Metal and Bone Drilling - The Thermal Aspects

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For my lovely wife, Huishan, and children,
Arthur, Brenda, Christopher, and Deanna.
–Albert Shih

For my lovely wife, Ploy, and son, Dylan.
–Bruce Tai

For my lovely wife, Xue Zhou, and children,
Chuyu and Yuanbao.
–Rui Li

Preface

This book summarizes advanced technologies on drilling and demonstrates the evolution of manufacturing from industry to healthcare. Drilling is an art and science. Manufacturing engineers and orthopaedic surgeons understand the importance and challenges of drilling, a seemingly routine process that is often overlooked by people who do not know manufacturing or orthopaedic surgery. Many engineers have dedicated their talent and career to advance the drill design, material, coating, manufacturing, and performance. Every advanced drill is a work of art. New technology is built on these advanced drills, which make high-performance drilling and drilling research possible.

Broad applications of titanium alloys in the aerospace, transportation, sporting equipment, and other industries have driven the research in machining of titanium alloys. Drilling, particularly the high-throughput drilling, is important because it is one of the most widely utilized and technically challenging processes for machining of titanium alloys. The drill tip starts to glow due to high temperature after rapid drilling only a few holes in titanium alloys. Compared to measuring the thrust force and torque using a dynamometer, it is more difficult to measure the drill temperature and even more challenging to find the spatial and temporal temperature distributions of a drill during drilling. Chapters 2 and 3 present our pathway, which is built on the drilling research in the past century, to gain in-depth understanding of drill temperature.

Another evolution in manufacturing is the emphasis on sustainability and the health and safety of workers in manufacturing plant. A group of dedicated and outstanding manufacturing and machine tool engineers worked together and demonstrated that the minimum quantity lubrication system was as productive as the traditional flood cooling with the central cooling system in a plant and could save the overall cost from the life cycle perspective. That was a milestone achievement. New technical challenges of rising workpiece temperature and the resulted thermal expansion during production with the minimum quantity lubrication give great research opportunities. This work will be presented in Chaps. 4 and 5.

We are very fortunate to work with orthopaedic surgeons on the frontier biomedical manufacturing research in bone drilling. We have learned that knowledge

in metal drilling can be applied to study bone drilling. There are many opportunities for innovations in bone drilling. This is a great task for manufacturing engineers and critically important for the future of biomedical manufacturing research to improve the quality and reduce the cost of healthcare. Our bone drilling research is presented in Chaps. 6 to 8.

It takes a village to create and finalize a book. We are greatly indebted to the researchers and collaborators who have guided and helped this team in the past decade on drilling research. We started from the late Professor S.M. Wu who was a giant in drilling research since the 1960s at the University of Wisconsin at Madison. Many of his students, particularly Dr. David Stephenson and Professor Jun Ni, continued his legacy and went to great lengths for drilling research in industry and in the University of Michigan at Ann Arbor. Our work is built on their past achievements. In the automotive industry, Drs. Richard Furness and John Agapiou are professors' professors in advanced drilling. We have learned a lot from them about drilling in high-volume production. Superior drills provided by Kennametal and technical knowledge and support from Dr. Qiang Wu and Parag Hedge made our metal drilling research possible. Outstanding orthopaedic surgeons, particularly Drs. James Holmes, Andrew Palmisano, and Todd Irwin, transformed and guided our bone drilling research. We greatly appreciate the graduate students and visiting scholars who have worked with us in drilling research, including Wenwu Wu, Ali Kazu, Yao Liu, Yiwen Wang, and Barry Belmont. The support from the US National Science Foundation (Program Directors: Drs. George Hazelrigg, Bruce Kramer, and ZJ Pei), US Department of Energy (Program Director: Dr. Raymond Johnson), Ford Motor Company (Dr. William Dowling), Department of Orthopaedic Surgery at the University of Michigan at Ann Arbor, and Springer Nature (Brinda Megasyamalan and Agnes Felema) were critical to make this research and book possible.

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Albert J. Shih is Professor in Mechanical Engineering, Biomedical Engineering, and Institute of Gerontology at the University of Michigan. He received his PhD from Purdue University in 1991 and was an Advanced Manufacturing Process Engineer at Cummins (1991–1998) and an Associate Professor at NC State University Mechanical and Aerospace Engineering (1998–2002). He has been a Faculty at the University of Michigan since 2003. In 2017, he was the Assistant Director of Education and Workforce in the Advanced Manufacturing National Program Office (AMNPO) at Gaithersburg, Maryland. His research area is manufacturing. He is a Pioneer in biomedical manufacturing, the application of manufacturing technologies to advance the safety, quality, efficiency, and speed of healthcare service and biomedical science. He has 10 US patents and a textbook, *Analysis of Machining and Machine Tools*, and authored or coauthored over 210 archival journal papers and 120 conference papers in manufacturing and biomedical sciences. He is the Recipient of the Fulbright Scholar, SME Frederick W. Taylor Research Medal in Manufacturing Research, ASME Milton C. Shaw Manufacturing Research Medal, Blackall Machine Tool and Gage Award, Society of Automotive Engineers Ralph R. Teetor Educational Award, and Best Paper Awards in ASME Manufacturing Science and Engineering Conference (MSEC), North American Manufacturing Research Conference (NAMRC), and International Conference on Frontiers of Design and Manufacturing (ICFDM). He is the President of the North American Manufacturing Research Institute (NAMRI) of SME (2019–2020), Fellow of ASME, SME, and CIRP.

Bruce L. Tai is an Assistant Professor and Mechanical Engineering Industry Advisory Council Faculty Fellow in J. Mike Walker ‘66 Department of Mechanical Engineering at Texas A&M University. He received his PhD in Mechanical Engineering from the University of Michigan at Ann Arbor in 2011 and his MS and BS from National Taiwan University in 2004 and 2006, respectively. He was a Research Faculty Member in the University of Michigan and held a joint appointment in the University of Michigan Health System (2012–2014). He had a long-term collaboration with the automotive industry on developing advanced machining

processes and with surgeons on innovative surgical tools and simulation models. His research interests generally encompass advanced machining processes, additive manufacturing processes, and surgical tools and simulation. His research has been supported by the National Science Foundation, US Department of Energy, and Orthopaedic Research and Education Foundation. He has published over 40 peer-reviewed journal papers and over 40 conference papers across the areas of machining, additive manufacturing, and biomedical engineering. He is the Recipient of the Best Paper Awards in ASME MSEC and ICFDM, SME Outstanding Young Manufacturing Engineer Award (2017), and ASME Blackall Machine Tool and Gage Award (2017).

Rui Li is a Professor at China Aerospace Science and Technology Corporation. He received his Bachelor's degree in Mechanics from the University of Science and Technology of China and his master's and PhD degrees in Mechanical Engineering from the University of Michigan at Ann Arbor. He has held a number of engineering and engineering management positions in Kavlico Corporation, Elekta, and China Aerospace Science and Technology Corporation (CASC). He has extensive engineering experience in mechatronic system design, machining process, mechanics, finite element simulation, thermal analysis, and materials science. He published over 30 articles and several patents in those areas. He received a number of awards, including Best Paper Award from NAMRI and Best Interactive Presentation Award from the International Astronautical Congress and recognized as a Young Space Leader by the International Astronautical Federation.