prototype, the value stream of MM for the specific process(es) and material(s) that are being considered must be analyzed. For this Action Plan, in addition to material type, that means also beginning to build value assessments for different shapes and niche use cases that maximize the overall value proposition of MM approaches (see Section II–earlier in this report). The conceptual MM equipment suite discussed in Section IV (and illustrated in Figure 11 of Section IV) provides a useful framework from which to build this prototype, and to help guide the specific, individual tasks in this action plan.

Task 2.1–Define feature sets for MM processes and exemplar parts

In order to help define conceptual MM process suites and parts, it is important to first develop a list of processes for each key feature of metamorphic manufacturing. These represent the individual operations that are part of an integrated metamorphic manufacturing process chain. It is equally important to define the features of exemplar products that could be produced by MM. This would entail development of a set of minimum viable features for different products that are well suited for MM. This task could be completed by a few experts working in MM, probably within about a month.

Task 2.2–Build prototypes of tools and products

Initial prototypes of MM tools, process lines, and products could then be made. These might be stimulated by competitions, or challenges, which could be issued and supported by government agencies, similar to DARPA's prize challenges. Once support funding is in place, prototypes should be able to be built within about a year. This type of competition could then be iterated, continually increasing the scope and difficulty, for example by adding more and more complex features to the exemplar component to be produced by the prototype system. Evaluation of the properties, part shapes, and estimated return on investment (ROI) of the product would help provide metrics for judging the level of success of the prototype systems that produce the exemplar prototype parts. It would be useful to compare the same parts made at multiple locations (hence the competition), to learn and create best practices. The competition would include building tools for making sample shapes (e.g., waffle, stringer, etc.), and creating corresponding process designs and feature libraries. Aircraft bulkheads or stringers would be good exemplar parts to foster development of MM prototype suites. Some metrics of progress for MM suite development for bulkheads could include small presses, small dies, and equivalent property or performance values of the bulkheads made (as compared to conventional techniques). Similarly, success metrics for prototype aircraft stringers could include more complex shapes being achieved, in addition to obtaining the same or better properties than extruded stringers. Depending on the level of existing equipment that is utilized to make these MM prototype suites, costs for this activity are roughly estimated to be \$300K–\$400K per prototype system. In addition to scientists and engineers, highly skilled technicians would be important contributors to such competition teams.

Action Plan 3:
Characterize critical-to-quality (CTQ) property drivers for MM materials

Task 3.1–Identify representative products or classes of products

The first step in this action plan is to identify representative products or classes of products for which to characterize critical-to-quality (CTQ) trees, or CTQs, for an MM use case. As discussed in Section VI, CTQs can be defined as the key measurable characteristics of a product or process whose performance standards or specification limits must be met in order to satisfy the customer.[68] This task can be accomplished by assembling a focus group of between 5–10 people. Team member organizational affiliations should include OEMs as well as fabrication shops. The group would come up with a list of products, as well as an initial list of potential materials and processes. This task should be able to be accomplished within 3–6 months, at an estimated cost of $10K–$20K, depending on the number of group members and the frequency of meetings/workshops.

Task 3.2–Identify key materials system, processes and requirements

Next, a group of MM-related practitioners should work together collaboratively to identify more specifically a key materials system (alloy), MM processes, the production methodology, and final product requirements. This group would be composed of experts from academia, national laboratories, materials suppliers, OEMs, and machine tool producers. Developing CTQs for MM will then encompass efforts such as evaluation of property distributions and performance needs, and developing datasets related to deformation, thermal processing, and microstructure. This group will thus work together (and/or work with other collaborators) to produce representative shapes and identify MM processing methodologies, including forming methods, tooling, and processing routes or pathways. Tests will then need to be performed to determine properties distributions and part performance, and identify controlling mechanisms of the processes that yield the desired properties and/or performance. These results can then be compared to traditional forming processes and existing standards.

This effort would most likely involve an iterative procedure between tasks 3.1 and 3.2, with the time and cost of each iteration becoming progressively less. The cost of this task would in large part be associated with characterization and testing, could be accomplished in 1-2 years, and could range from $200K—$700K (not including any capital costs for new equipment), depending on the number of iterations required.

Task 3.3–Compile and curate MM data

Similar to Task 1.6, the data developed in Task 3.2 is expected to be robust and of great value to the MM community, and thus will need to be stored in a repository(ies), curated, and made accessible to the community. Since this data is related to CTQs, it will be vital to have standards development organizations involved in (and possibly lead) this effort. The underlying data, methodologies, and characterization results from Action Plan 3 should be published in journals and other publications, and the higher-level, final data related to CTQs can be published as tables and design curves by the participating standards organization(s).

Action Plan 4:
Develop an MM internship

In lieu of presenting information in the same task format as action plans 1–3, this action plan is more amenable to a single narrative format. An internship model was developed by the MM lead study team; the primary purpose of such an internship program would be to help train the next generation of engineers in metamorphic manufacturing approaches. In particular, this team-based, multidisciplinary internship (or fellowship) program would teach the emerging workforce about collaborative MM technology development, as well as help them develop some business skills.

