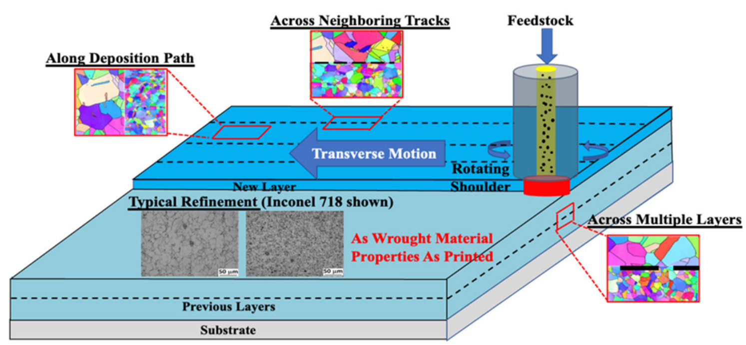
Next Generation Additive Manufacturing (NextGen AM)

Principal Investigators: *Professors I. S. Jawahir, Fazleena Badurdeen, Julius Schoop, Haluk Karaca and Dr. James Caudill*

ISM in collaboration with the Army Research Laboratory (ARL) is engaged in a multi-year research program focused on rapidly advancing the state-of-the-art in additive manufacturing (AM). Novel fusion-based and solid-state AM technologies are being employed to manufacture next generation materials systems for DoD and Industrial applications. The following AM technologies are currently being established in this program:

1. Additive Friction Stir Deposition (AFSD)
2. Magnetically Assisted Laser Directed Energy Deposition (MDED)
3. Cold Spray Additive Manufacturing (CSAM)
4. Aerosol Jetting Multi-Material AM (AJAM)
5. Wire Arc Additive Manufacturing (WAAM)
6. Smart Solid-State and Fusion-Based AM

MELD AFSD (left) and VRC CSAM Systems (right)



Site-Specific Process Control and Material Refinement in AFSD

A new, state-of-the-art AM research laboratory is currently being developed within ISM that will house several unique AM systems, including those above. The first will be operational in early summer (the remaining systems are anticipated in the fall) and will include a MELD L3 AFSD system, as well as a CSAM system from VRC Metal Systems. Both are solid-state AM technologies, where layer building mechanisms are based on plastic deformation at elevated temperatures, rather than melting and solidification. This leads to highly stable and consistent manufacturing processes, in which unwanted phase transformations and tensile residual stresses can be avoided, and site-specific material properties can be engineered in unique configurations.

For AFSD, these characteristics will be harnessed to develop novel nanostructured and functionally graded materials. For CSAM, our initial research focus is on developing mathematical models which describe the influence of velocity gradients within the supersonic flow field on the resulting material properties and defect generation.

ISM researchers are utilizing these new technologies to push the boundaries of innovation and help establish UK as a world leader in advanced AM.

Contact: *Dr.* James Caudill **E-mail:** james.caudill@uky.edu **Phone:** 1-(606)-275-9293

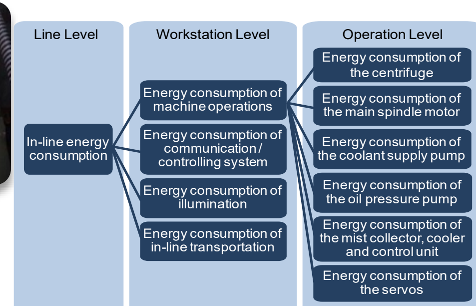
Sustainable Machining Processes

Principal Investigator: *Prof. I. S. Jawahir* *www.engr.uky.edu/ism/research/smr*

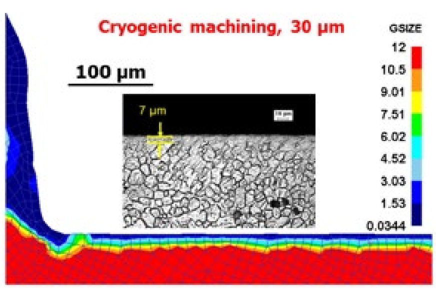
The Sustainable Machining Research Group within the Institute for Sustainable Manufacturing (ISM) at the University of Kentucky has been actively involved in experimental investigation, modeling and optimization of machining operations focusing on developing fundamental understanding of process mechanics and applications.

