Welding in the World
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REVIEW ARTICLE

Welding Engineering at Ohio State University—75 years

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Abstract
This paper celebrates the 75-year history of the OSU Welding Engineering program. It includes a brief history of the program, details regarding the academic mission, and current research activities. It also provides an outlook for the program into the future.

Keywords Welding Engineering · Education and training

1 Introduction

The importance of the engineering-related aspects of welding was recognized at The Ohio State University (OSU) in Columbus, Ohio, during the 1930s when a series of six annual conferences were held to discuss the technical aspects of welding and to promote welding as a manufacturing process. As a result of this and a strong impetus provided by the importance of welding for national defense during World War II, a Department of Welding Engineering was established at OSU in 1948. This year marks the 75th anniversary of the Welding Engineering degree. In that time span, Welding Engineering at OSU has evolved into an academic/research program that is recognized throughout the world. It currently represents the only accredited engineering program in the USA offering a Bachelor of Science (BS) degree in Welding Engineering. In addition to the unique BS degree, Master of Science (MS) and PhD degrees in Welding Engineering are also offered. The program has evolved significantly over the years driven by the needs of industry, and by new technology, materials, and analytical tools that have resulted in new welding processes and techniques to assess weld quality and structural integrity. This article tells the story of the Welding Engineering program at OSU and provides an update on its current status and future direction.

2 Brief history of the Welding Engineering program

In the years following World War I, arc welding processes were increasingly recognized as a viable technique for welding and repairing iron and steel. This led to increasing interest in welding throughout the world, including the USA. A small group of faculty in the Industrial Engineering Department at OSU began promoting welding as a manufacturing technique that eventually led to the organization of six welding conferences held annually from 1932 to 1937. This resulted in the establishment of a combined Industrial/Welding Engineering degree program, strongly supported by James Lincoln of the Lincoln Electric Company, that was launched in 1938. That year, J.R. (Ray) Stitt was the first faculty member hired specifically to support the IE/WE program. Between 1938 and 1944, 20 IE/WE degrees were granted, but the program was interrupted by World War II. The faculty supporting this activity was located in the Industrial Engineering building (Fig. 1) which eventually became the home of the Welding Engineering Department.

In 1947, Robert S. Green was hired to lead an effort to establish a Welding Engineering Department at OSU which was officially launched on January 1, 1948. The curriculum that Professor Green put in place included courses in metallurgy, mechanics and strength of materials, machine design, structural design, and electrical engineering. These core areas would form the basis of the multi-disciplinary curriculum that still exists today. The curriculum also required a “hands-on” component which allowed students to gain an appreciation of welding by learning the manual skills required (Fig. 2). The first class of true welding engineers

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Fig. 1 Industrial/Welding Engineering building on OSU main campus circa 1920

Fig. 2 Students learning oxyfuel welding in 1958

graduated in 1948. In the 50s and 60s, the number of faculty in the Welding Engineering Department averaged about three, and the department was heavily dependent on courses taught by other engineering departments. The MS degree in Welding Engineering was approved in 1956.

Beginning with freshmen students enrolling in the Fall of 1969, the BS degree program for all OSU engineering departments was reduced from 5 to 4 years. The number of graduates, which included veterans returning from the Vietnam War on the GI bill, ranged from 10 to 30 students.

The late 70s and early 80s saw a dramatic increase in the number of undergraduate students, with class sizes growing to 30–40 students (see data on degrees awarded in next section). This rapid growth in enrollments, combined with the strong support of alumni and industry prompted Dean of Engineering Donald Glower to support a major department faculty hiring initiative. Under the leadership of Department Chairs Roy McCauley (1954–1979) and Karl Graff (1979–1987) the faculty size increased to nine by 1982, with the hiring of faculty from industry, national laboratories and academia with expertise in robotics and controls, laser welding, computational modeling and design, joining of advanced materials, and nondestructive testing. This new group of faculty rapidly expanded and modernized the Welding Engineering curriculum and revitalized the welding engineering laboratories. The increase in faculty size and the development of additional upper-level courses also allowed the establishment of a PhD degree which was approved in 1985.

In 1979, the National Science Foundation (NSF) awarded one of the nation's first Industry/University Cooperative Research Center (I/UCRC) initiatives to the Welding Engineering Department. This prestigious award had the immediate effect of boosting research activity with a corresponding increase in graduate students. By the mid-1980s, the hiring of a faculty member with expertise in polymer joining increased the total number of faculty in Welding Engineering to 10—the highest level in its history. In 1984, under the leadership of Department Chair Karl Graff and through the financial support of the State of Ohio Thomas Edison Program, OSU partnered with The Welding Institute (TWI) and Battelle Memorial Institute to create the Edison Welding Institute (EWI). Research funding from EWI further supported faculty research and the rapidly growing PhD program. More details of the early history of Welding Engineering at OSU can be found elsewhere [1].

In 1994, the department received another large grant from NSF to build a comprehensive education and training program known as National Excellence in Materials Joining Education and Training (NEMJET). Through this program, which involved OSU's College of Education to incorporate new instructional methods and pedagogies, over 10,000 pages of instructional materials were created representing the largest single collection of English language teaching material dedicated to the engineering aspects of materials joining. This material, continually modified to reflect advances in the technology, is still used in courses at OSU and other universities and supports continuing education and training programs. It also allowed the establishment of an online distance education program that was initiated in 2003. More details on the distance education program are provided later.

In 1995, as part of a major College of Engineering restructuring, the Welding Engineering and Industrial and Systems Engineering departments were merged into a new department—Industrial, Welding, and Systems Engineering (IWSE)—in an effort to consolidate much of the university's manufacturing expertise into a single department. In 1996, with EWI planning for a new building on the West Campus, and an OSU priority of razing the obsolete and deteriorating Welding Engineering Laboratories building, the EWI and OSU leadership collaborated on a creative plan to co-locate EWI and the OSU Welding Engineering program in a new West Campus building. This facility, known as the Edison Joining Technology Center (EJTC), opened in 1998 and represents the largest welding/joining education and research facility in the Western Hemisphere with approximately 135,000 square feet of space and over 300 personnel (including students). The Welding Engineering program occupies approximately 35,000 square feet (3250 m^2) in the EJTC consisting of modern laboratories, a student computer laboratory, faculty and graduate student offices, and training facilities (Figs. 3 and 4).

