Pacific Northwest
NATIONAL LABORATORY

Solid Phase Processing @ PNNL

REVOLUTIONIZING U.S. METALS MANUFACTURING FROM CONCEPTION TO DEMONSTRATION TO DELIVER BETTER, GREENER, AND MORE AFFORDABLE PRODUCTS.

Reaching a net-zero economy by 2050 will require new manufacturing approaches and technologies capable of producing greener, more cost-effective materials that can do more. Pacific Northwest National Laboratory (PNNL) is revolutionizing the manufacture of next-generation metal alloys and components with partners across industry, academia, and government sectors. Together, we are driving the discovery, development, and demonstration of scalable, advanced manufacturing approaches that will be key tools in unlocking the net-zero economy of the future.

A NEW APPROACH TO METALS MANUFACTURING

For the past 5,000 years, the manufacture of metals has required large amounts of energy in the form of heat. Heat is used to melt metals into alloys with specific performance characteristics. Traditionally, metals manufacturing has relied on fossil-based energy to generate that heat, resulting in a large carbon footprint.

In a radical new approach to metals manufacturing called Solid Phase Processing (SPP), PNNL smashes this age-old paradigm by applying mechanical energy instead of external heat to alloy and form metal products. This approach has given rise to a suite of scalable manufacturing processes that require less energy and are more environmentally sustainable than conventional methods. Because SPP approaches are fundamentally different, they enable the manufacture of entirely new metal products that cannot be produced through conventional processes while driving down the need for costly alloying elements.