The internship program would run over the summer (~3 months) and would first offer a short course of about one week, for the interns/fellows to learn the basics of MM and the goals and activities of the program. The interns would be composed of teams of about 3–5 students, from different disciplines or sub-disciplines associated with MM. Targeted disciplines could include materials science and engineering, mechanical engineering, design, robotics, software engineering, industrial engineering, and business. Initially team members might all come from the same institution. Each team would have a mentor who has familiarity with MM; the mentors could also serve as the teachers of the weeklong short course. As the program grows, many mentors and students would be recruited, and professional societies could help identify candidates for both.

After the weeklong course, each team would travel to no more than three locations (preferably within the same organization) over much of the remainder of the summer, to learn more about specific aspects of MM within companies (OEMs and other vendors/suppliers), institutes, national laboratories, or other MM stakeholder organizations. These partner organizations will also serve as sponsors of the program. It would be especially beneficial to build on the existing cooperative education infrastructure, since sponsored internships are already integrated into several universities.

> *...the primary purpose of such an internship program would be to help train the next generation of engineers in metamorphic manufacturing approaches. In particular, this team-based, multidisciplinary internship (or fellowship) program would teach the emerging workforce about collaborative MM technology development, as well as help them develop some business skills.*

Teams would spend ~10 weeks at the participating organizations, then at the end of the summer each team would provide a final report and presentation to the mentors and/or program coordinators. The report and presentation will not only summarize what they learned about MM, but build a technology and business case for MM (e.g., product opportunities, MM facilities available and/or required, market gaps, cost/benefit analyses, etc.). If there are multiple teams, the final team presentations could be judged to establish first and second place winners for best presentation/report.

A key to the program is to garner sponsorship from different companies or other organizations involved as hosting partners. The benefit for such organizations would be to have the interns contribute to various aspects of the organization's manufacturing, product development, and/or research programs, as well as to provide a great recruiting vehicle for potential future employees (at companies) or postgraduate research associates, young investigators, and/or new faculty (at universities and national laboratories). A team might spend the summer at different locations within one large company that has different business lines or subsidiary companies, e.g., United Technologies Corporation (UTC), General Electric (GE), or Ford Motor Company. Other types of organizations that might host the intern teams include manufacturing institutes (e.g., Lightweight Innovations for Tomorrow (LIFT) or the Advanced Robotics Manufacturing Institute (ARM), or government organizations such as the National Institute of Standards and Technology (NIST), the Naval Surface Warfare Center (NSWC), or Oak Ridge National laboratory (ORNL). These organizations will have to have existing metamorphic manufacturing capabilities, underlying components, and/or interest; this aspect may require approval by a board or consensus vote, perhaps by the internship mentor group. Other agencies or organizations could also sponsor this program without serving as hosts, such as the National Science Foundation (NSF) Innovation Corps (I-Corps) program, or some of the manufacturing innovation institutes.

Benefits of this program to the interns, include: (1) excellent first-hand experience to help them narrow their choices for future employment and/or help them get hired; (2) technical knowledge gained in MM and supporting technologies; (3) real world experience as to product development, manufacturing processes, research, engineering application, and business cases; (4) the ability to work productively and efficiently within a multidisciplinary team.

Action Plan 5:
Establish a shared technology demonstration facility

Task 5.1–Establish small MM facilities

The first step in this action plan is to establish a small metamorphic manufacturing facility. This would include convening a technical advisory committee, determining a governance model, establishing staffing, and assembling the initial equipment and resources. This could be accomplished by selecting one or two facilities with some level of existing MM expertise and capabilities, in order to reduce costs and set up time. Depending on the MM capability level of the existing facilities and structure, the rough costs for establishing such a small facility would be on the order of $1M to $3M, and it is estimated that this facility could be made operational within a year. Metrics of progress and success would include obtaining program funding, convening the technical advisory committee, developing the small MM system design, demonstrating MM process line capability, and providing a vision or scalability plan for a larger, shared, central MM facility. Key organizations involved would be the initial facility partners, the funding support organizations, and an existing data repository partner for housing the MM data. This small facility would be quite valuable for demonstrating MM concepts, and providing the vision for a larger, central MM facility.

Task 5.2–Develop a kit for desktop MM device

In parallel with Task 5.1, a kit for a very small (relative to task 5.1) MM desktop device could be developed and made accessible to a wide range of users. This task would also be very closely related to Action Plan 8 below. An objective would be an integrated, single, relatively simple design flow, instead of multiple processing units. This is sometimes referred to as a one design kit concept.[88,89] Ideas and lessons learned could be adopted from the Arduino open-source electronics platform kits for hardware and software related to building a variety of different sensors and actuators.[89] In the case under consideration here, the desktop MM kit would contain an integrated open-source software suite, with equipment and hardware designs and data formats. A metric for progress would be a kit that results in a desktop MM unit being built for $75K or less. Costs to develop all the software, hardware designs, tests, and MM desktop demonstration unit(s), before the final kit is made available to the public, are roughly estimated to be as much as $2M, and the time to reach that point is estimated to be between 18 and 24 months. Such a kit could result in great public awareness of and interest in MM. This task dovetails directly with Action Item 8, which considers in more detail the development of an actual desktop prototype MM machine, or desktop MM unit.

