AMM Newsletter

Advanced Methods for Manufacturing

Issue 8 • September 2018

Advanced Methods for Manufacturing Program Update

The Advanced Methods for Manufacturing program (AMM) has two clear, quantifiable objectives. It supports projects that have the potential to:

- Reduce the construction time of new nuclear plants by six months or more, and,
- Reduce the cost of components for nuclear power plants by at least 20 percent

Projects funded through the AMM program continue to make progress toward those goals. This newsletter covers three of those projects that are underway at Oak Ridge National Laboratory, Texas A&M University, and the Electric Power Research Institute.

In FY2018, two projects were added to the AMM program through the Nuclear Energy University Program (NEUP) Funding Opportunity Announcement (FOA). Argonne National Laboratory will evaluate the use of pulsed thermal tomography for non-destructive evaluation of additively manufactured reactor components. In addition, the University of Pittsburgh is exploring integrating dissolvable supports, topology optimization and microstructure design to drastically reduce costs in developing and post-processing nuclear plant components produced by laser powder bed additive manufacturing. Both projects are funded at $1 million.

Two significant projects also will receive funding through the Industry FOA. BWXT is developing a process for nuclear design and manufacturing through the integration of advanced software with AM processes. Holtec International will advance and commercialize a cutting-edge technology known as hybrid laser arc welding (HLAW) for use in nuclear structures and systems. Additional information on the Industry FOA is available at: https://www.id.energy.gov/NEWS/FOA/FOAOpportunities/FOA.html

In addition, both NovaTech and Mainstream Engineering have received Phase 2 grants under the Small Business Innovative Research Program to continue additive manufacturing related projects.

AMM annually publishes a summary of all current projects receiving awards. The 2018 edition was published in July and can be found at: https://www.energy.gov/sites/prod/files/2018/08/f54/2018%20AMM%20Award%20Summaries.pdf

DOE conducted a Webinar in August 2018 covering the Consolidated Innovative Nuclear Research (CINR) FOA for FY2019. The Scopes of Work for the CINR, and information about the application process are available at the Webinar Web site: https://neup.inl.gov/Lists/Headlines/AnnouncementDispForm.aspx?ID=182

Each year, AMM conducts a Program Review workshop with updates and findings from the principal investigator for each project. The workshop is currently scheduled for Dec. 4-6, 2018, at the Manufacturing Demonstration Facility in Knoxville, TN.

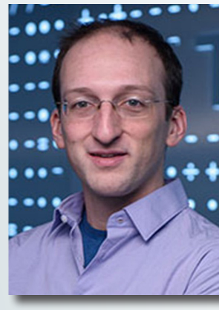
Copies of the presentations from the meeting held by the U.S. Nuclear Regulatory Commission in November 2017 to discuss Additive Manufacturing for Reactor Materials & Components are available at: https://www.nrc.gov/docs/ML1733/ML17338A880.html

AMM national technical director, Bruce Landrey, has established a system that allows interested parties to register to receive AMM newsletters, publications and event announcements. The registration site can be reached at: https://visitor.r20.constantcontact.com/manage/

In This Issue

Advanced Surface Plasma Nitriding for Development of Corrosion Resistant and Accident Tolerant Fuel Cladding





Lin Shao
Texas A&M University

Don Lucca
Oklahoma State University

Michael Short
Massachusetts Institute of Technology

In harsh reactor environments involving stress, corrosion, and irradiation damage, nuclear fuel component materials can experience severe microstructural changes and various kinds of degradation. These changes impact not only the lifespan of the components, but also reactor safety and reliability. Although numerous studies have shown that a surface nitride layer can increase hardness, wear resistance, oxidation resistance, and corrosion resistance, no systematic investigation has been done pertaining to nitriding effects on fuel component materials. Furthermore, currently existing plasma nitriding techniques have not been able to uniformly coat the surface of complicated structures.