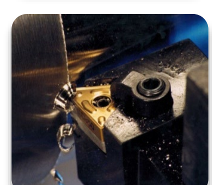
A major sustainability issue in machining is the indiscriminate use of cutting fluids, which impose an economic and environmental burden, and are hazardous to operator health due to long-term exposure. Hence, considerable research effort is being directed towards developing, implementing and advancing dry, near-dry and cryogenic machining processes as substitutes for the traditional flood-cooled machining. This research is also aimed at modeling the machining processes to achieve improved surface integrity, to enhance product performance and life.

Current major research focus areas are:



- Predictive modeling and optimization of ***dry, near-dry and cryogenic machining operations*** (turning, milling, drilling, etc.)
- Process modeling and analysis of machining performance ***(tool-wear/tool-life, chip-form/chip breakability, surface integrity, part accuracy and cutting forces/torque/power, etc.)***.





Current and most recent projects include:

1. *Sustainable (dry, near-dry and cryogenic) machining of aerospace Ti and Inconel alloys*
2. *Cryogenic machining of lightweight automotive Al and Mg alloys for improved surface integrity*
3. *Near-dry and cryogenic burnishing of Mg, Co-Cr-Mo and Ti alloys for biomedical applications*
4. *Friction stir processing and cryogenic machining for achieving ultrafine grains in Mg alloys*
5. *Cryogenic drilling of CFRP for improved surface integrity and functional performance*
6. *Slip-line predictive models for machining of stainless steels and Ti alloys*
7. *Optimization of sustainable machining processes*

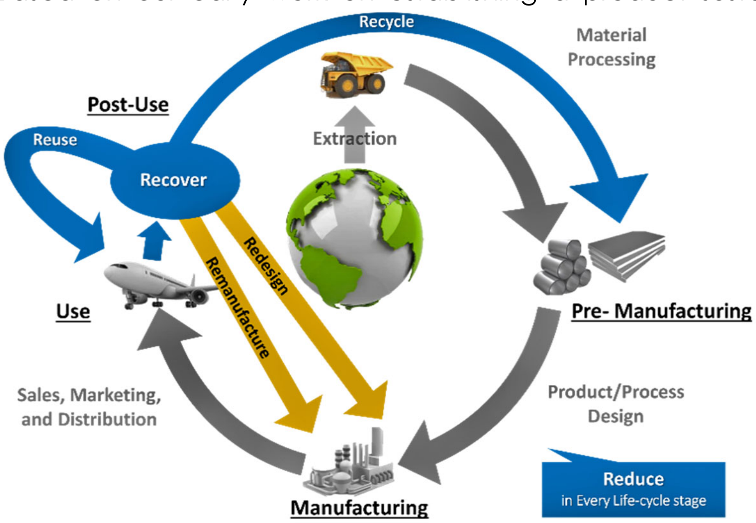
Contact: Prof. I. S. Jawahir **E-mail:** is.jawahir@uky.edu **Phone:** 1-(859)-323-3239

Sustainable Product Design for Circular Economy

Principal Investigators: *Prof. I. S. Jawahir, Prof. Fazleena Badurdeen and Prof. K.E. Rouch*

The need for developing sustainable products has recently gained much momentum due to their significant societal impacts and the inherent environmental benefits. The starting point to achieve improved product sustainability is to study the product life-cycle as a closed-loop system. Total product life-cycle considerations involving all four life-cycle stages ***(pre-manufacturing, manufacturing, use, and post-use)*** and the use of 6Rs **(Reduce, Reuse, Recycle, *Recover, Redesign, Remanufacture*)** are the central parts of our work on sustainable product design. The 6Rs serve as technological elements for enabling and operationalizing the Circular Economy in manufacturing.