Task 5.3–Establish a large MM shared facility

Building off of Task 5.1, a large, shared, central facility or program for metamorphic manufacturing should then be designated and built. Although centralized, large volume (and component size) MM capabilities could be staged as a program run among multiple facilities or sites, the optimum model would be the establishment of a single central facility. This task would begin by leveraging the lessons learned in Task 5.1 and in Action Plan 2 (building prototype suites and exemplar parts; establishing a small MM facility), in combination with surveying existing facilities that might serve as the site(s) for such a large MM facility. In particular, this effort would utilize the vision for scalability developed in Task 5.1. Similar to Task 5.1, Task 5.3 activities would entail some combination of adapting or establishing a technical advisory committee, a governance model, staffing, equipment suite(s), and other hardware and software resources. The capability and maturity of an existing facility from which this center might be established would strongly influence the costs involved, with the need to build an entirely new equipment suite at the upper range of the costs. These costs could thus likely be in the $5M–$25M range. Funding sources for both the establishment and sustainability of this large MM facility could include government agencies that support the Manufacturing USA network—such as the Department of Energy (DOE), Department of Defense (DoD), and/or Department of Commerce (DOC)—as well as industrial partners, and possibly national laboratories. The time to establish such a central facility could vary between 1–3 years, again depending on to what level an existing facility can be utilized.

Task 5.4–Demonstrate MM capabilities

After it has been established, the large MM facility would then undertake various activities that are critical to accelerating MM implementation on a broad scale. Such activities could include round-robin testing, prototyping, demonstrating at a large trade show (e.g., the International Manufacturing Technology Show (IMTS), the Defense Manufacturing Conference (DMC), etc.), and model validation. Additionally, benchmarking competitions and activities (see Action Plan 1), MM education and training (see Action Plan 4), developing standards for parts made by MM (see Action Plan 3), and proposing and executing "grand challenge" problems (see Action Plan 8) could all be supported by such a MM central facility. Grand challenge problems could in turn result in high-value MM applications, and optimum MM toolsets or equipment suites. The facility could also host university competitions and encourage MM technology demonstrations. All of these activities would enhance and accelerate commercial follow-on projects, industry buy-in, and optimum utilization of MM by industry. Metrics of progress would include the long-term sustainability of the central facility, the total number of funded projects addressing the various activities mentioned previously, and the number of participating organizations. Some other organizations that could also play a role in the usage and sustainability of such a facility include materials suppliers, vendors for small and large systems, universities (faculty and students), and professional societies (MM competitions).

Action Plan 6:
Foster small organizations-led industry based projects and R&D opportunities

The tasks in Action Plan 6 apply to smaller organizations, as opposed to large industrial companies. Some examples include startups/spinoffs from university laboratories, incubators and/or technology parks (which are now associated with many universities), as well as perhaps some more aggressive small-to-medium sized companies who are willing and/or able to take on some risk in the short term, for potential long-term payoffs.

Task 6.1–Educate small organizations (as opposed to large companies) on MM benefits

One of the first steps in stimulating MM projects and R&D opportunities within small and medium-sized organizations is to educate them on the benefits, and/or value proposition of MM. After identifying a list of smaller organizations/businesses for which MM might be a good fit, the potential benefits could be communicated through workforce development resources including videos, brochures, and publications, as well as offering short courses and or webinars on MM. Presentations in conjunction with existing events or conferences (e.g., via professional societies) could also be planned, and representatives from small organizations could be invited to attend these events. Key MM stakeholders that could develop and distribute such resources, and plan and promote such events, include MM researchers, engineers, and other practitioners within universities, national laboratories, large companies, and professional societies. Most of these efforts could be executed in a very short timeframe (6-12 months), but should then be ongoing. Estimated total costs for such efforts is on the order of $300K (not including any full-time staff). Some metrics of progress for these initiatives could be: (1) total downloads or distributed copies of materials; (2) attendance at MM webinars, courses, professional society conference sessions, and/or MM-related committee meetings; (3) total MM funding proposals submitted, particularly in the realm of Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) proposals; (4) new businesses started based on MM technology.