This project aims to develop a hollow cathode plasma nitriding technique for surface modification of fuel cladding and component materials, driven by the need to increase corrosion resistance and accident tolerance with better structural integrity and compatibility with both coolants and nuclear fuels. Different from conventional techniques, this project uses a hollow cathode cage to force the plasma to be uniformly distributed. Therefore, the final nitride layer formation is not affected by the shape or geometry of the materials inside the cage. Starting with alloys of DOE interest, the team applies this plasma nitriding technique to produce a nitride layer on the surface of a number of alloys. The project involves Texas A&M University for nitridation experiments, ion irradiation, and structural characterization; Oklahoma State University for mechanical property testing; and Massachusetts Institute of Technology for corrosion and oxidation testing.

Continued on next page

316L: 525°C, 1.5 Torr

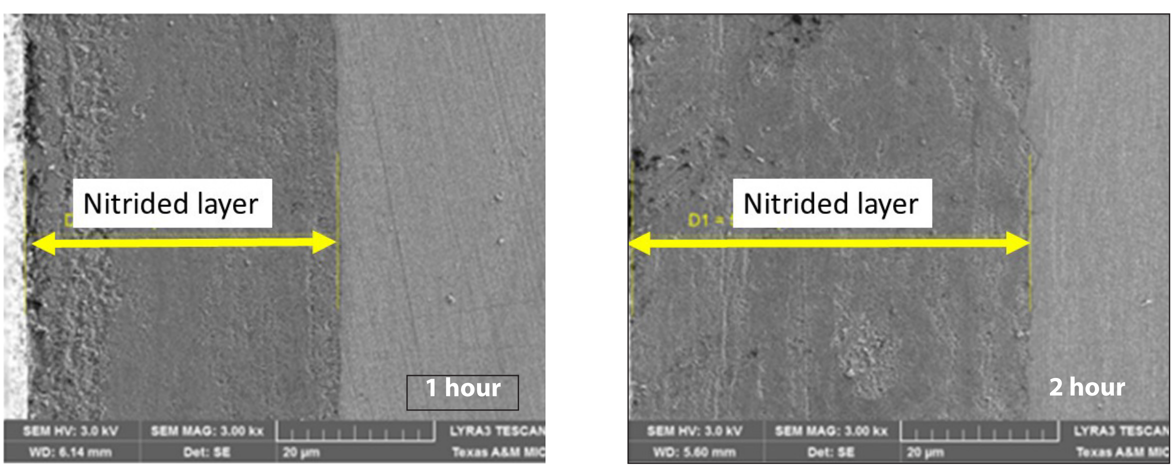


Figure 1. Scanning electron microscope images of nitrided 316L cross sections after nitridation at 525°C and 1.5 Torr for one hour (left) and two hours (right). The dark contrast regions are nitrided layers due to plasma nitridation.

Continued from previous page

Current Status

The team has identified all major parameters to achieve uniform nitride layers on various alloys, including 316L, HT-9, and Zircaloy 4. Diffusion kinetics, identification of nitride phases, and mechanical property changes have been studied. Through a combination of transmission electron microscopy for structural characterization, cross-sectional indentation for hardness changes, cross-sectional second ion mass spectrometry for nitrogen profiling, cross-sectional Raman analysis for nitride layer formation, we have obtained a comprehensive understanding of nitridation effects on microstructural and property changes, as well as the correlation between the two.

Figure 1 shows cross sections of 316L after nitridation for one hour (left) and two hours (right). The nitride layers are clearly visible in darker contrast. The thickness of the nitride layers is used to estimate diffusion lengths of nitrogen in nitride formation. The extracted diffusivities, as shown in Figure 2, follow an Arrhenius temperature dependence. These data help to predict and control the thickness of the nitride layers under arbitrarily selected nitridation conditions.

The study was extended to reactor components of complicated geometry to demonstrate the suitability of the technique to realistic applications, as shown in Figure 3. The technique can be applied to fuel cladding or spacers or other light water reactor (LWR) fuel components.
The third year of the research has focused primarily on corrosion resistance testing in boiling water reactor (BWR) and pressurized water reactor (PWR)-characteristic coolants. So far, studies have shown that nitridation can significantly increase corrosion resistance.