The period from 2005 to 2010 saw the retirement of many of the faculty who were hired in the 70s and 80s including David Howden, Dick Richardson, Charles Albright, Dave Dickinson, and Chon Tsai. To manage through this period of change a transition planning committee was formed in 2008 and led by former chair Karl Graff. The plan that evolved outlined a bold strategy for growth of the research program that would, in turn, support hiring of new Welding Engineering faculty. In 2010, NSF awarded OSU Welding Engineering another Industry/University Cooperative Research Center (I/UCRC) focused on development of welding/joining technology for the energy sector. This center has evolved into the Manufacturing and Materials Joining Innovation Center (MA^{2}JIC) and is one of the largest and most successful of its kind in the USA. This center and its evolution will be described in more detail in a later section.

Fig 3 Welding Engineering building on main campus prior to its demolition in 1998

Fig 4 Edison Joining Technology Center on OSU's West Campus

Also, in 2010 the Welding Engineering program separated from the newly named Integrated Systems Engineering department and merged with the Materials Science and Engineering department. This move had no effect on the WE curriculum or degree programs and has had a strong positive effect on the research activities within Welding Engineering. The reader is referred to an update of the WE program published in 2014 that provides a snapshot of the program and its outlook at that time [2].

In 2015, the retirements of Professors Lippold (Welding Metallurgy) and Rokhlin (NDE) and the continued growth of the program in terms of students and research support led to the hiring of four new assistant professors. In addition, two "Professors of Practice" were also hired. Professors of Practice (or "clinical" faculty) are typically individuals with considerable industry experience who can share their experience and knowledge in the classroom. These faculty support the academic program through classroom teaching and may also be involved in research. The program also supports "Research Professors" whose primary responsibility is to conduct research projects and train graduate students assigned to those projects.

In 2015, David Lincoln and the Lincoln Electric Company endowed the Lincoln Professorship, the first of its kind in the history of the Welding Engineering program. This Professorship is currently held by Assistant Professor Boyd Panton. The current faculty in the Welding Engineering program are listed in Table 1. More details regarding the Welding Engineering faculty can be found at https://mse.osu.edu/faculty-research/welding-engineering.

Over its 75-year history, Welding Engineering at OSU has grown from a small academic program that supplied welding engineers to US industry into an internationally recognized leader in materials joining whose graduates can be found around the world. A summary of the initiation, growth and evolution of Welding Engineering at OSU is provided as a timeline shown in Appendix 1.

3 The OSU Welding Engineering academic program

The Welding Engineering program at OSU offers degrees at the Bachelor of Science (BS), Master of Science (MS), and PhD levels. The BS Welding Engineering (BSWE) program is designed to be completed in 4 years and includes a number of engineering and science pre-requisites that are offered outside the program, as described below. The MSWE program is normally completed in 2 years and may include a thesis requirement, but a non-thesis option is offered as well. The PhD program requires both course work and a dissertation that consists of original scientific work performed by the candidate.

All three of these degree programs require competence in the four foundational disciplines of Welding Engineering: (1) welding process technology, (2) metallurgy/materials science, (3) design and structural integrity, and (4) non-destructive evaluation (NDE).

BSWE degree program Courses required within the BSWE program are listed in Table 2. Note that the first 2 years of the program consist of essential engineering/science courses that are required by the general engineering curriculum at OSU. A student's first exposure to the Welding Engineering discipline occurs in the 2nd semester of the second year with the "Introduction to Welding Engineering" course and a hands-on arc welding laboratory course. The latter consists of training in the setup and use of common arc welding processes including SMAW, GTAW, and GMAW.

Within the "core" undergraduate curriculum there are two required courses focusing on welding processes that

Table 1 Current Welding Engineering faculty at Ohio State University

Faculty	Title	Education	Area of focus
Avi Benatar	Professor	PhD, Mechanical Engineering, Massachusetts Institute of Technology	Joining of plastics and composites, welding design, high power ultrasonics
Antonio Ramirez	Professor	PhD, Materials Science and Engineering, Univ. of Sao Paulo (Brazil)	Welding metallurgy, friction stir processing, additive manufacturing
Wei Zhang	Professor	PhD, Materials Science and Engineering, Penn State University	Modeling, stress analysis, structural integrity
Dave Farson	Associate Professor	PhD, Electrical Engineering, Ohio State University	Laser and arc welding processes, ultrasonic testing
Carolin Fink	Assistant Professor	PhD, Mechanical Engineering and Welding Engineering, University of Magdeburg (Germany)	Welding metallurgy, weldability testing
Xun Liu	Assistant Professor	PhD, Materials Science and Engineering, University of Michigan	Hybrid welding processes, welding design
Boyd Panton	Assistant Professor (Lincoln Professor)	PhD, Mechanical Engineering, Univ. of Waterloo (Canada)	High energy density welding processes, micro-joining, additive manufacturing
Desmond Bourgeois	Assistant Professor	PhD, Welding Engineering, Ohio State University	NDE, structural integrity and performance, corrosion
Boian Alexandrov	Research Professor	PhD, Welding Engineering, Technical University of Sofia (Bulgaria)	Welding metallurgy, weldability evaluation, additive manufacturing
David Phillips	Professor of Practice	PhD, Welding Engineering, Ohio State University	Welding engineering fundamentals, welding processes, welding metallurgy
Menachem Kimchi	Associate Professor of Practice	MS, Welding Engineering, Ohio State University	Resistance and solid-state welding processes
Dennis Harwig	Associate Research Professor	PhD, Welding Engineering, Cranfield University (UK)	Arc welding and hybrid processes, robotic additive manufacturing, in situ monitoring and control

Table 2 Undergraduate Welding Engineering curriculum (technical courses only)

Year	Autumn semester	Spring semester
1	Engineering Survey Fundamentals in Engineering I Calculus I Physics I	Fundamentals of Engineering II Engineering Mathematics I Chemistry for Engineers I
2	Intro to Materials Science and Engineering Engineering Mathematics II Physics II Statistics for Engineers Statics and Mechanics of Materials	Differential Equations for Engineers Thermodynamics Introduction to Welding Engineering Arc Welding Laboratory Electrical Circuits and Devices Computer Programing
3	Structural Transformations in Metals Materials Processing Laboratory Physical Principles in Welding Processes I Welding Engineering Design I	Physical Principles in Welding Processes II Welding Metallurgy I Welding Design II Nondestructive Evaluation Fundamentals of Manufacturing Engineering
4	Welding Metallurgy II Industrial Experience Senior Design I Technical Electives	Senior Design II Engineering Economics Technical Electives

address the common arc welding, resistance welding, solid-state welding, and HED (high energy density) welding processes. There are also two required courses addressing welding metallurgy that include structural steels, stainless steels, and nonferrous alloys (nickel-base, aluminum-base, and titanium-base). Two design/structural integrity courses and a course that reviews NDE principles are also required. Outside of Welding Engineering focus areas, students are required to take courses in electrical engineering, mechanical engineering, computer programming, materials science and engineering, and manufacturing engineering. Relative to other engineering curricula at OSU, the Welding Engineering BS degree requires the most technical breadth.