Task 6.2–Survey needs and constraints of smaller organizations

In conjunction with Task 6.1, it is equally important to survey the particular needs and constraints of these smaller organizations. In the context of metamorphic manufacturing, these needs could be framed in terms of shortcomings of existing subtractive- and additive-based manufacturing processes and materials. In more general terms, the idea is to identify how MM techniques can improve the competitiveness and/or goal achievement of these organizations. Such a survey(s) could take 3–6 months to distribute, receive responses, and analyze the results, and would necessitate perhaps the equivalent person-hours of a full time employee (FTE) working over that that timeframe. Technical professional societies are very well suited to execute such a survey, and some possible societies include TMS, the Association for Iron & Steel Technology (AIST), ASM-International, the American Society of Mechanical Engineers (ASME), the Society of Manufacturing Engineers (SME), the Institute of Electrical and Electronics Engineers (IEEE), the IEEE Robotics and Automation Society (IEEE RAS), and the Society for the Advancement of Material and Process Engineering. Relevant government establishments could also play a role in this survey effort, such as the NIST Hollings Manufacturing Extension Partnership (MEP), the Manufacturing USA network, and perhaps state and local industry organizations.

Task 6.3–Identify collaborative partnerships

After or during execution of Tasks 6.1 and 6.2, collaborative partnerships that could include some of these smaller organizations could be identified and/or developed. This effort should also take 3–6 months to establish such collaborations, with funding needed for the costs of organizing and maintaining such partnerships estimated to be anywhere from \$50K to \$200K, depending on the size of the partnership (i.e., the number of organizations and engaged MM community members). Professional societies such as TMS or any of the others mentioned in Task 6.2 could help establish and run such partnerships, and the funding support could be provided by a combination of government sponsors and the participating partner organizations.

Task 6.4–Disseminate funding agencies' request for proposals from small businesses

Another way to involve small business in MM manufacturing is for funding agencies to issue MM-related requests for proposals (RFPs) especially targeted for small businesses. These RFPs would be for SBIR or STTR programs centered about metamorphic manufacturing, or at least the foundational elements (and/or integration thereof) that contribute to MM. Additionally, venture capitalist funding opportunities could be investigated. Potential agencies that could issue such RFPs include DoD, DOE, NSF, NASA, and the Department of Commerce (DOC). It would likely take 1–2 years from the time of the release of this report for such RFP calls to go out, and then 1–2 years for the first project results to begin to be presented, published, and or transitioned toward application in industry. The level of funding for individual SBIR or STTR programs would be on the order of $100K for phase 1 projects, $500K–$1M for phase 2 projects, and $1M+ for phase 3 projects. Metrics of success for this effort would include the total dollar amount of the funding calls and the number of agencies participating. Even more important would be the metrics of success associated with the research and/or development projects resulting from the funding support, including number of presentations, publications, patents, and new products, as well as any resultant enhanced manufacturing capabilities, greener manufacturing methods, or reductions in the time and/or cost of product development and production. University investigators could also team with the small businesses on these MM R&D programs, thus involving graduate students, interns, and postdoctoral fellows in these programs, and therefore potentially providing leveraging (in both directions) with the intern program in Action Plan 4.

Task 6.5–Designate existing demonstration facilities for MM R&D

Another way to foster MM R&D projects is to designate an existing demonstration facility for MM R&D. This task thus dovetails directly with Action Plan 5 above. Such R&D projects could include not only big industry, universities, and national laboratories, but smaller organizations as well. LIFT would be the most obvious existing facility to engage in leading such an effort, perhaps working with a professional society, but other Manufacturing USA institutes or national laboratories could also play leading roles. Full engagement of many such MM demonstration facilities and R&D projects with smaller organizations could take several years, and measurable metrics of success could include how many "local demonstration facilities" are engaged, how many small organizations are engaged, and how many MM R&D projects are generated as a result of this effort. Examples of possible local demonstration facilities could include the following regional centers: (1) West–Lawrence Livermore National laboratory (LLNL), (2) South–Oak Ridge National Laboratory (ORNL); (3) East–NIST, NSWC; and (4) Midwest–NASA, the Air Force Research Laboratory (AFRL). Costs are roughly estimated to be tens of millions of dollars for this effort (plus staffing – for which existing staff could be leveraged), depending on the number of demonstration facilities that are engaged and the number of R&D projects that are supported. Possible funding sources include DOE, DoD, NIST, ORNL, the Manufacturing USA Network, and individual institutes within Manufacturing USA such as LIFT, ARM, and America Makes.

Action Plan 7:
Formulate and address a set of MM grand challenge problems (GCPs)

For this Action Plan, instead of tasks, some potential grand challenge problems (GCPs) are provided. In most cases, it would be better to develop some of the prototypes or demonstrators in Action Plan 2 and Action Plan 5 before undertaking the grand challenges. Also in this vein, GCP 7.1 could almost be considered a demonstrator itself.