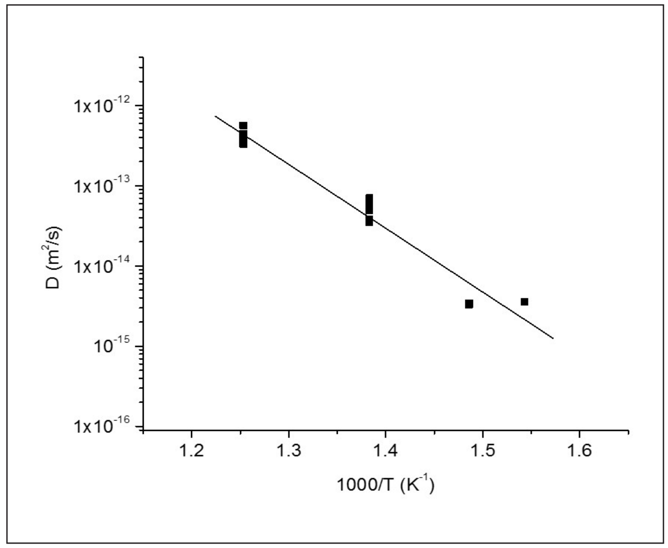


Figure 2. Extracted nitrogen diffusivities as a function of nitridation temperatures in nitrided 316L.

Conclusion

We have obtained main nitriding parameters for LWR-relevant alloys and successfully applied the technique to complex structures. The project is currently in its last stage of optimizing the process to achieve the best corrosion resistance. The project impacts the development of accident-tolerant fuels for improved corrosion and oxidation resistance.

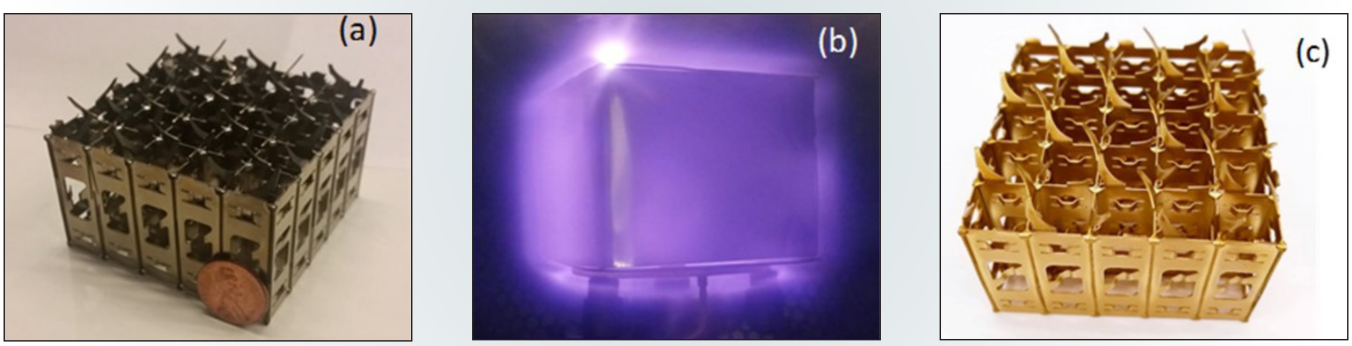


Figure 3. Images of Westinghouse fuel assembly spacer samples (a) before nitridation, (b) during the nitridation, and (c) after the nitridation. The golden color after nitridation comes from nitride layers forming on the surfaces.

SMR Vessel Manufacture/Fabrication/Demonstration Project

David W. Gandy
EPRI

Craig Stover
EPRI

Will Kyffin
Nuclear-AMRC

Matt Cusworth
Nuclear-AMRC

Keith Bridger
Bridger Welding Engineering

Many of the same manufacturing/fabrication technologies that were employed for light water reactor (LWR) plants built 30 to 50 years ago are also being employed today to build advanced light water reactors (ALWRs). Manufacturing technologies have not changed dramatically for the nuclear industry even though more efficient production processes are available that could significantly reduce the overall cost of components. New technologies that can accelerate production and reduce costs are vital for the next generation of plants, small modular reactors (SMR), and Advanced GEN IV plants to ensure they can be competitive in the current and future market.