The program also offers numerous technical elective courses (Table 3) in each of the four disciplines that allow students to specialize in areas of individual interest. These courses are in a constant state of flux depending on the perceived needs of the students for successful careers in industry. For example, new courses on additive manufacturing, novel/hybrid welding processes, and arc welding procedure development have been recently added to meet the needs of industry. Additional courses to address “green” energy technologies, semi-conductor manufacturing, and intelligent manufacturing are being considered for the near future.

The curriculum is designed such that students can complete the course requirements in 4 years. For students who transfer into the program midway through or after the 2nd year, an additional year may be required to complete the BSWE degree.

MSWE program The MSWE degree was introduced in 1956 in recognition of the need for more specialized training in Welding Engineering than could be obtained with the BSWE degree alone. Candidates for the MSWE degree often come from other programs (mechanical engineering, industrial engineering, etc.) in order to prepare for careers in the Welding Engineering field. The MSWE degree can be completed with or without a thesis and includes a depth and breadth requirement. For the depth requirement, students can choose a sequence of courses in one of the following areas: welding processes, metallurgy, design, non-destructive evaluation, and joining of plastics and composites. For the breadth requirement, students take one course (usually the first introductory course) in the remaining four areas that they have not selected for their specialization. In addition, they can typically take one or two technical electives which could be outside Welding Engineering. Most on-campus MS students select the thesis option, while nearly all online students select the non-thesis option. However, even the non-thesis option includes a smaller culminating open-ended independent study project. More details regarding the online program are provided below.

PhD program Again, recognizing the need to provide highly trained students with a specialization in welding science and engineering to industry, national laboratories and academia, a PhD program was introduced in 1985. Initially, the PhD in Welding Engineering was typically pursued by students who already had or recently acquired an MS degree in Welding Engineering or another engineering discipline, but now students can be directly enrolled into the PhD program with a BS degree in an engineering discipline from an accredited college or university. The PhD program includes a sequence of courses specializing in one of the following areas: welding processes, metallurgy, design, non-destructive evaluation, and joining of plastics and composites. In addition, students select one of the remaining areas for a minor (fewer courses) and an outside Welding Engineering minor that is related to their research work. The PhD dissertation is an extensive body of research work that advances the knowledge in materials joining or an allied field.

Table 3 Technical elective courses in Welding Engineering by discipline area

Discipline	Courses
Welding processes	High energy density welding processes Resistance welding Brazing and soldering (two courses) Solid-state welding Codes/arc welding procedure development Novel/hybrid welding processes
Metallurgy/materials science	Weldability Welding of plastics and composites Adhesive bonding
Welding design/structural integrity	Fitness-for-service Computational modeling
Non-destructive evaluation	Ultrasonic testing
Other	Additive manufacturing Welding robot programming

Online MSWE program The online, web-based MSWE program was established in 2003 in order to expand the availability of a Welding Engineering education to a wider audience, in particular individuals working in industry and unable to attend the university on a fulltime basis. Online courses were first offered in the 1998–1999 academic year and grew rapidly to the point where virtually all graduate courses were available online. Because of logistics issues, there is no thesis required, but students complete an independent study project that is often associated with their engineering responsibilities at their place of employment. Similar to on-campus MSWE students, each online student is assigned a faculty advisor. The program is designed for engineering professionals who typically take one or two courses per semester, requiring approximately 3–4 years to complete the program.

Over 2500 Welding Engineering degrees have been awarded since the start of the program in 1948. The evolution of the Welding Engineering program at OSU can perhaps best be tracked by the number of degrees awarded in any given academic year. That information is provided in the two charts shown in Fig. 5. As noted earlier, the program grew slowly during its first 30 years, limited to some extent by the low number of faculty and absence of significant research programs to attract graduate students. By the late 70s, the addition of faculty and the increase in research, driven in part by the establishment of the Center for Welding Research, resulted in significant increases in students from the 1980s forward. These data also include students who earned an MSWE degree through the online program introduced in 2003.

4 Research activities

Fundamental and applied research has been part of the Welding Engineering activity at OSU since the 1960s. In the late 1970s and early 1980s, the significant increase in faculty and the impact of the Center for Welding Research stimulated an increase in research activities. The addition of the PhD in 1985 allowed research to be conducted at a much higher level and eventually helped to attract highly talented students and faculty. In the early days (1950s–1970s), most research activity at OSU was focused on welding processes and NDE. With the increase in faculty with a variety of backgrounds in the 1980s, the research portfolio became much broader with a range of specialties including welding metallurgy, weldability, fitness-for-service, high energy density welding processes, and joining of polymeric materials. It was during this period that Welding Engineering at Ohio State emerged as one of the leading universities in the world with a concentration in welding/materials joining.

The current research program within Welding Engineering encompasses a number of technical areas with process technology, process modeling, welding metallurgy, and weldability among the strongest of these programs. Annual funding for research performed by Welding Engineering faculty and staff is on the order of $5 million/year, supporting 30–40 on-campus graduate students.

4.1 Manufacturing and Materials Joining Innovation Center

The centerpiece of current research activities is the NSF I/UCRC now known as *MA^{2}JIC* (Manufacturing and Materials Joining Innovation Center). This center was established in 2010 in conjunction with Lehigh University, Colorado School of Mines, and the University of Wisconsin, with Ohio State serving as the lead university. The I/UCRC concept uses NSF "seed funding" to develop a technology roadmap and attract organizations (industrial companies, national labs, and research centers) who pay an annual membership fee. The members select the research topics and the results of the research projects are shared among the member organizations.