Based on our early work on establishing a product sustainability rating, our team of faculty, researchers and graduate students subsequently engaged in a major NIST-sponsored project and developed a novel ***Product Sustainability Index (ProdSI)*** for manufactured products and validated for automotive, aerospace and consumer electronic products. This work has recently been extended to include ***total life-cycle cost modeling*** and ***circular product design*** to determine the ***effectiveness of post-use options such as reuse, redesign, remanufacture and recycle.***

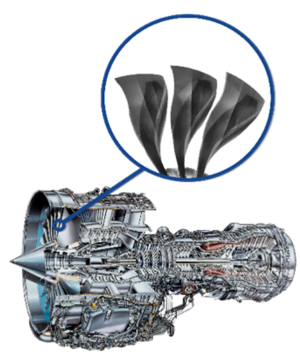


Current and most recent projects include:

- *Sustainability evaluation of autobody and laser printers*
- *Total life-cycle cost modeling and optimization for sustainable in product design*
- *Metrics-based evaluation of sustainable products*
- *Circular product design and product circularity evaluation*
- *Predictive design for improved functional performance of components*
- *IoT applications with Big Data for total life-cycle, multi-generational product design*

	Product I	Product II
PSI	0.66	0.59

	Aluminum BIW	Steel BIW
PSI	0.62	0.43



Contact: Prof. I.S. Jawahir and
Prof. Fazleena Badurdeen

E-mail: is.jawahir@uky.edu
badurdeen@uky.edu

Phone: 1-(859)-323-3239
1-(859) -323-3252

ISM Institute for Sustainable Manufacturing

University of Kentucky

Brazing and Compact Heat Exchangers Research Program

Principal Investigator: *Prof. Dusan P. Sekulic* www.engr.uky.edu/ism/research/bshe

The Brazing and Compact Heat Exchangers Research Laboratory of the Department of Mechanical Engineering at the University of Kentucky's College of Engineering is a research unit within the Institute for Sustainable Manufacturing (ISM).

The laboratory performs fundamental and applied research for development of state-of-the art joining technologies, such as controlled atmosphere brazing of aluminum, brazing of refractory materials, brazing dissimilar materials, bonding ceramics, wetting and spreading of liquid metals. This program combines fundamental research and technological advances relevant to practical applications. Intense work on sustainability issues involving manufacturing processes is ongoing.

The research group has been one of the pioneers in developing *in situ* visualization of brazing and soldering sequences of materials' phase transformations. Reactive flow of molten metal over rough substrates has been also experimentally and theoretically studied to enable and/or improve bonding characteristics of various metal and/or metal vs. non-metal systems.

The Brazing Laboratory has received support from science/engineering foundations, such as National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), Department of Energy (DOE), Department of Defense (DoD), Kentucky Science and Engineering Foundation, etc. Industrial partners included GE Aviation, Caterpillar, SAPA, Gränges, Delphi, Lincoln Electric, Ceradyne/Semicon Associates, KB Alloys, Hanon Systems, and many others. Collaborations with research teams on various projects have been ongoing with academic institutions such as Washington State University, MIT, Ohio State University, Udmurt State University (Russia), Leuven University (Belgium), Ilmenau University of Technology (Germany), Harbin Institute of Technology (China), and others.

Recent Projects:

- *Brazing of aluminum alloys in space* (NASA)
- *Evaluation for brazing alloys* (Undisclosed partner)
- *Wetting of liquid metals on rough surfaces* (NSF)
- *Mechanistic study of aluminium controlled atmosphere brazing processes* (Gränges)
- *Analysis of brazeability of aluminum TRILLIUM™ brazing sheet* (SAPA)
- *Investigation of high temperature nano-composite braze for refractory metals* (Ceradyne)
- *Assessing manufacturing sustainability on the shop floor: modeling of energy* (GE Aviation)

Controlled Atmosphere Brazing Furnace

Hot-stage Microscopy System

Contact Angle Analyzer

Heat Exchanger Analyzer

Casting Furnace

Contact: Prof. Dusan P. Sekulic **E-mail:** dusan.sekulic@uky.edu **Phone:** 1-(859)-257-2972

ISM Institute for Sustainable Manufacturing

University of Kentucky

Welding Research Program

Principal Investigator: *Prof. Yuming Zhang*

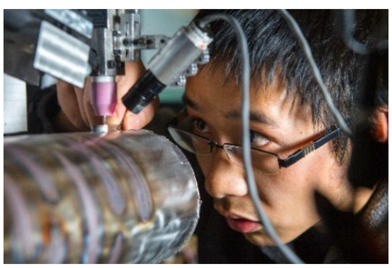
www.engr.uky.edu/ism/research/wr

The Welding Research Laboratory at the University of Kentucky is focused on system identification, adaptive and predictive control, neurofuzzy modeling and control, machine vision systems, and various sensors with applications to welding/manufacturing automation, especially to the development of innovative electrical arc welding processes with improved productivity/controllability.