This project will demonstrate and test several new technologies with the goal of producing critical assemblies for a two-thirds scale demonstration SMR reactor pressure vessel (RPV). Through the use of electron beam welding (EBW), powder metallurgy-hot isostatic pressing (PM-HIP), diode laser cladding (DLC), bulk additive manufacturing, and advanced machining, the Electric Power Research Institute (EPRI) and the United Kingdom (U.K.)-based Nuclear Advanced Manufacturing Research Centre (Nuclear-AMRC), together with a number of other industrial team members, seek to demonstrate that critical sections of an SMR RPV can be manufactured and fabricated in less than 12 months and at a cost savings of more than 40 percent compared to today's technologies. The project aims to demonstrate and test the impact that each of these technologies can have on future production of SMRs, and explore the relevance of the technologies to the production of ALWRs, SMRs, GEN-IV, ultra-supercritical fossil, and supercritical CO^2 plants. The project, if successful, may accelerate deployment of SMRs in both the United States (U.S.) and ultimately throughout the world.

Tasks

In the March 2016 AMM Newsletter (1), the project tasks for the current project were described. Task 1 of the project is focused on manufacture and fabrication of the lower assembly (Figure 1) of the NuScale reactor at 2/3-scale. The lower assembly consists of a lower RPV head, a lower RPV flange shell, upper and lower flanges, and an upper transition shell. Each of these components will be produced and assembled between Q4-2017 to Q3-2019.

Current Status

- Detailed work packages have been developed for the following tasks/subtasks:
  - EBW development, DLC development, machining, PM-HIP of individual components, heat treatment, etc.
  - Flange welding, head welding, vertical welding, circumferential welding
  - Lower assembly

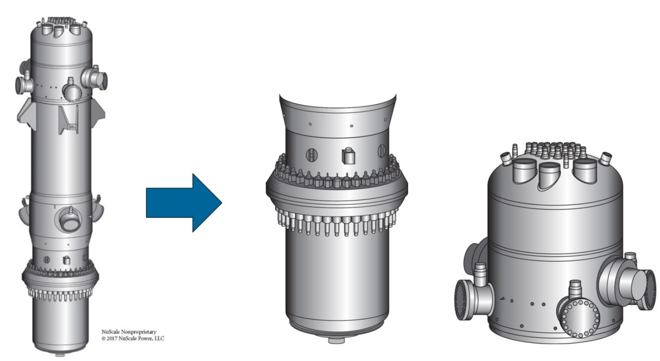


Figure 1. Upper and lower assemblies of the NuScale Power reactor are being assembled at 2/3-scale under this program.

Continued from previous page

Figure 2. A 44 percent diameter (50-inch, 1270mm) A508 Grade 3, Class 1 upper reactor head that includes 27 penetrations and weighs 3640lbs (1650kgs) was produced via PM-HIP

Figure 3. A 2/3-scale, one-half diameter lower reactor head (~70 inches (1780mm) in diameter, 6910lbs (3135kgs) was also produced via PM-HIP.

- A 44 percent diameter (50-inch, 1270mm) A508 Grade 3, Class 1 upper reactor head that includes 27 penetrations and weighs 3640lbs (1650kgs) was produced via PM-HIP (Figure 2).
- A 2/3-scale, one-half diameter lower reactor head (~70 inches (1780mm) in diameter) was also produced via PM-HIP (Figure 3).
- Four major forgings including an upper and lower RPV flange, the lower RPV shell, and the pressurizer shell were manufactured.
- EBW parameters and geometry for SA508 Grade 3 Class 1 girth welds were established and demonstrated.
- Key performance variables (KPVs) were established for the DLC process for SA508 substrates. Using DLC, it is possible to produce both 1-layer and 2-layer clads that meet ASME IX requirements.