GCP 7.1–"Forged in Fire"-like competition demonstration

An MM competition could be issued, somewhat analogous to the *Forged in Fire* bladesmith competition series televised on the History channel.[90] This competition dovetails somewhat with the Action Plan 2–Task 2.2 competition on building prototypes of tools and products. For this activity (7.1), a competition or series of challenges could be issued to manufacture MM parts with complex features, and superior properties/performance. LIFT ran a preliminary student competition in this way that demonstrated the fabrication of complex component shapes from plasticine.[1,2] The judging could be based on metrics associated with properties/performance (e.g., load bearing capability or other functional requirements of the part), speed of part production, final aesthetic appearance of a consumer product, etc. This type of competition could be led by a professional society, a Manufacturing USA institute, a national laboratory, or a university, and entrants could include small businesses, university groups, national laboratory teams, and manufacturing institutes. This challenge could be launched in about 18–24 months, and would first involve obtaining funding support, followed by defining the specific challenge parameters (part geometry, material, etc.), and then executing a strong communications campaign beginning at least a year in advance of the competition, in order to attract entrants and give them time to produce the part(s). An example of a technically related competition is the TMS Bladesmithing competition for students,[91] which is held every two years, and in the off years includes presentations by the winners and other entrants at the TMS Annual Meeting & Exhibition. The bladesmithing event is now on its 3rd iteration and attracts 20–25 student teams at each competition.[91] The MM competition suggested here would involve considerably larger, more automated, and more expensive processing equipment, as well as experienced practitioners/professionals. Roughly estimated costs to execute such a competition, including a monetary prize to attract teams and recoup some of their costs, are on the order of $100K–$500K depending on the size of the monetary award, the breadth and level of the communications/marketing campaign, the competition planning and judging, and the final awards presentation event. Metrics of success of this grand challenge could include number of entrants, number of twitter followers, and sustainability of the competition.

GCP 7.2–Submarine hull prototype

This grand challenge entails using MM techniques to build a large-scale, high-strength steel submarine hull prototype with considerably fewer welds than a conventional hull prototype. This effort is estimated to take 3 years and cost on the order of $15M. Financial support could be provided by the US Navy, the Defense Advanced Research Projects Agency, and/or the Office of the Secretary of Defense. Although this is indeed a "grand" challenge, it addresses a longstanding issue of high impact, and could result in many spin-off applications as well. Examples of some measures of success would be the elimination of 50% of the welds, or the capability of using new or gradient materials.

GCP 7.3–Space vehicle application

This grand challenge is similar in theme to GCP 7.2. But in this case it is more of an open suggestion to use metamorphic manufacturing to produce a component for space vehicle application, perhaps in a satellite. This grand challenge problem is left open for definition by experts in this area. Once the specific grand challenge is defined, the methodology, costs, and participating organizations (NASA and others) can all be determined.

GCP 7.4–Unmanned transportation platform application

A MM grand challenge problem could also be centered about unmanned transportation platforms. Potential examples include smart structures for autonomous cars, unmanned aerial vehicles, or unmanned underwater vehicles. Taking the autonomous car example further, MM could be applied to developing a car with most of the electronics embedded inside the vehicle body, as well as various sensor platforms throughout the car. Multifunctional and embedded components could include light detection and ranging systems for distance measurement, structural health monitoring components, antennae, and lightweight structural components. Costs for addressing this type of problem with MM are estimated to be large (on the order of $10M), but could have huge impact. A number of corporations as well as government and defense department agencies would be interested in this type of application, and could be approached for support.

GCP 7.5 Medical application(s)

Finally, a MM grand challenge problem could be built around a medical application. One example of a potential application domain is medical imaging (e.g., magnetic resonance imaging (MRI) and/or x-ray computed tomography (CT) equipment components). Metamorphic manufacturing could help achieve designs that dramatically decrease the amount of particulate cleaning due to production of chips or powder during component manufacture. Metamorphic manufacturing could also be used to produce highly customized, complex part geometries. Experts working with medical equipment should collaborate with MM practitioners to identify the most promising, highly impactful grand challenge in this area, and also help to identify relevant funding sources (e.g., within the National Institutes of Health (NIH), industry, etc.).

Action Plan 8:
Create a desktop prototype MM machine

Analogous to how desktop 3D printers brought additive manufacturing to the attention of a much wider audience, development of affordable small MM machines with modular components and standardized features could greatly accelerate and grow the awareness, uptake and adoption of metamorphic manufacturing by a broader audience, and thus support the future success of MM technologies. This action plan involves designing and assembling a desktop prototype MM machine, or desktop MM unit, which could also serve as the basis for the MM desktop kit described in Task 5.2 under Action Plan 5. Some key features and activities are identified here to support the development of a desktop MM machine to support hobbyists, students, entrepreneurs, researchers, and other users, in both technology demonstration and workforce development efforts. The purpose, key features, envisioned capabilities, and development pathways of an integrated MM desktop machine are thus described in some detail below.

The overarching purposes for the development of desktop MM units are to generate enthusiasm for MM among the science and engineering community; familiarize the future manufacturing and materials workforce with new, innovative MM technologies; conceptualize different MM desktop unit configurations and standard/essential unit components; and help elucidate evolving R&D needed to jump start MM technology development. In particular, low-force (5–20 ton) incremental forming would be integrated into the MM desktop unit, to be used for entrepreneurial activities, research purposes, workforce development, and small demonstrations.