From 2010 under the leadership of Dr. S. Suresh Babu, the center then known as the Center for Integrated Materials Joining Science for Energy Applications (CIMJSEA) grew rapidly and reached 20 member organizations in the first 2 years and exceeded 40 members at the end of its first 5 years. Based on the broad membership and research portfolio of the center, the name was changed to *MA^{2}JIC* in 2015. The center has sustained as one of the most successful of the NSF/IUCRCs based on both number of members and membership revenue. Currently, there are five universities involved in the program: OSU, Colorado School of Mines, University of Tennessee, University of Waterloo (Canada), and Penn State University. The center currently supports 34 faculty, 2 staff support personnel, 23 PhD students, 15 MS students, 43 undergraduates, and 6 high school interns.

Since its inception in 2010, the center has produced over 150 graduates, including over 60 MS and 40 PhD students. Many of these students have gone on to work for companies who supported the center. Since 2015, more than 70 organizations have been members of the center. A list of those members is provided in Appendix 2.

Research activities within the center are grouped around three thrust areas as described in the following. More detail can be found at the center website (https://ma2jic.osu.edu/).

Material/joint performance The focus is on the understanding and optimization of welded/printed materials performance when exposed to industry service environments. This is assessed using a multitude of variables including:

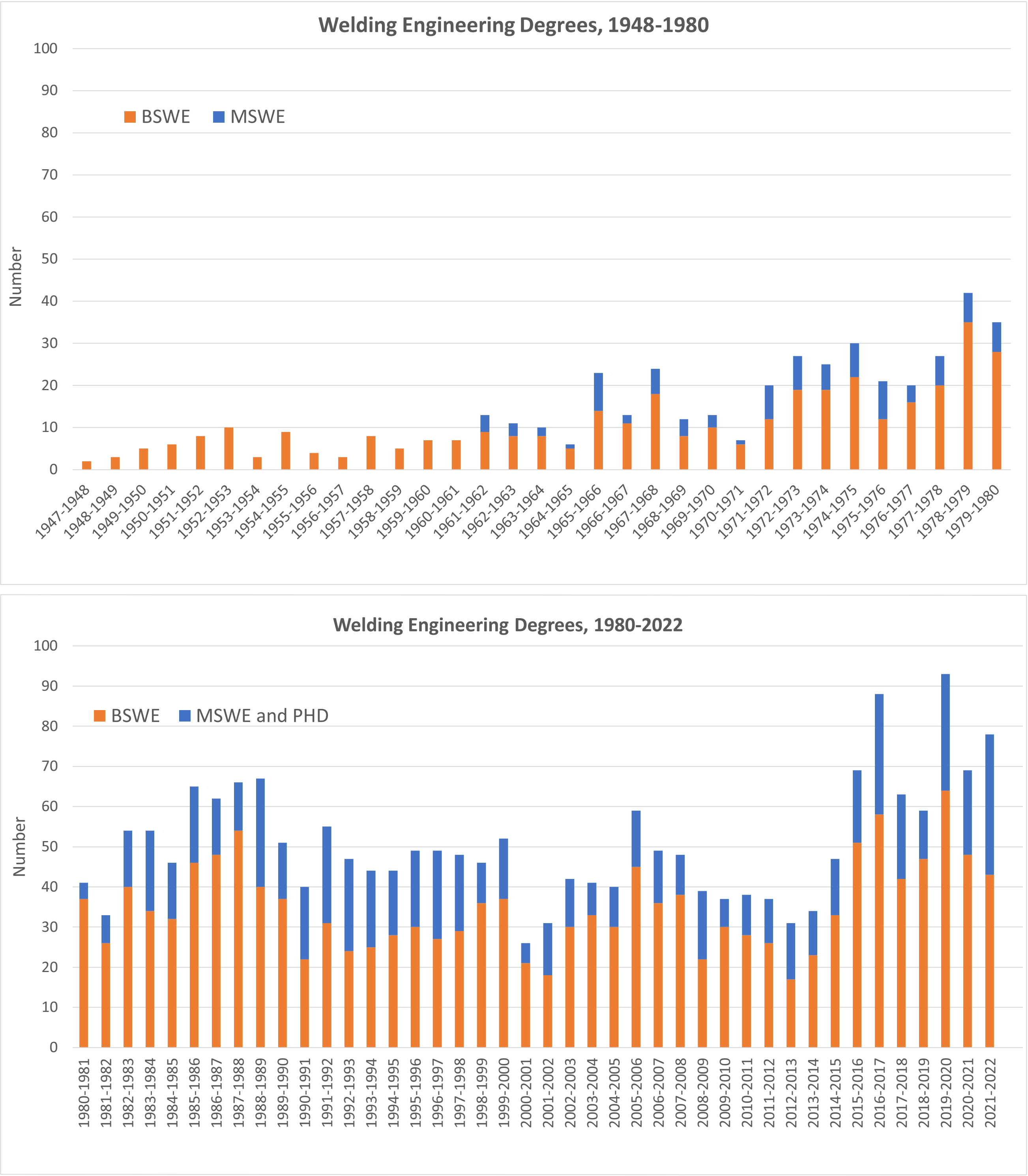


Fig. 5 Histogram showing number of degrees offered in Welding Engineering from 1948 to 1980 (top) and 1980 to 2022 (bottom)

material composition, welding/printing process and techniques, and service conditions. Dynamic material performance includes examination of the effects of strain, fatigue and corrosion with validation, and development of models based on experimental results. The goal of this thrust area is to optimize materials, welding, and printing solutions, as well as addressing the code requirements governing industry.

Additive/process development/control The goal is to promote innovation and development in additive manufacturing and joining processes. Areas of interest and focus include metal additive manufacturing, brazing, advanced arc welding, solid-state joining, sensors, process monitoring and control, and the use of machine learning and artificial intelligence to improve these processes.

Materials/microstructure/weldability The motivation is the development of a better understanding of the fundamentals associated with structural failure, creating new and revolutionary methods to quantify the materials weldability/printability, and to seek standardization. This thrust area also studies the interconnected effects of microstructure, thermomechanical history and composition on weldability/printability, and applies real-time NDT techniques to monitor joints and printed components. The overarching goal is the development of a better understanding of long term structural integrity and predictability of joints and printed materials.

Research conducted through the center represents only a fraction of the activity within the Welding Engineering program. Some of the major research efforts currently ongoing are summarized in the following sections.

4.2 Process technology

The Welding Engineering laboratory hosts advanced arc, laser and resistance welding equipment, supported by Professors Harwig, Panton, Ramirez, Alexandrov, and Fink. Arc directed energy deposition (DED, also referred to as wire arc additive manufacturing) is a significant growth area being developed collaboratively with EWI, who hosts several large format robotic DED systems for applied research and prototyping. The majority of commercial robotic welding systems have been transformed into DED systems using computer-aided manufacturing software that creates a digital twin of the robot cell and process. A range of advanced interdisciplinary faculty projects are ongoing to optimize experimentally and computationally DED feature-microstructure-property relationships of advanced material applications such as ultra-high strength steels, stainless steels, bronzes, and functionally graded materials.