In the coming weeks, the investigators plan to manufacture two, one-half diameter lower RPV head sections that are approximately 70-inches (1780mm) in diameter. The two sections must be stood vertically in the HIP vessel since no vessel currently exists that can produce the large RPV sections lying flat. Once produced, the HIP capsules will be removed, the component will be machined to final diameter, and then welded together using EBW. Major sections of the transition shell will also be produced with anticipated completion in Q2-2019.

In parallel, additional development for all major girth welds and vertical welds is underway at the Nuclear-AMRC (UK), along with DLC development and demonstration. The EBW development is expected to be completed in Q4-2018.

Impact, Value, Implications

If successful, the impact of the current SMR manufacturing/fabrication project will be dramatic in terms of cost reduction, quality, and schedule. Below are a few of the projected outcomes from the project:

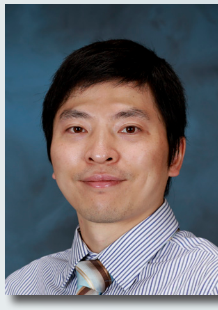
- Demonstrate an advanced welding technology, EBW, for fabrication of reactor components, which is expected to reduce welding time by 90 percent over conventional welding processes and methods.
- Demonstrate PM-HIP methods to manufacture difficult-to-produce sections of the SMR (upper and lower reactor heads, plenum, access covers, etc.) in as little as a few months each.
- Potential to eliminate in-service inspection requirements for no fewer than five out of seven full-diameter circumferential welds through the use of the EBW process and solution annealing.
- Develop/demonstrate DLC technologies that can apply thin (~1mm) layers of cladding using robotics. The overall volume of material required for cladding will be reduced by 75 percent resulting in a substantial cost savings across the entire vessel inner and outer clad surfaces.

Acknowledgements

The principal investigators would like to recognize Vern Pence (NuScale Power), Victor Samarov (Synertech- PM), and Michael Blackmore (Sheffield Forgemasters-UK) who will be instrumental in production of major components in this project.

Improving Weld Productivity and Quality by Means of Intelligent Real-Time, Close-Looped, Adaptive Welding Process Control through Integrated Optical Sensors

Jian Chen (PI), Roger Miller, Zhili Feng, Oak Ridge National Laboratory (ORNL)
Yu-Ming Zhang, University of Kentucky
Robert Dana Couch, Electric Power Research Institute (EPRI)



Jian Chen
Oak Ridge National Laboratory

In today's industry, weld quality inspection for manufacturing nuclear reactor structures mostly relies on post-weld nondestructive inspections. If defects are identified, the reworking (or scrapping if beyond repair) of manufactured structures is costly and time-consuming. This project aims to develop a novel close-looped adaptive welding quality control system based upon multiple optical sensors. It will enable real-time weld defect detection and adaptive adjustment to the welding process conditions to eliminate or minimize the formation of major weld defects typically encountered in welding high-performance engineering structural materials for nuclear structural components. By reducing weld defects and therefore the rework required for defect mitigation, the system can significantly decrease the component fabrication cost, accelerate the deployment schedule, and increase the integrity and reliability in a variety of nuclear reactor designs and components.

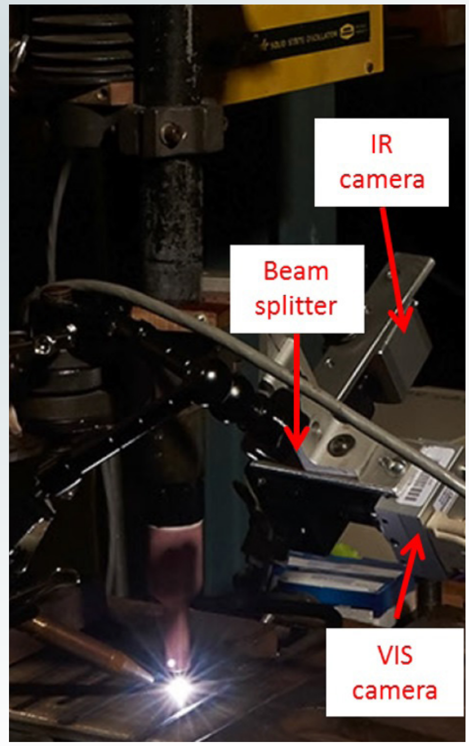


Figure 1. Multi-optical sensing system.