The key features of the desktop unit would follow the essential STARC elements described earlier. Some elements are evolving in technology readiness quite rapidly (S-Sensing, R-Robotics and C-Computation) and the challenges are largely in integration. The earliest of such units may omit thermal control and dimensional sensing to perform open-loop cold forging. But the overall design should be adaptable to include the other modules as well. Candidate control systems in more advanced desktop units may include induction coils for heating, and a controlled-gas tent to allow hot forging of oxidizable metals. Sensors could include vision systems for geometric measurements and object detection, and thermal cameras for temperature measurement. Sensing may initially be quite crude and could evolve to estimate local strain distributions. Initial kit actuators may be based on simple Enerpac® C-Clamps with interchangeable tool ends that can be sized so that the applied pressure sufficiently exceeds the workpiece flow stress. Hydraulic or mechanical actuation can be used to drive deformation. Robotics would be employed for positioning the workpiece relative to the deformation tools and can advance the work incrementally after each forming operation. In advanced applications, closed-loop control can be used to minimize dimensional errors.

Finally, a digital thread would maintain data through the entire MM process, would entail a communication framework for data flow, and would support ICME-enabled design, digital twin modeling, and materials qualification. A digital thread has been described broadly as "the communication framework that allows a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives...," while digital twin refers to "a digital model of a particular asset that includes design specifications and engineering models describing its geometry, materials, components and behavior...."[61] While some iteration and trials would be required to develop a viable demonstration system, it should be possible to develop a standard kit where the cost of parts is between $50k and $100k for a single system designed for low-temperature alloy forming (such as aluminum, bronze or brass). Total cost will depend upon the final design, number of units to be sold and the price of some elements (e.g., small robots, 3-D laser scanners and Programmable Logic Controllers (PLCs)). The estimated cost of a desktop unit containing such features is thus between $50K and $100K. The costs could be driven even lower, since at time of this writing, very low cost hobbyist robots and dimensional sensing units are becoming available. It is an important open question if these units could be adapted to this task. Figure 13 conceptualizes a potential implementation where a low-capacity robot may change tools and position work on a press large enough to incrementally form the component.

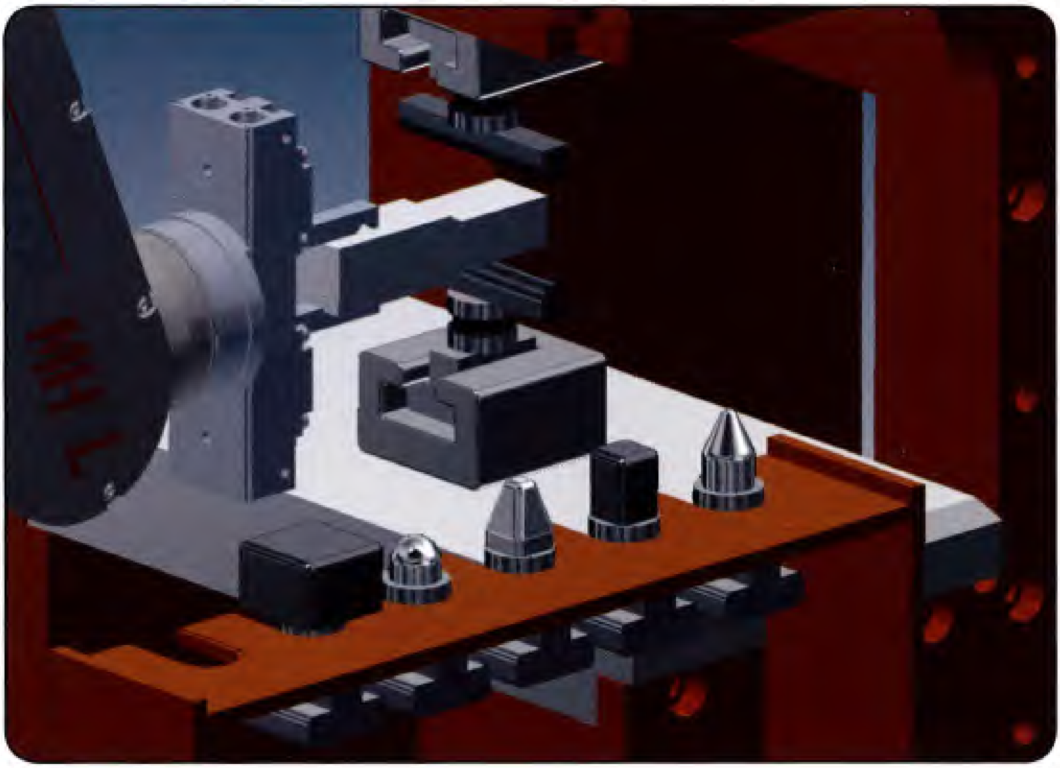

Figure 13. Conception of a low force robot able to change tools and position work on a larger press.