Research on intelligent multi-process robotic digital manufacturing that combines subtractive, additive, and transformative processes is another growth area to support the shortage of skilled labor and accommodate high integrity, high mix, low volume applications needed for maintenance, repair, and custom system components. OSU works closely with a number of wire consumable manufacturers who collaborate to develop improved fusion welding consumables for welding and DED applications. OSU also has a range of advanced arc and laser process capabilities for narrow groove, high deposition, high-speed welding, and cladding applications.

Another active research area at OSU is welding/joining for lightweight vehicle structures made of advanced high strength steels, aluminum and magnesium alloys, plastics, and polymeric composites. These are all topics of great importance to the transportation industry, especially automotive companies. A strong focus is on resistance spot welding based technologies for dissimilar joining of aluminum alloy to high strength steel. Another active research area is high power ultrasonic-assisted joining and manufacturing, including ultrasonic-assisted resistance spot welding, ultrasonic-assisted soldering, and ultrasonic softening of materials.

Research led by Professor Panton concentrates on laser and electron beam processes including their hybridization with other processes and their use in additive manufacturing. Advanced in situ monitoring and characterization methods are used to develop process-structure-properties relationships that can support predictive process development (see example in Fig. 6). Current highlights of this work include the commercialization of patent-pending technologies for joining of shape memory alloys to dissimilar metals for aerospace and medical applications, hybrid laser-arc and laser-hot wire welding for naval and automotive applications, and welding and additive manufacturing in space.

4.3 Hybrid welding processes

Considerable recent research activity has focused on ultrasonic-based manufacturing and welding processes, led by. Prof. Xun Liu and funded primarily through the National Science Foundation (NSF). This technology includes ultrasonically-assisted resistance spot welding (URW), wire arc additive manufacturing, and material deformation processes. The application of hybrid processes to metallic systems has been shown to result in improved/optimized microstructural features and enhanced mechanical properties. In particular, the URW process has shown great potential in the welding of battery foils for vehicle electrification (Fig. 7).

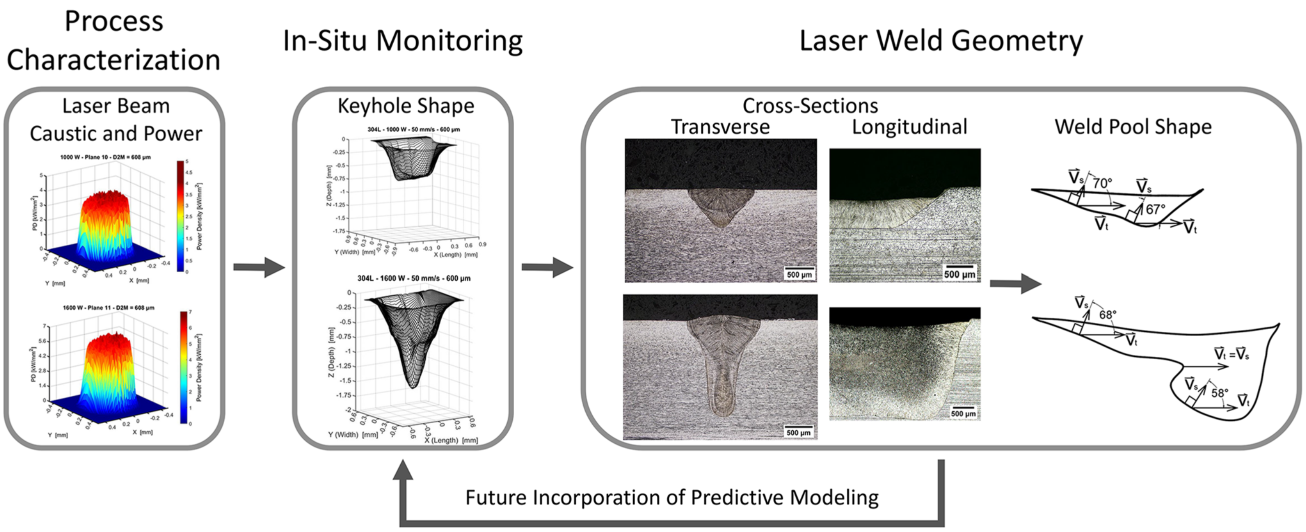


Fig 6 Laser process characterization, in situ monitoring, and weld geometry prediction, courtesy B. Panton [3, 4]

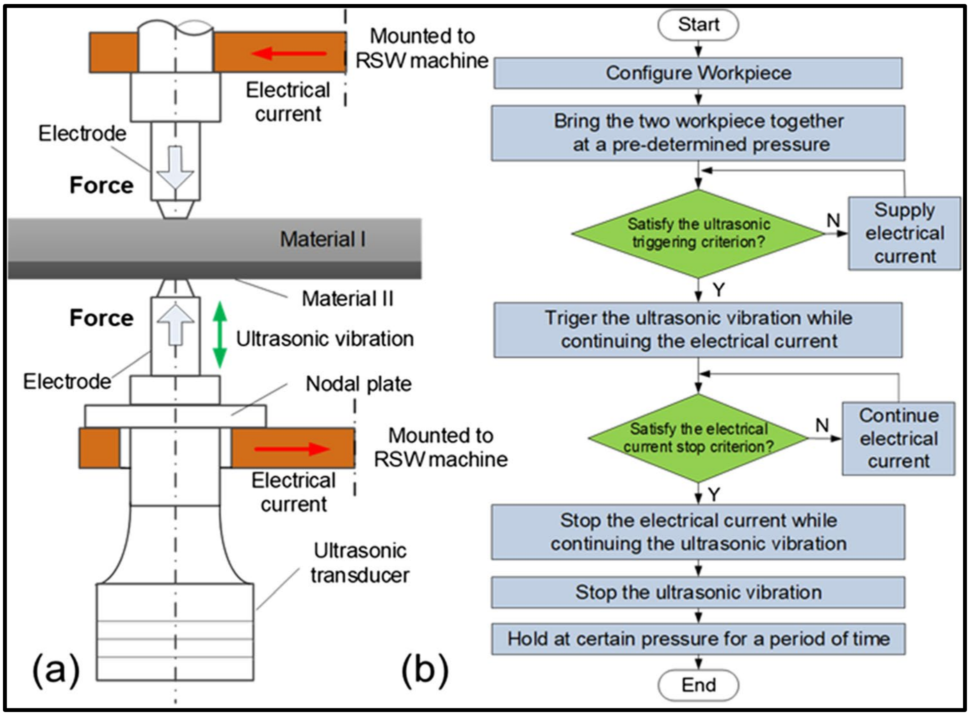


Fig. 7 Ultrasonic resistance welding process (courtesy X. Liu)

Prof. Liu has also worked with NASA on multi-physics computational modeling of the self-reacting friction stir welding process (SRFSW), where the material constitutive model is calibrated with hot torsion tests considering the unique thermo-mechanical conditions during FW/SRFSW. For more information on hybrid processes and the Manufacturing X laboratory go to https://mse.osu.edu/mfxg.