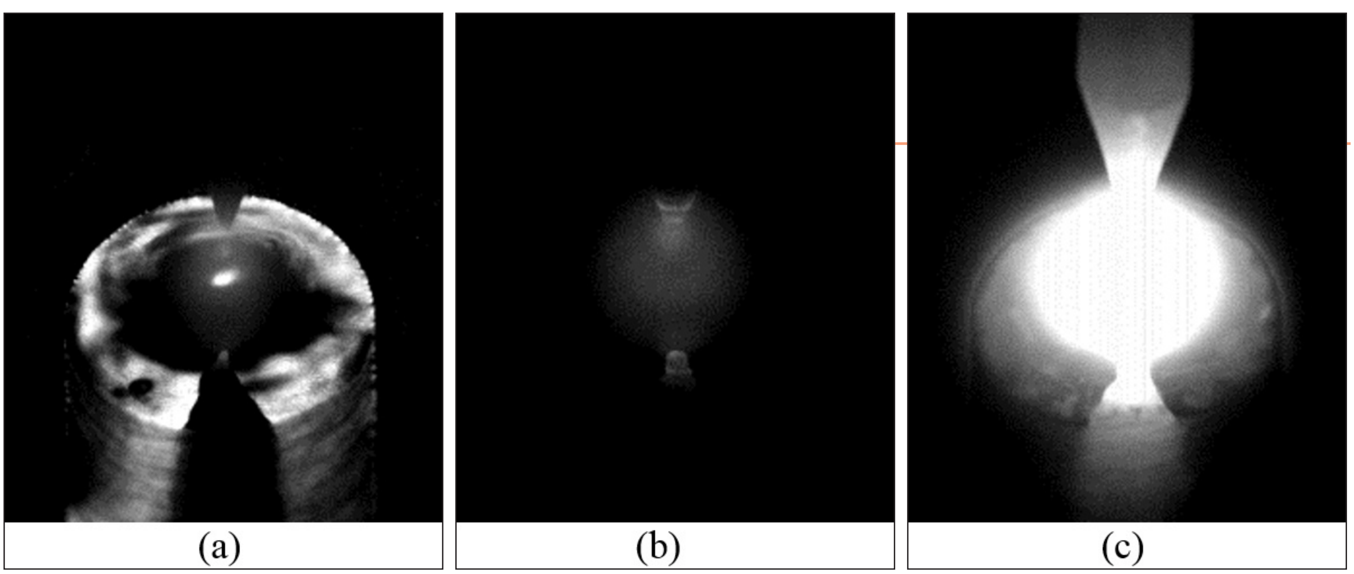


Figure 2. VIS images obtained by: (a) short exposure time and laser illumination, (b) short exposure time without laser (c) long exposure time without laser.

Continued from previous page

Accomplishments

A prototype system has been integrated and tested. As shown in Figure 1, the hardware mainly consists of a visible (VIS) camera, an infrared (IR) camera, a beam splitter that reflects VIS light and transmits IR light, and a pulsed diode laser as an auxiliary illumination sources. The surface profile of the weld pool and the stress evolution adjacent to the weld fusion line can be monitored in real time.

To visualize the weld pool, three types of images as illustrated in Figure 2 are acquired from the VIS camera by adaptively controlling the exposure time and laser pulsing. These images are processed in real time by a computer to extract three-dimensional information about the weld pool surface. An artificial intelligent algorithm correlates the information to the weld penetration depth and certain weld defects such as lack-of-fusion. An adaptive control algorithm is applied to ensure the quality of the weld. Figure 3 demonstrates the effectiveness of quality control during welding a multi-pass U-groove joint. The initial welding condition without adaptive control resulted in partial penetration on the root pass and side-wall lack-of-fusion defect on the subsequent pass. With adaptive control enabled, a full penetration weld was achieved on the root pass and the lack-of-fusion defect was avoided.