Examples of capabilities envisioned for this desktop MM unit include: (1) A desktop robot with up to a meter radius of travel with long and compliant grips that may keep the robot from thermal or shock damage for holding, cold working, or hot working workpieces; (2) a dedicated robotic arm (e.g., mounted on an XY platform) for positioning the workpiece changing tools; (3) a 3-D laser scanner to measure part configuration and software to interpolate strain from these measurements, and (4) modest heating inexpensively accomplished with a salt-bath or flame system, such as a propane forge. All systems will be controlled and data acquisition performed using a central computer and local programmable logic controllers (PLCs). Before deployment, there would be a few other prerequisites. The MM desktop unit software tools would have to be developed, and it would be best to disseminate the source code to the community (open source) in order to provide a framework for customizing the technology (e.g., tool carousel control, process pathway customization, etc.). Since the community needs a common platform to successfully deploy the desktop MM unit in workforce development and technology demonstration, standardized pieces of equipment should be developed, to permit various MM desktop unit configurations (i.e., similar to the MakerBot model for 3D printing). This type of unit especially dovetails with the MM desktop kit concept in Task 5.2 of Action Plan 5.

One potential pathway for developing such MM desktop units is to encourage small and medium-sized businesses to design MM desktop units by taking advantage of SBIR funding opportunities in the manufacturing domain. Another pathway is contest platforms, which could also be used to inspire innovative technology solutions from prospective users. These contests could have some combination of the following objectives: (1) designing a fully integrated MM desktop unit, (2) developing the software suite for an MM desktop unit, (3) creating open-source manufacturing pathway algorithms (e.g., executing various tool changes) and material process models, and (4) demonstrating the ability of a desktop unit to develop high-value small parts. This fourth objective overlaps with grand challenge problem 7.1 under Action Plan 7.

VIII. Concluding Remarks

Metamorphic manufacturing (MM) is a high-value, potentially disruptive manufacturing technology, referred to here as the third wave of digital manufacturing (following CNC machining and additive manufacturing). More specifically, MM is an approach to manufacturing that relies on closed-loop, numerically controlled, incremental forming to simultaneously achieve complex shapes, specific engineering properties, and local microstructures.Although many of the foundational technologies underlying MM are beginning to come to maturity, the full vision of MM has not been realized because these component technologies have not yet been synthesized into a cohesive whole, which in fact is what the MM-related programs advocated in this report aim to accomplish. These foundational technologies include the five fundamental elements previously mentioned—Sensors, Thermal control, Actuators and forming tools, Robotic manipulation systems, and Computation (STARC)—as well as incremental deformation, data management and sharing, machine operations, and materials processing.

> *The strong value proposition for MM (Section II), foundational underlying technologies (Section III), fundamental STARC elements and conceptual MM equipment suite (Section IV), challenges and needs (Section V), high-level recommendations (Section VI), and in-depth action plans and tasks (Section VII) presented here are meant to all work together to help the community achieve* ***the ultimate goal of this report: to jump start the development, emergence, and growth of this potentially disruptive technology, and make quantifiable progress within the next 3 years.***

This report on *Metamorphic Manufacturing: Shaping the Future of On-Demand Components* captures and consolidates the ideas and outputs from a group of internationally recognized technical experts from a variety of disciplines including materials science and engineering, manufacturing, mechanical engineering, machining, and robotics. The strong value proposition for MM (Section II), foundational underlying technologies (Section III), fundamental STARC elements and conceptual MM equipment suite (Section IV), challenges and needs (Section V), high-level recommendations (Section VI), and in-depth action plans and tasks (Section VII) presented here are meant to all work together to help the community achieve the ultimate goal of this report: to jump start the development, emergence, and growth of this potentially disruptive technology, and make quantifiable progress within the next 3 years.

As alluded to in the preface, scientists, engineers, designers, policy makers and others who read this report are challenged to use the information provided here to stimulate direct action. Although the specific recommendations and detailed action plans and tasks presented here should not be viewed as all-inclusive, readers of this report could indeed begin to act upon many of them almost immediately, and are also challenged to use this information to learn, impart knowledge to others, and stimulate the development of additional ideas and activities that could contribute to this new manufacturing technology.

More specifically, it is our desire that the readers of this report would not only find its content informative, but that many would begin addressing the action plans and recommendations outlined here by either: (a) initiating and contributing to specific research, development, and implementation efforts within their organizations, (b) providing fiscal support for such activities, and/or (3) getting involved soon in some of the facilities development, grand challenge problems, competitions, conferences, publications, educational activities, industrial collaborations, and other activities detailed in Section VII. There is great potential for accelerating the development and widespread adoption of this potentially revolutionary technology, metamorphic manufacturing, in order to help produce what could be the next wave of digital manufacturing, and the time to act is now.

