Women in Engineering and Science

Stacey M DelVecchio *Editor*

Women in 3D Printing

From Bones to Bridges and Everything in Between

Springer

Women in Engineering and Science

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To Kerry, my partner in life, and to Carole,
my mom and biggest fan.

Foreword 1

The Medici Effect and the Importance of Women in Manufacturing

In 2004, Frans Johansson published *The Medici Effect*, which emphasizes the need for diversity for innovation. His hypothesis is based on the Medici Dynasty in the fourteenth century and its role in the birth of the Renaissance. The Medici's financial support of painters, poets, scientists, architects (a variety of disciplines working closely together on diverse problems) led to an explosion of innovations. We still see this today in pockets of industries where architects work with entomologists on new designs of energy-efficient building, roboticists study nature to understand locomotion and manipulation. One of my most rewarding programs was when I worked with a microbiologist to use bacteria to synthesize magnetic nanoparticles for ferrofluids. Diversity is the fuel for innovation. Our greatest source of fuel for diversity is gender.

There are numerous trailblazers in gender diversity in sciences. Marie Curie was the first woman to win a Nobel Prize and the only person to win the Nobel Prize in two scientific fields. She was followed by her daughter, Irene Joliot-Curie, who received the Chemistry Prize in 1935. However, the statistics still show that women account for less than one third of those employed in scientific research and development across the world. But trends are changing in certain disciplines of science and engineering. When compared to other industries, including non-STEM, the representation of women among board directors in the information technology industry have experienced the sharpest increase, from 14.8% in 2018 to 17.9% in 2019 [1]. As an example, Dr. Deborah Frinke recently joined Oak Ridge National Laboratory as the director of the National Security Sciences Directorate. Dr. Fricke is a computer scientist that specialized in cybersecurity and was the director of research at NSA from 2013 to 2020. What is it about computer science that attracts women to the field? How do we catalyze gender diversity in manufacturing?

Manufacturing has always been a male-dominated profession. However, there have been exceptions. We saw during World War II that the engines of production would have halted without women in manufacturing as exemplified by Rosie the Riveter. Closer to my home institution, Oak Ridge National Laboratory (ORNL), the Manhattan Project depended upon the Calutron Girls who monitored the control panels that separated uranium isotopes. There have been trailblazers in manufacturing leadership. Dr. Susan Smyth, the 2020 President of the Society of Manufacturing Engineers (SME) is a Fellow of SME and National Academy Member. She was the chief scientist for global manufacturing at General Motors and director of their Manufacturing Systems Research Labs, directing the creation of GM's global manufacturing R&D strategies. In additive manufacturing, Dr. Dawn White invented and patented ultrasonic additive manufacturing and founded Solidica in 1999, which later became Fabrisonic. Dawn continues to be a serial entrepreneur in manufacturing. Both women are technical, innovative, and insightful, making them natural manufacturing leaders. Susan and Dawn have been manufacturing trailblazers. We now need manufacturing road pavers, more women to see the vast array of career opportunities in manufacturing. Rosie the Riveter and the Calutron Girls showed women could excel on the shop floor while Deborah, Susan, and Dawn have shown they can excel in the boardroom. Can additive manufacturing help fuel the fire for gender diversity in manufacturing?

I believe so and am optimistic. For ten years I was a mentor for the FIRST Robotics program. FIRST created an environment that encouraged diversity and hands-on collaboration where young men and women worked together solving challenging problems in a very compressed schedule (6 weeks). It truly is an intramural sport with a focus on manufacturing. For five years, Oak Ridge National Laboratory opened the Manufacturing Demonstration Facility up to these students, providing them direct access to the latest additive manufacturing tools. I saw an explosion of innovative ideas from the students when they were provided the opportunity to print parts for their robots. I remember it took just one or two confident women (younger versions of Deborah Fricke, Susan Smyth, and Dawn White) to show that they could have fun with science and engineering and they could stand shoulder to shoulder with the young men problem-solving (as well as using 3D printers and power tools). What became more interesting to me is I noticed over time that these women exhibited natural leadership skills. They were organized, creative, confident, and calm (more than me) in stressful situations. I have continued to see this today with young women I recruit and work with (one of whom is an author of a chapter in this book). Today, 29% of women, compared to 15% in 2015, believe schools actively encourage female students to pursue careers in manufacturing with 42% of women today ready to encourage their daughters or female family members to pursue manufacturing careers [2]. These are trends that excite me.

It is with this background, and my belief that diversity fuels innovation, that I am thrilled to see a book on additive manufacturing authored by women, many of whom are technical and business leaders in the additive manufacturing community.