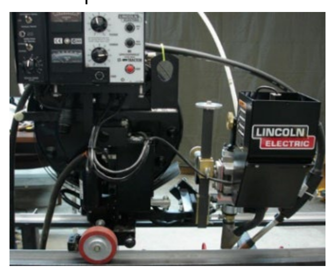
The Welding Research Laboratory projects include advanced sensing, control, learning/modeling, and intelligent robotic systems with application to real-time monitoring and control of innovative welding processes, human welder modeling, human welder centered control, human-robot collaborative systems, and intelligent welding robots as gained from efforts supported by the NSF, Navy, National Labs and industry with a total funding of $7.5 M.

Current research thrusts of the Welding Research Lab are focused primarily on:

- Learning and Modeling of Human Welder Response Behaviors for Intelligent Welding Robots
- Deep Learning of direct high dynamic weld pool image for Intelligent Monitoring and Control of Weld Joint Penetration
- Learning of Complex Human Welder Intelligence from Big Data Generated from Augmented and Virtual Reality Welding Systems
- Analytic Weld Pool Model Calibrated by Measurements with Application to Real-Time Monitoring and Control of Invisible Weld Pool underneath the Work-piece



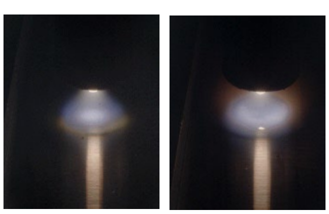
Learning Human Welder Intelligence



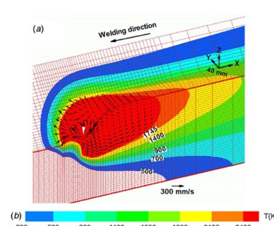
Double-electrode GMAW

Machine-Human Cooperative Control of Welding Process

Triple Camera System



High Dynamic Range Images



Temperature Fields

Contact: Prof. Yuming Zhang **E-mail:** yuming.zhang@uky.edu **Phone:** (859)-323-3262

ISM Institute for Sustainable Manufacturing

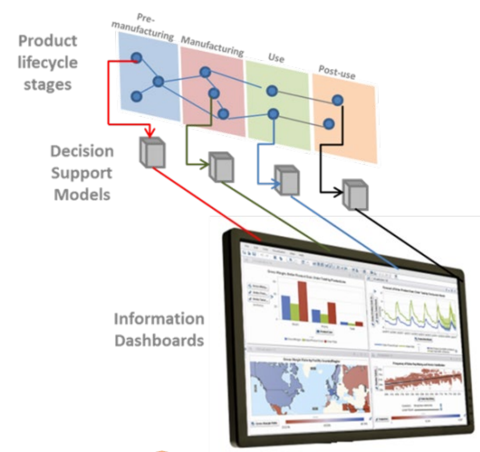
University of Kentucky

Sustainable Manufacturing Systems and Supply Chains

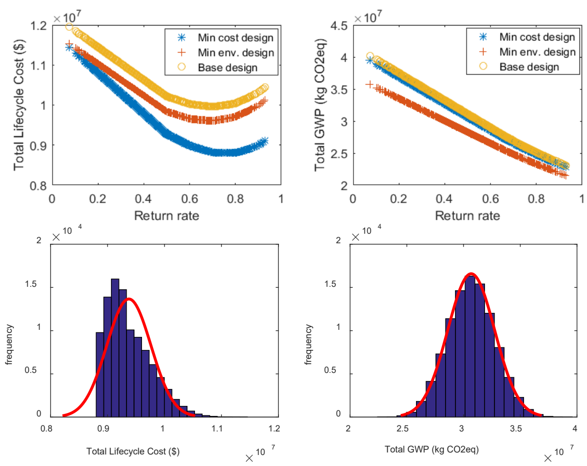
Principal Investigator: *Prof. Fazleena Badurdeen* www.engr.uky.edu/ism/research/mssc