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Appendix A

Full list of all categories and challenges identified

Category	Challenge
Standards and Specifications	Lack of existing certification and qualification standards for MM-based components; • Will necessitate model-enabled solutions
	Undeveloped taxonomies, standards, and terminologies (e.g., ASTM terminology for additive manufacturing); • Defining part class (process, equipment, sequential/control), material class, and data structure
	Lack of specifications and standards for MM processes & outputs

Design, Modeling and Simulation	Lack of generalized "lightweight" (i.e., fast/low accuracy/quick-check) models for evolutionary shape estimation for broad material classes; • "Light-weight" model coupled to ML-enabled process to evolve with time and experience; • Hierarchical modeling with stepwise refinement to predict shape and properties; Should begin efforts with a simplified part (e.g., cylinder)
	Need for fast, accurate prediction of force, shape, failure mechanism, microstructure, local interfacial contacts; • Must understand which equations are truly applicable to accurately predict materials behavior in MM-processes
	Secondary processes to complete parts (e.g., coatings, inspections, finishing) are difficult to assess/select and complicates simulation efforts
	Lack of shape-making capability to achieve desired forged properties of intermediate-sized parts with complex features (e.g., iso-grid structures)
	Mechanics-based design tools (e.g., CAD/CAM) are not ready or are underdeveloped for MM-based process planning
	Lack adequately fast algorithms & systems to translate external shape change (delta) to local strains/stresses and estimate voxel temperature
	Unclear how to optimize MM processing pathways
	Lack of methods/tools to conduct MM-specific multi-objective optimization to assess cost of different MM process approaches (e.g., time and temperature control, number of hammer hits, etc.; within set boundary range)
Digital Data	Unclear of the big data needs for 1) collecting/predicting process requirements, 2) using ML-enabled approaches to automatically build data sets to inform design models
	Successful MM-based design will require key, currently unavailable datasets on alloy composition and feedstock condition
	Difficult to select MM process routes without robust alloy-dependent digital materials data

Feedstock and Tool Materials	Determining which tool materials are most effective (considering thermal expansion/contraction, lubrication, texture, vibrational control, etc.) for a given application
	Metamorphic manufacturing methods necessitate new lubricants (e.g., transparent, conductive) for large shear and compression; • These lubricant must have downstream compatible and minimal environmental harm
Materials Behavior/ Characterization	Lack of comprehensive, quantitative, predictive understanding of processing-structure-property-performance (PSPP) relationships for a majority of possible MM materials (e.g., springback; local property prediction; "back"-projection [for process design])
	Lack of fundamental material characterization methods for capturing the high strain state and complex strain states in incremental forming
	Microstructural evolution of defects from non-traditional feedstock sources is not fully understood
	Lack understanding of bulk forming limits with different materials compositions and temperatures; • Unclear how to assess and incorporate errors in property measurements
	Material performance is subject to secondary processes (e.g., coating) and is therefore difficult to predict
	Characterizing global/local interactions in materials (e.g., how local deformation affects global geometric accuracy)
	How to compensate for machine stiffness (particularly for large parts)

Sensors and Process Control	Linking process monitoring (sensor selection for precise/accurate data collection) with process control (adjusting process to make "in-spec" part)
	How to integrate robots into a closed-loop controlled deformation process for a. Sample Rotation; b. heated/sensing robot arms [e.g., if sample cools too much, locally heat it]; c. controlled quench/cooling; d. hardness indenter in robot arms
	Current equipment suites (e.g., press; robot; sensors; control integration; specific tools) are not optimized or designed to handle MM methods
	Metamorphic manufacturing approaches require advanced actuator controls with sufficient acceleration/deceleration (1 m/sec) and high precision and accuracy (~0.1mm)
	Ability to monitor/control millimeter (mm)-scale tooling and know how to compensate for tool degradation
	Conducting rapid dimensions assessments/measurements of MM parts (including real-time)
	Limited understanding of which signals coming from process are useful mechanisms for sensing parameters of interest (i.e., indirect measurement)
Value Proposition	No existing map of the process- & material-specific value stream for MM; • Critical need of value-assessments for different shape classes and niche use cases that maximize value proposition of MM approaches
	Unclear what MM-based component size is sufficient for scaling beyond subscale

Workforce/ Cultural	Need for skilled, multidisciplinary, and multifunctional tradespeople (to install, debug, integrate, etc.; processing science and digital interface and hands-on skills)
	Next-generation faculty hires must establish/encourage the next generation of multi-trade or multidisciplinary future educators for MM to be successful
	Retention of MM knowledge is paramount; requiring leading innovators (i.e., "super-operators") to transfer their MM experiences into best practices
	Metamorphic manufacturing approaches will be difficult to adopt as it requires 1) a shift from traditional centralized methods to distributed, cloud-based, transactional manufacturing and 2) learning from collective experiences
	Must ensure existing workforce has ongoing educational offerings to remain competitive in MM field
	Metamorphic manufacturing adoption requires buy-in from both operators and their companies

TMS

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Promoting the global science and engineering professions concerned with minerals, metals and materials