Oak Ridge National Laboratory Lonnie J. Love,
Oak Ridge, TN, USA

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2. Giffi, C., et al.: Women in Manufacturing: Stepping Up to Make an Impact That Mattters, D

Foreword 2

I first met Stacey DelVecchio during a #3DTalk panel I co-organized with Barbara Hannah, founder of Cyant, during the international conference RAPID+TCT 2018. The panel discussion was about the adoption of additive manufacturing into the overall manufacturing process. At the time, Stacey was the Additive Manufacturing Product Manager at Caterpillar and already an authority in the implementation of 3D printing in her industry. I was quite impressed by her insights and experience implementing additive manufacturing at Caterpillar.

As the founder of the Women in 3D Printing organization, I am always eager to know other female professionals in our industry, hear about their background, involvement in the additive manufacturing industry, and current contributions in our industry.

I am sincerely impressed by Stacey. From her 30-year long career at Caterpillar, managing the additive manufacturing factory, to now running her consulting firm, StaceyD Consulting, Stacey did not forget to inspire and encourage more women to follow her steps! A true advocate for women in engineering, she served as the president of the Society of Women Engineers in 2014.

Her work with this book is another testimony to her dedication for a more gender--balanced additive manufacturing industry. Each of the women you'll hear from in this book have brought a considerable contribution to the additive manufacturing industry and 3D printing technologies, whether by accelerating the use of additive manufacturing in their respective industries, pushing the boundaries of machine capacities, advancing materials, or developing key software features.

This book is about the wide-spreading adoption of additive manufacturing for industrial applications, and exploring the technical advancements that are happening to enable this wider adoption. Stacey decided to do so by featuring some of the female individuals who are contributing to these advancements. The Women in 3D Printing organization has now been around for 6 years, and I am extremely proud and thankful for the work that has been done in our industry for such a book to even exist. I am grateful to Stacey and the 10 other women featured in this book for their everyday work, facilitating the adoption of 3D printing, and sharing their work throughout this book.

Women in 3D Printing
Berkeley, CA, USA

Nora Touré,

Preface

Look online or in industry periodicals and you'll find large amounts of information about 3D printing or additive manufacturing. There's also considerable information in these same online sources about the men, women, and companies that are major contributors to the industry and technology. But there are very few published books about the contributors to this rapidly evolving industry. And there are no published books about the amazing female champions in the field. This book highlights these impressive women and their contributions to the industry of 3D printing.

My sincere thanks to all of my chapter authors who willingly volunteered to share their stories. Some of these authors I know well, some are references of colleagues, and some are simply impressive women I read about. This book would be literally nothing without them. Thanks also goes to my mentor in this process, Jill Tietjen; my sounding board and proofreader, Holly Teig; and my numerous colleagues who were always there to help with technical content or general perspective.

Peoria, IL, USA Stacey M DelVecchio

About the Book

In this book, each chapter is written by a technical leader in 3D printing that happens to be a woman. Their stories are extremely different, not only in their industry within 3D printing, but also in the types of work they are doing. Some of the women are deep in research, some are focused on outreach, and some are managing the business of 3D printing; some of these women are just starting their careers while others are seasoned professionals. All are accomplished engineers. If you're looking to learn about the technical specifics of 3D printing, this is not the book for you. If you're looking for a glimpse into the variety that 3D printing has to offer both technically and from a career perspective, then read on to learn about what these inspiring women have done. At the end of each chapter, you will find a biography of the chapter author and co-authors.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
3DP	Three-dimensional printing or 3D printing
AAAS	American Association for the Advancement of Science
ABS	Acrylonitrile butadiene styrene
AC	Additive construction
ACES	Automated Construction of Expeditionary Structures
ACI	American Concrete Institute
ACL	Anterior cruciate ligament
ADF	Alloy development feeder
AISI	American Iron and Steel Institute
AIAA	American Institute of Aeronautics and Astronautics
Al_2O_3	Aluminum oxide
AL 6061-T6	Aluminum alloy 6061
ALP	Alkaline phosphatase
AMUG	Additive Manufacturing Users Group
AR	Augmented reality
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
AUVSI Foundation	Association for Unmanned Vehicle Systems International Foundation
AW	Apatite-wollastonite
BC	Boron carbide
BJP	Binder jet printing
C	Carbon
Ca	Calcium
CAD	Computer-aided design
CANRIMT2	Canadian Network for Research and Innovation in Machining Technology
C_f	Carbon fiber
CaP	Calcium phosphate