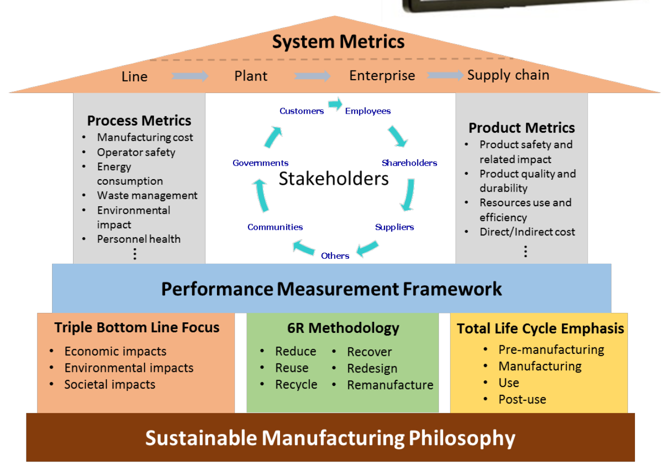
The Sustainable Manufacturing Systems and Supply Chains Research Laboratory at the University of Kentucky's Institute for Sustainable Manufacturing is engaged in research to advance model-based capabilities to enhance efficiency, productivity, quality and sustainability of next generation manufacturing systems and supply chains.

Socially responsible manufacturing in a resource constrained world requires adopting a closed-loop approach to material flow that considers the total lifecycle from pre-manufacturing, manufacturing, use through the post-use stages over multiple lifecycles. This program targets using analytical techniques to model, evaluate, assess and improve manufacturing systems and entire supply chains for more sustainable manufacturing. The goal is to develop model-based capabilities to not only maximize economic gains but also to minimize negative environmental and societal impacts to all stakeholders when designing and operating manufacturing systems and supply chains.



The 6R methodology of reduce, reuse, recycle, recover, redesign and remanufacture provides a framework to achieve such closed-loop flow. The extended emphasis on environmental and societal aspects is essential to increase value to all stakeholders.





Some recent/on-going projects include:

1. *Digitally-integrated tools for sustainable product design and evaluation*
2. *Sustainable supply chain modeling and optimization*
3. *Supply chain risk modeling, resilience and robustness analysis*
4. *Sustainable and reconfigurable manufacturing systems design*
5. *Extending lean manufacturing practices for sustainable manufacturing*

Projects are supported by external funding and conducted in collaboration with industry.

Contact: Prof. F. Badurdeen **E-mail:** badurdeen@uky.edu **Phone:** 1-(859) -323-3252

Sustainable Operations Management

Principal Investigator: *Prof. Wei Li* www.engr.uky.edu/ism/research/som

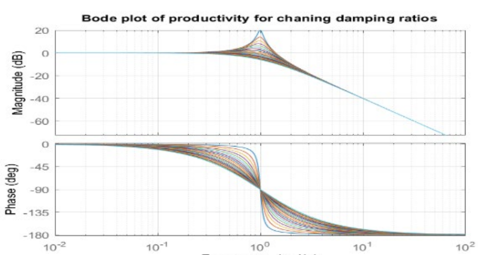
Research in the Sustainable Operations Management (SOM) Laboratory at the University of Kentucky focuses on optimization, adaptive scheduling and control in serial processes. SOM faces the following three fundamental challenges, which are trade-offs among inconsistent performance metrics, *NP*-completeness or *NP*-hardness for individual optimization problems, and stochasticity of factors involved in balancing trade-offs. These challenges may cause high production cost and holding cost in manufacturing, or low service rate and long waiting time in healthcare. By integrating optimization, control theories, and probability and statistics, we model the steady state of physical flows and value flows in serial processes and provide sustainable solutions to trade-off balancing. The research group in the SOM Lab is filling the gaps between theoretical research and industrial application.

Major research focus areas:

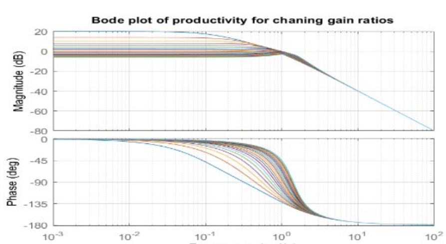
- *Optimization for concurrent design in manufacturing and healthcare*
- *Balancing trade-offs between bias and variance in multivariate analyses*
- *Balancing Trade-offs between inconsistent KPIs in industry*
- *Steady state of serial processes with stochastic disturbances*

Current and most recent projects:

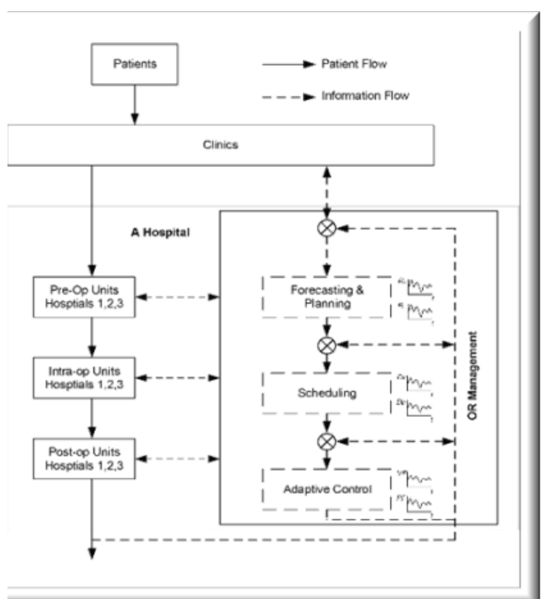
- *Modeling steady state of assembly lines for a local automotive company*
- *Improving the stability of trade-off balancing in one-stage production*
- *Developing heuristics for flowshop scheduling with stochastic processing times*
- *Lagrange relaxation in modern portfolio theory for bin packing problems*



Productivities for changing damping ratios



Productivities for changing gain ratios



Scheduling across peri-operative processes

Contact: *Dr. Wei Li* **E-mail:** wei.mike.li@uky.edu **Phone:** 1-(859)-257-4842

Integrated Computational and Experimental Manufacturing Engineering (ICEME) Program

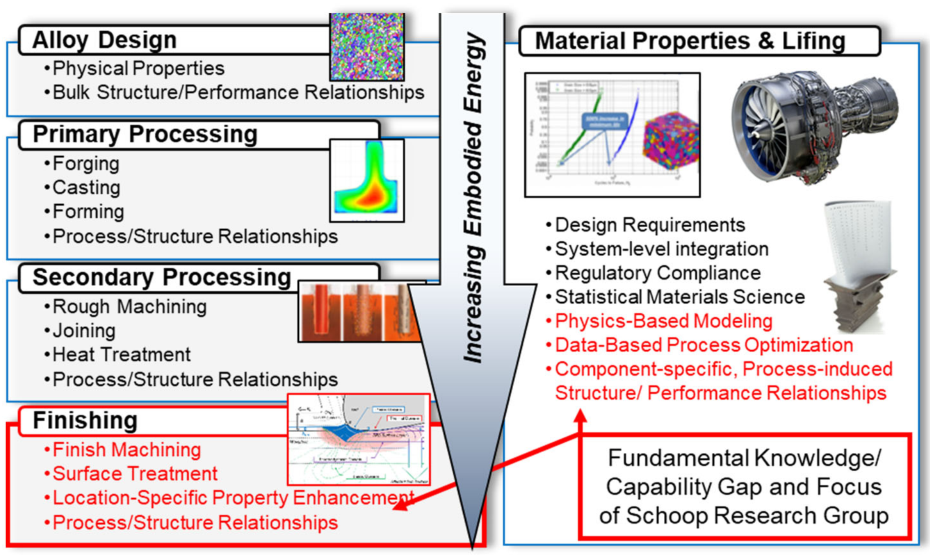
Principal Investigator: *Prof. Julius Schoop* www.engr.uky.edu/ism/research/iceme

The Integrated Computational and Experimental Manufacturing Engineering (ICEME) research program at the University of Kentucky seeks to develop significantly more efficient, industrially relevant real- time computational models and corresponding experimental characterization techniques of surface integrity in machining and finishing processes. Our novel approach is calibrated with a small set of advanced experiments and operates in real-time to allow manufacturers to:

- *Efficiently determine feasible process parameter ranges (feeds, speeds, tool hones, etc.)*
- *Quickly develop optimized 'machining recipes' for new materials and cutting tools*
- *Reliably predict and eliminate white layers, deformed grains and sub-surface cracks*
- *Predict and pro-actively engineer process-induced residual stresses and deformation*

Aerospace OEM's continue to invest significant resources to improve the performance of structural and propulsion systems with new metallic, ceramic and composite materials. These novel materials, such as advanced nickel-based superalloys, gamma titanium-aluminide and ceramic matrix composites (CMCs), are capable of operating at increasingly higher temperatures, which allows for more efficient turbine operation. However, while there have been tremendous advances in the Materials Science of turbine materials that operate at elevated temperatures and extreme loading conditions, the Manufacturing Science necessary to process them efficiently under manufacturing-specific thermomechanical regimes has been lacking.