4.4 Process modeling

From the 1990s through the early 2000s, the major topics of process modeling led by Profs. Tsai and Farson included prediction of welding-induced residual stress and distortion as well as prediction of weld pool transport phenomena, respectively. Since Prof. Zhang joined the faculty in

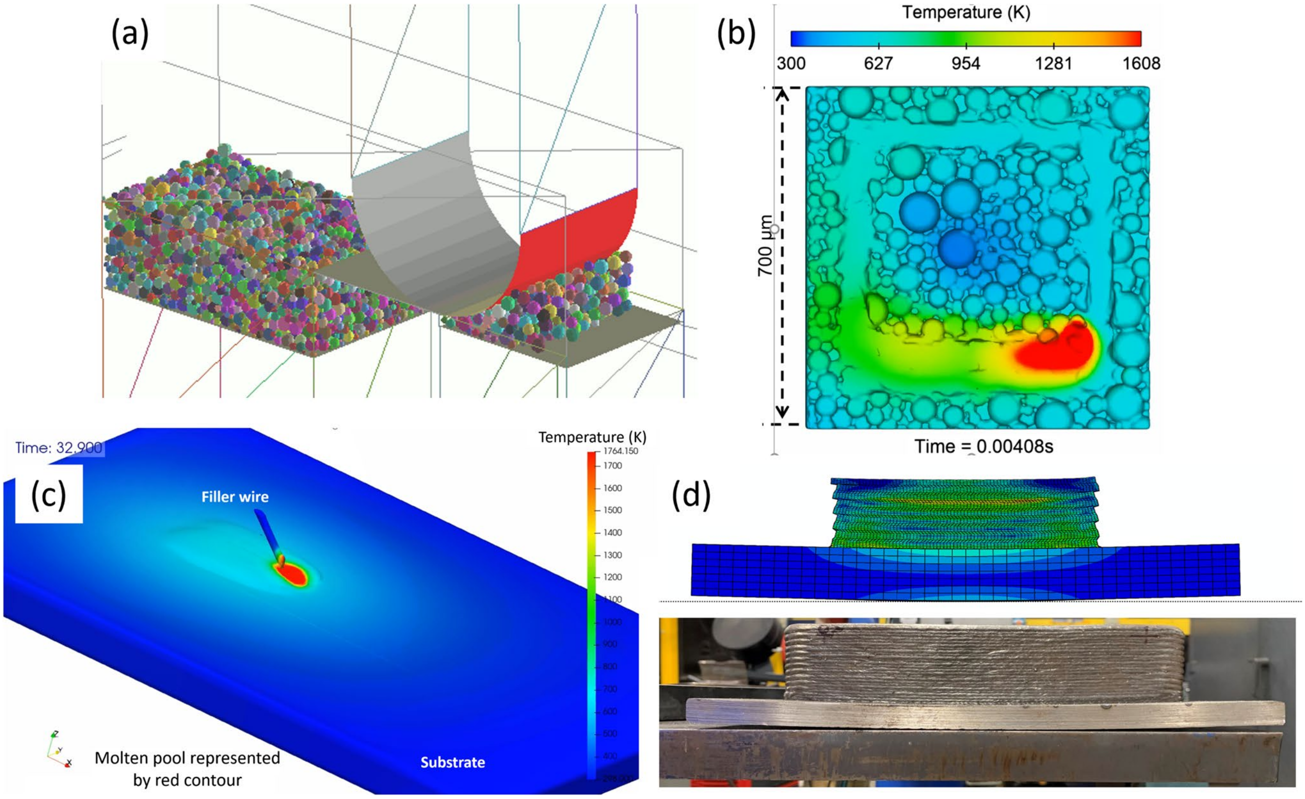


Fig. 8 Example of multi-physics and multi-scale process modeling of welding and additive manufacturing: **a** meso-scale simulation of particle packing in a powder bed, **b** molten pool simulation in laser powder bed fusion, **c** molten pool simulation of temper-bead welding, and **d** thermomechanical simulation of distortion and its experimental validation (courtesy W. Zhang)

2013, a primary focus of process modeling has been the development of multi-physics and multi-scale models and the application of these models to better understand joint properties for various fusion and solid-state based welding and additive manufacturing processes. An example of the application of these process models is shown in Fig. 8. With the emergence of additive manufacturing, research on process modeling has been extended to simulate laser particle interaction in powder bed fusion additive manufacturing (supported by the Office of Naval Research and NASA), prediction of microstructure evolution, residual stress and distortion in wire-arc additive manufacturing of high-strength and high-toughness steels (supported by the US Air Force and Ingalls Shipbuilding), and prediction of microstructure and defects during friction stir welding (supported by NASA).

Weldability Material weldability and weldability testing have been focal points of research in the Welding Engineering program for the last 40 years. Initiated by Prof. Baeslack in the 1980s and continued by Prof. Lippold through 2015, this effort is now led by Professors Alexandrov, Fink, and Ramirez. The weldability laboratory at OSU features a number of testing facilities for quantifying weldability including the following: Varestraint Test, Cast Pin Tear Test, Gleeble (hot ductility test, strain-to-fracture test, and PWHT cracking test), Delayed Hydrogen Cracking Test, and the Implant Test (hydrogen cracking). For each of these tests, standardized procedures have been developed at OSU to ensure validity and reproducibility. In addition, the fundamental mechanisms associated with the weldability of structural materials has been a strong focus of the weldability research at OSU. For example, fundamental studies on weld solidification cracking, ductility-dip cracking in Ni-base filler metals and interface cracking in dissimilar welds have revealed the mechanisms and proposed solutions for these weldability issues. An example of the use of the TransVarestraint test to quantify weld solidification cracking susceptibility in Ni-base alloys is shown in Fig. 9.