Strain and distortion of the materials adjacent to the fusion line during welding can be monitored by a unique high-temperature digital image correlation (DIC) approach. Meanwhile, temperature is measured by the IR camera or thermocouples. In addition, stress evolution is also derived in real time with a novel procedure. Figure 4 shows the transverse strain distribution and the stress evolution during a laser welding process.

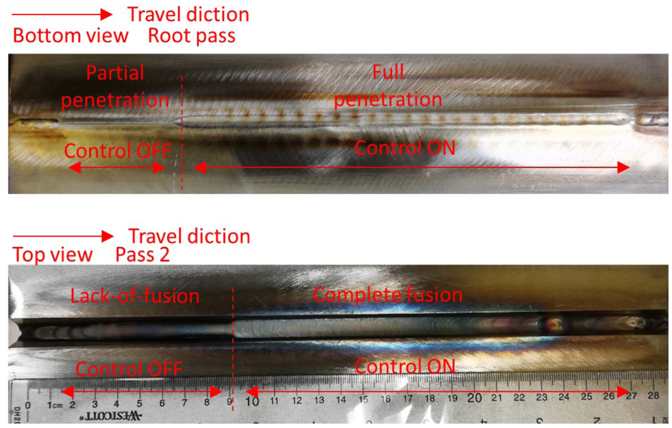


Figure 3. Adaptive control to achieve full-penetration on the root pass and complete side-wall fusion on the subsequent weld pass.

Conclusion

A prototype system, including integrated optical sensors and real-time data acquisition and processing software, was developed. Evolution of strain, stress, and distortion adjacent to the fusion line during welding was measured in real time. Important features were extracted from images and correlated to the weld penetration state and lack-of-fusion defect. Adaptive welding control was achieved to ensure full-penetration and defect-free welds on multi-pass thick-sections of U-groove joints.

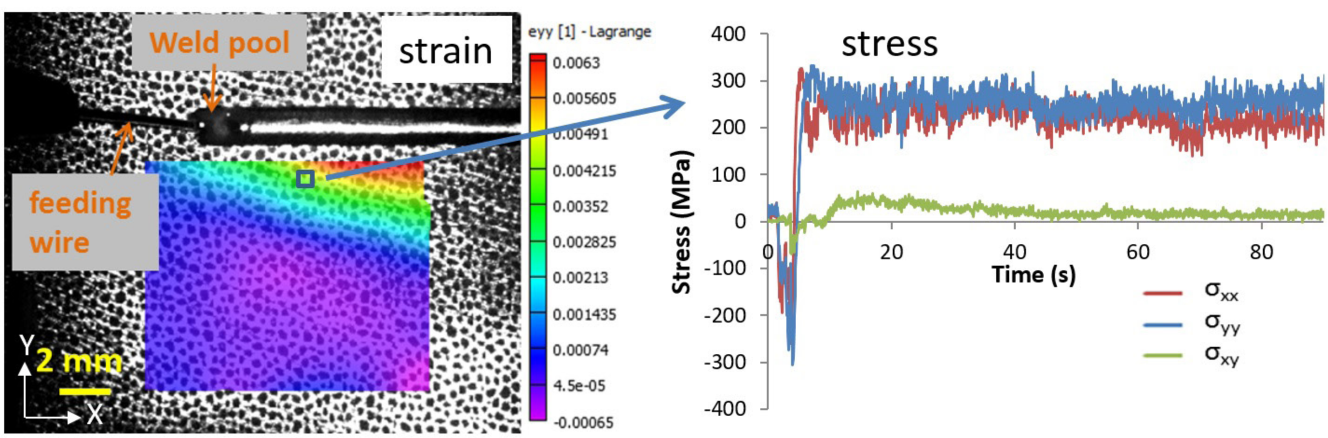


Figure 4. Transverse strain distribution and stress evolution during laser welding.

To submit information or suggestions, contact
Tansel Selekler at **Tansel.Selekler@nuclear.energy.gov**.