Through in-situ experimental observation of cutting, burnishing and sliding (tribological) processes using digital image correlation in ultra-high speed (up to 2 million frames/second) microscopy, the Schoop research group is characterizing the complex behaviors of materials undergoing extreme strains, strain rates and temperature gradients that occur around the cutting-edge during machining operations. Using this internationally unique experimental setup, highly efficient semi- analytical, physics-based models of cutting (machining, grinding) and severe plastic deformation processes (e.g., burnishing) are constructed, validated and calibrated.



The long-term vision of the ICEME research program at the University of Kentucky is to Integrate finish manufacturing processes, such as machining and mechanical surface treatments, into the currently materials- focused Integrated Computational Materials Engineering (ICME) paradigm (see Figure). In this way, machinability and optimum process parameters would be known and optimized from the very beginning in new materials, allowing producibility and manufacturing costs to be quantified early during the design stage, avoiding unexpected bottlenecks during manufacturing.

On this path, we closely collaborate with OEMs, suppliers and shops to ensure we are actionable solutions to real-world production issues in difficult-to-machine materials and components.

Contact: Prof. Julius Schoop **E-mail:** julius.schoop@uky.edu **Phone:** 1-(859)-323-8308

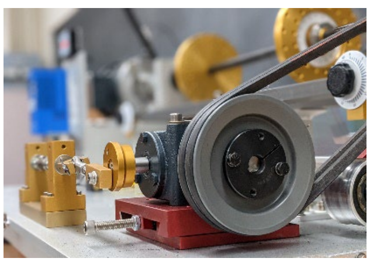
Augmented Intelligence for Smart Manufacturing (AISM) Lab

Principal Investigator: *Prof. Peng (Edward) Wang* http://manufai.engr.uky.edu/

Scientific, technical, and societal advances are increasingly dependent on new insights, theories, and tools to exploit data effectively for the timely delivery of relevant and accurate information and for knowledge discovery. Our lab explores machine learning (ML) and artificial intelligence (AI) for improved pattern recognition and information extraction towards smart, data science-enhanced manufacturing. Also, we target bridging AI and manufacturing domain knowledge together, creating augmented intelligence and ML tools for interpretable and trustworthy applications in production plants. Active projects include:

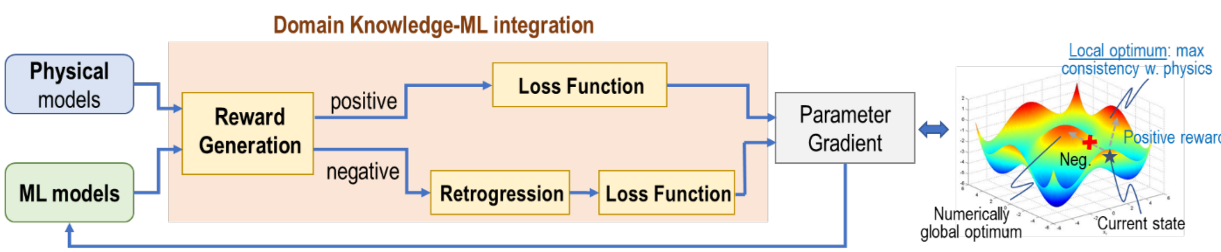
- Machine performance monitoring, fault diagnosis, and predictive maintenance
- Manufacturing process (e.g., welding, additive manufacturing) modeling, quality prediction, and optimization towards improved manufacturing efficiency and quality assurance
- Human-robot collaboration, endowing robots critical thinking and continuous learning