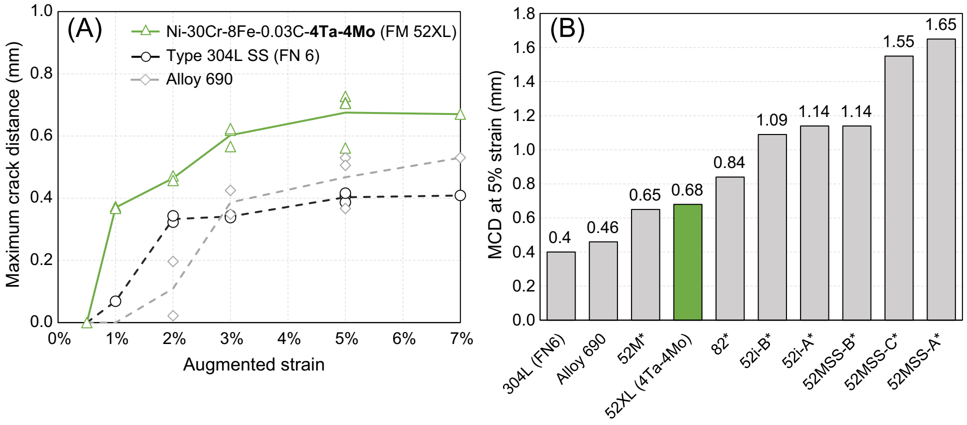


Fig. 9 Example of TransVarestraint test results for quantifying weld solidification cracking susceptibility in Ni-base filler metals in comparison to Type 304L SS, courtesy C. Fink [5]

Research led by Professor Fink involves the weldability and printability of metals and alloys, and associated microstructure evolution and defect phenomena. This involves combining computational and experimental techniques to improve quantification and understanding of metallurgical and thermo-mechanical processing effects on microstructure formation and cracking in the semi-solid and solid-state. Her research also focuses on structural steels, nickel-base alloys, and bronze alloys used in a number of critical engineering applications, and is supported by the National Science Foundation, Office of Naval Research, Federal Highway Administration, and the National Shipbuilding Research Program.

The Center for Weldability Evaluation has been established at OSU to recognize the importance of “weldability” and provide a coordinated approach to the topic. The mission of the center is to (1) address the effect of welding and additive manufacturing (AM) processes on the properties and service performance of both conventional and advanced alloys, (2) support the introduction of advanced materials in power generation and power conversion systems, (3) develop innovative tools and methods for weldability evaluation, and (4) involve undergraduate, graduate, and post-doctoral students in cutting-edge research on weldability.

As noted above, the center is equipped with a variety of conventional and unique experimental and computational tools for evaluation of the weldability and service performance of welds and AM components. The center has attracted considerable research funding from industry and federal agencies, and has involved many graduate and undergraduate students, and postdocs in weldability-related research. Both domestic and international organizations representing the power generation, oil and gas, petrochemical, aerospace, and heavy manufacturing sectors have supported research projects in this center.

Nondestructive evaluation (NDE)/nondestructive testing (NDT) The Welding Engineering program at OSU has long been the home of a strong research effort in non-destructive evaluation. That effort is now led by Prof. Bourgeois who has recently built the world’s third micro-resolution ultrasonic imaging system. His research focus is on the continuous development of ultrasonic imaging techniques that can achieve microscopic resolution used for advanced material characterization, assist in the optimization of joining processes, and provide a thorough, in-depth inspection for critical engineering components. Currently, this work funded by the US Department of Energy (DoE) uses the micro-resolution ultrasonic imaging system to identify and characterize deleterious microstructures that have the potential of causing failure in steels. The micro-resolution ultrasonic imaging system has been successful in identifying different regions of the weld microstructure. Further development is underway to incorporate convolutional neural networks to facilitate identification of deleterious regions and reduce misinterpretation associated with human error.

5 Outlook

Reflecting the academic curriculum shown in Tables 2 and 3, the OSUWE program continues to focus on the four foundational areas established in the early years of the program: joining processes, materials/weldability, design and structural integrity, and nondestructive evaluation. While the emphasis in each of these areas has fluctuated over time, the curriculum has remained relatively stable in teaching the fundamental principles in each area. Faculty hiring is also driven by expertise in these areas since faculty is expected to contribute to the academic mission in at least one of these areas.

In general, the curriculum and research activities tend to reflect the needs of industry, since the majority of graduates from the program find positions in industry. The importance of *MA^2JIC* regarding the research activities within OSUWE cannot be overstated since over half the research funding and a large fraction of the graduate students are supported through this industry-driven center. A key element in the future success of the OSUWE program will be the sustainability of this center when it "graduates" as an NSF-supported center after 15 years in 2025. Its evolution as an independent, industry-supported center will be essential for maintaining a strong materials joining effort at OSU and its partner universities.

Faculty will need to respond to an ever changing technical landscape where advances in artificial intelligence, remote sensing, rapid data analysis, and other technologies will demand changes in curriculum and research focus. While the pace of change was relatively slow through the first 60 years of the program, new technologies emerge almost overnight that influence the materials joining community. The rapid evolution of additive manufacturing from a laboratory curiosity just 15 years ago to its current status as a viable and powerful industrial technology is just one example.

Without a doubt, innovative joining technologies will continue to evolve that provide new opportunities for joining both conventional and advanced materials and which will challenge the welding engineers of the future. The rapid evolution of friction stir welding (now over 30 years since its introduction in 1991) is another example of how a novel laboratory discovery can come to revolutionize the welding industry in such a short span of time. The ability to not only develops new joining technologies, but to successfully apply them to important technology areas will become the job of future welding engineers.

The development and application of hybrid joining technologies at OSU is an example of this effort. The successful combination of ultrasonic energy with conventional resistance welding and friction stir welding processes has been demonstrated and applied. Considerable research is also ongoing in the area of additive manufacturing, particularly with regards to arc directed energy deposition (DED), also referred to as wire arc additive manufacturing (WAAM).