C_f/SiOC	Carbon-fiber-reinforced silicon oxycarbide
CCM	Coordinate measuring machine
CLIP	Continuous liquid interface production
CMC	Ceramic matrix composites
CNC	Computer numerical control
Co	Cobalt
CRADA	Cooperative Research and Development Agreement
CT	Computed or computerized tomography
D1, D7, D21	Day 1, day 7, day 21
D2C	Direct to customer
DASH	Direct additive-subtractive hybrid
DED	Directed energy deposition
DIW	Direct ink writing
DLP	Digital light processing
DLS™	Digital Light Synthesis™
DMD	Direct metal deposition
DMLS	Direct metal laser solidification (or sintering)
DO	Distraction osteogenesis
EB	Electron beam
EBM	Electron beam melting
EBPBF	Electron beam powder bed fusion
EPU	Elastomeric polyurethane
ERDC	Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
FDM	Fused deposition modeling
FFF	Fused filament fabrication
FGM	Functionally gradient material
FRF	Frequency response functions
F.SWE	Fellow, Society of Women Engineers
HA	Hydroxyapatite
HAZ	Heat affected zone
HIP	Hot isostatic pressing
hTERT-MSCs	Human mesenchymal stromal cells
IJP	Ink jet printing
IP	Intellectual property
ISO	International Organization for Standardization
LENS	Laser engineered net shaping
LMD	Laser metal deposition
LPBF	Laser powder bed fusion
MC	Magnetic caloric
MCM	Magnetic caloric material
MD	Maltodextrin
MMC	Metal matrix composite
MOST	Michigan Tech Open-source Sustainability Technology

MRI	Magnetic resonance imaging
MSAM	Multi-scale additive manufacturing
MVP	Minimum viable product
NEST Tech	Next Evolution Sense Technology
NHL	National Hockey League
NRMCA	National Ready Mix Concrete Association
NSF	National Science Foundation
NSERC	Natural Sciences and Engineering Research Council of Canada
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PA	Polyamide
PAA-Na	Ammonium polyacrylate
PBF	Powder bed fusion
PCP	Preceramic polymer
PIP	Polymer infiltration and pyrolysis
PLLA	Poly-L-lactic acid
PPE	Personal protective equipment
PUF	Physical unclonable function
PVP	Polyvinylpyrrolidone
QD	Quantum dots
R&D	Research and development
RepRap	Self-REPlicating RAPid prototyper
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures (from the name in French)
RPM	Revolutions per minute
TE	Tissue engineering
TEC	Thermal expansion coefficient
RM	Regenerative medicine
ROI	Region of interest
SBF	Simulated body fluid
SCC	Self-consolidating concrete
SEM	Scanning electron microscope
SIMP	Solid Isotropic Material with Penalty
Si_3N_4	Silicon nitride
SiC	Silicon carbide
SiC/SiC	Silicon carbide fiber in silicon carbide matrix
SiC_f	SiC fiber
SiO_2	Silicon dioxide
SiOC	Silicon oxycarbide
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering

SM	Subtractive manufacturing
SMA	Shape-memory alloy
SNR	Signal to noise
SNS	Spallation neutron source
SOM	Skidmore, Owings, and Merrill
SS	Stainless steel
STL	File format for 3D printing
STEM	Science, technology, engineering, and mathematics
STEAM	Science, technology, engineering, arts and mathematics
SWE	Society of Women Engineers
Ti	Titanium
TiC	Titanium carbide
Ti-6Al-4 V (Ti64)	A titanium alloy
TRB	Transportation Research Board
UHTC	Ultrahigh-temperature ceramic
UHTCMC	Ultrahigh-temperature ceramic matrix composite
USACE	US Army Corps of Engineers
UV	Ultraviolet
UV-VIS	Ultraviolet-visible spectroscopy
VR	Virtual reality
WC	Tungsten carbide
WC-Co	Tungsten carbide infiltrated with cobalt
Wi3DP	Women in 3D Printing
XCT	X-ray computed tomography

Contents

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Chapter 1
Introduction

Stacey M DelVecchio

Introduction

Emerging technologies are typically subject to public hype and 3D printing (i.e. additive manufacturing) is no exception. At times, people said 3D printing was going to take over the world. We were going to be printing everything, everywhere. At the same time, others were saying the technology would never get out of the prototype phase. Of course, the reality lies somewhere in between and many a heated debate has been had on what that reality actually is. For those of us working in the world of 3D printing, we have all encountered people that feel passionate about both extremes of the present state and the future of the industry.

But let's step back and level set on what we mean by 3D printing versus additive manufacturing. You'll see the chapter authors of this book use both terms interchangeably which is common in the industry. The terms "additive manufacturing" and "3D printing" both refer to creating an object by sequentially adding build material in successive cross-sections, one stacked upon another [1]. Additive manufacturing is where you add material versus subtractive manufacturing (i.e., machining), where you subtract material. Additive manufacturing tends to be the more inclusive term and is generally associated with industrial applications. From an engineering specification perspective, the American Society of Testing and Materials (ASTM) and the International Organization for Standardization (ISO) refer to the seven families of additive manufacturing seen in Figs. 1.1 and 1.2 as the broader descriptor, rather than the seven families of 3D printing. As additive manufacturing gained the attention of the media when some of the early desktop printers hit the market in the early 1990s, the term "3D printing" became popular [2]. The 3D printing terminology was compared to a 2D inkjet printer connected to a computer, making the term "3D printing" easier to visualize. This is why you will often see the

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