Machine fault simulation testbed

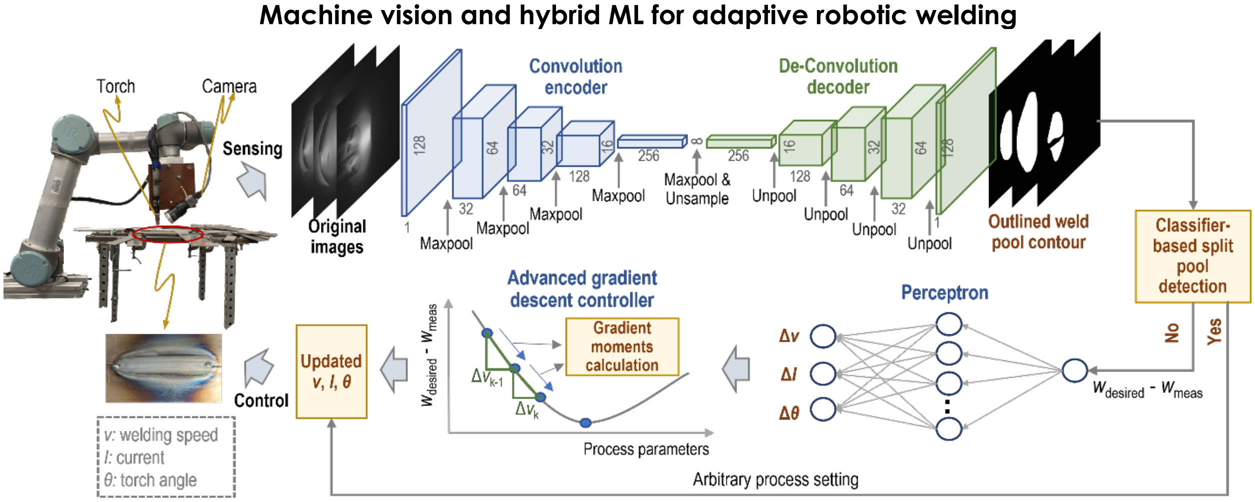


Collaborative robot

Physically interpretable ML model development



Machine vision and hybrid ML for adaptive robotic welding

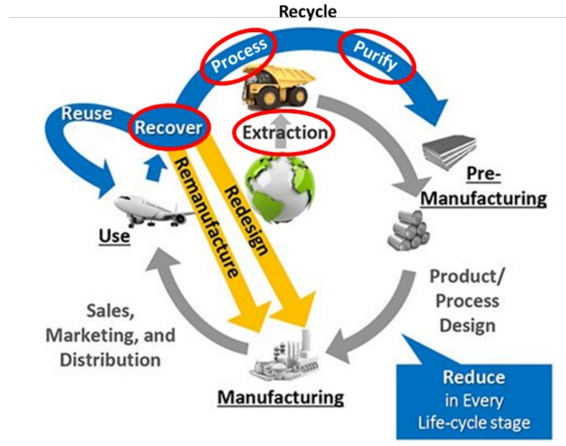


Contact: Prof. Peng "Edward" Wang **E-mail:** Edward.Wang@uky.edu **Phone:** 1-(859)-562-2415

Strategic Materials and Recovery Technologies (SMaRT) for Sustainable Manufacturing

Principal Investigator: *Prof. J. M. Werner* https://smart.engr.uky.edu/

The Strategic Materials and Recovery Technologies (SMaRT) Group within the Institute for Sustainable Manufacturing (ISM) at the University of Kentucky has been actively involved in developing methods and technology for the recovery of rare earth elements in addition to critical and valuable materials. As the earth's resources are finite the recovery, processing and purification of end of life materials is a critical issue of our time.



Jawahir, I. S., and Ryan Bradley. "Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing". Procedia CIRP, Vol. 40, 2016, pp. 103-108

To achieve a significant impact for the circular economy, active research into closed loop hydrometallurgical techniques for both rare and critical metals is the focus of active research. Commercialization of patented technologies is also ongoing with UK developed IP from research.

Current major research focus areas are:

- The recovery of rare earth elements from coal byproducts.
- The development of a novel closed-loop metal recovery system to produce high purity copper and other recoverable metals.
- Development of a "resource recovery" center to develop technology and training for the recovery of critical energy materials.

- Current and most recent projects include:
  1. *Feasibility study to recover rare earth elements and critical materials from coal refuse via heap leach*
  2. *Development of a process for the recovery of high-value metals from electronic waste*
  3. *Multi-sourced collaboration for the production and refining of rare earth and critical metals*
  4. *Pilot plant in Providence, Kentucky to develop recovery and concentration methods for rare earth elements*
  5. *Campus sustainability project to recover metals from student recycled electronics*

Contact: Prof. J. M. Werner **E-mail:** joshua.werner@uky.edu **Phone:** 1-(859)-257-0133