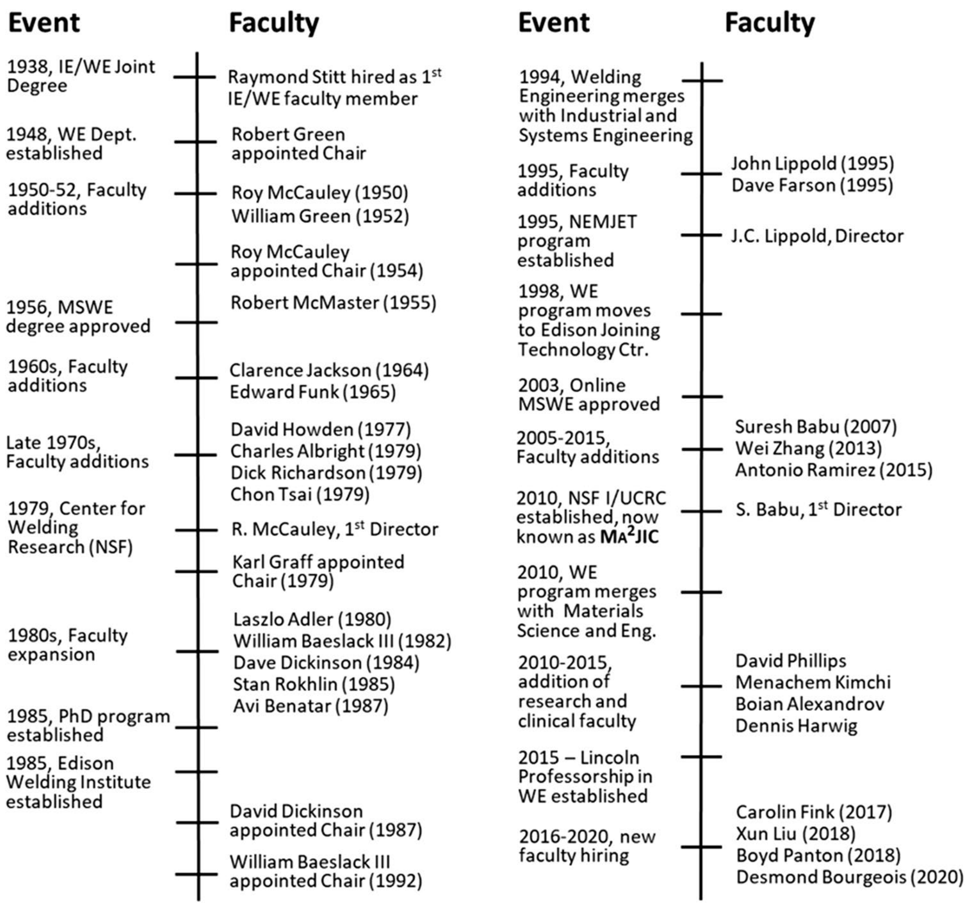
There is a continuing trend towards advanced process characterization and in situ monitoring for welding and additive processes. These technologies enable highly accurate process control which opens new spaces for process-structure-properties exploration. This control can improve quality and increase the reliability of high volume or critical components. By effectively characterizing the process, parameters can be transferred among machines which significantly reduces time and resources for process mapping. There are major efforts in the integration of advanced characterization and monitoring tools with predictive modeling and closed-loop control, which again demonstrates the multi-disciplinary nature of Welding Engineering and the opportunities it provides.

The evolution and introduction of new engineering materials has always been a challenge for the materials joining community. Most of these "advanced" materials are developed without any consideration for welding and joining, which ultimately limits their engineering usefulness. A key element in the success of these new materials must be the consideration of "weldability" during the material design stage. This will require the development/use of appropriate computational and experimental/validation methods during the alloy development process. Good progress has already been made in the use of these techniques for filler metal development, but gaps in the technology and their application still exist.

Despite over 80 years of study of the fundamental nature of fracture and fatigue, the engineering world still experiences unexpected and often catastrophic failures. Not surprisingly, many of these failures are associated with components that have been joined in some fashion. The complex thermo-mechanical nature of welding/joining creates microstructures, residual stress distributions, and imbedded defects (often undetectable) that can compromise structural integrity. While powerful algorithms exist for predicting material behavior, the input data for these computational tools often does not exist because of the complexity of material response associated with materials joining. In addition, the continued evolution of advanced nondestructive inspection techniques and data interpretation is needed to validate and certify the appropriate level of structural integrity.

In summary, the need for highly skilled welding engineers/scientists will undoubtedly continue into the foreseeable future. Technological challenges associated with "green" energy, lightweight structures, "intelligent" manufacturing, electronic devices, medical devices and procedures, and many other areas will place increasing demands on the skills required by welding/joining engineers. The Welding Engineering program at OSU must adapt, as it has in the past, to reflect changes in material development and manufacturing practices that ensure a safe and sustainable world.

Appendix 1. OSU Welding Engineering timeline



Appendix 2. MA^{2}JIC members 2015–2023

Acute Technologies
Alstom
Air Force Research Laboratory (AFRL)
Air Products
AO Smith
Arcelor Mittal
Arconic
Areva
Astaras
AZZ Welding Services
B&W Power Generation
B&W Nuclear Operations
Battelle
Benzell
Bechtel Marine Propulsion
Boeing
Branson
BWX Technologies
Cameron
CBMM
Cloos Robotic
Center of Industrial Services (CIS)
Coldwater Machine
Devasco
Edison Welding Institute (EWI)
Electric Power Research Institute (EPRI)
ESAB
ESI-SYSWELD
Elementum 3D
ExxonMobil
Fiat-Chrysler
Fluor Marine
Fronius TPSI
General Electric
GKN Aerospace
Ground Vehicle Systems Center
Hobart (ITW)
Honda America
Honeywell
Huntington Alloys
Huys Industries
Idaho National Laboratories (INL)
IPG Photonics
Knightsbridge Strategic LLC
Laserline
Lincoln Electric
Los Alamos National Laboratory (LANL)
Metals Technology
Miller Electric
Motoman
NASA
NIST
Oak Ridge National Laboratory (ORNL)
Osaka Transformer Company DAIHEN
Oshkosh Corporation
OTC Industrial Technology
Petrobras
Pipeline Research Council
PPL Generation
Quintus Technologies
Rolls Royce
Sandia National Laboratory
Schlumberger
Shell
Soteria BIG
Special Metals
Stellantis
Stress Engineering
Suncor
TARDEC
Technip FMC
ThermoCalc
TriTool
Vallourec
Voestalpine Bohler
Wolf Robotics
Xiris Automation

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Declarations

Competing interests The authors declare no competing interests.

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