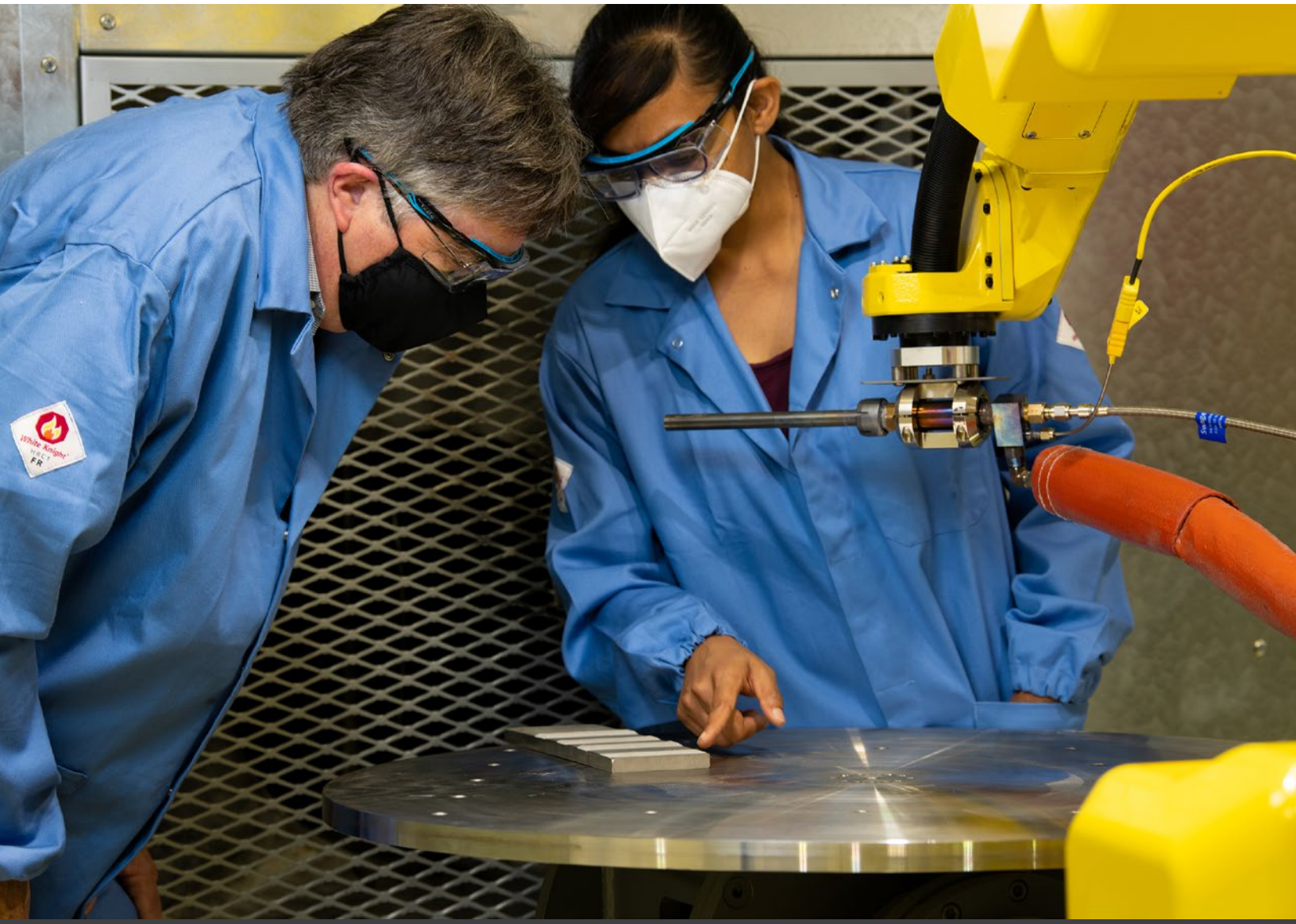
SPP METHODS AVAILABLE AT PNNL

Friction stir welding for joining similar and dissimilar metals without melting.

Shear Assisted Processing and Extrusion (ShAPE™) for metal alloying and extrusion.

Friction stir processing for locally modifying metal properties and healing defects.

Cold spray for coatings and infrastructure repair.



In cold spray processing, feedstock particles are propelled at supersonic velocities to impact surfaces with sufficient energy to form a strong bond and create a dense deposit that can be more effective than traditional welding for material repairs. *(Photo by Andrea Starr | Pacific Northwest National Laboratory)*

HIGH-PERFORMANCE PRODUCTS THAT REQUIRE LESS ENERGY AND RESOURCES

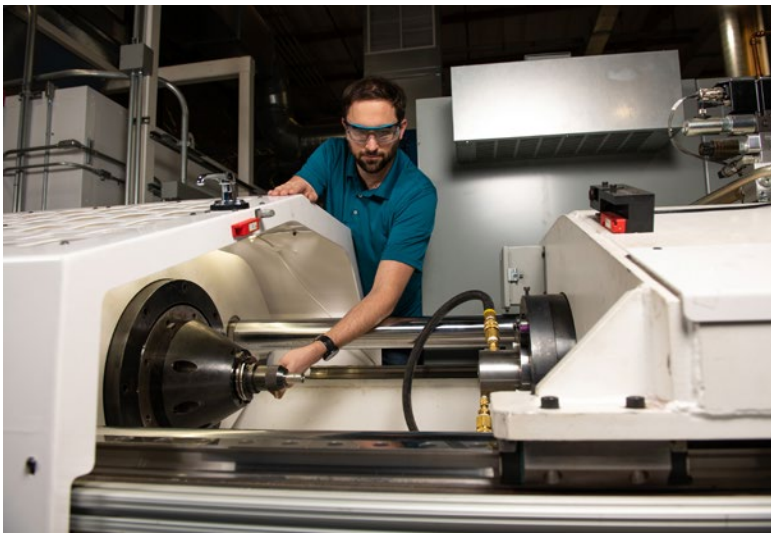
Because SPP methods eliminate the need to heat metals to high temperatures to form alloys, create welds, or produce specific forms, they require less time, energy, and expense than conventional metals manufacturing. This substantially decreases greenhouse gas (GHG) emissions while simultaneously delivering better products.

Less energy

SPP methods are greener and more energy efficient. Friction stir welding (FSW) can reduce the energy required to join metals by up to 80% compared to conventional gas arc welding. ShAPE™ reduces energy requirements by 85% compared to conventional extrusion processes—which can reduce greenhouse gas emissions by up to 92%.

Lower costs

SPP methods reduce the cost of manufacturing high-performance alloys, making them affordable for a broader range of applications. One example is high strength aluminum alloys, which have seen limited use because of their high manufacturing costs. Using ShAPE™ processing, these same aluminum alloys can be manufactured 10 times faster and without pre- and post-extrusion heat treatments, cutting costs by 60%.



ShAPE™ technology uses a combination of linear and rotational shear forces to produce extruded products like tubes, wires, and bars that have significantly improved properties. *(Photo by Andrea Starr | Pacific Northwest National Laboratory)*

SPP approaches can provide:

- **Reduced greenhouse gas emissions**—up to 92% less than conventional methods.
- **Significant energy savings**—an over 50% decrease in manufacturing energy, with as much as an 80% decrease using the FSW method and 85% using ShAPE™.
- **Lower manufacturing costs**—up to 60% less using ShAPE™.
- **Next-generation, high-performance products**—like ultra-conductive copper and aluminum metals via ShAPE™ and cast aluminum with 10 times improved fatigue life via friction stir processing.
- **Enhanced manufacturability**—including 10 times faster extrusion of aluminum alloys using ShAPE™.
- **Longer operational lifetime**—like cold spray coatings that increase wear resistance of stainless steel turbine blades by more than 300%.

Better products

SPP methods yield products that are impossible with conventional processes. FSW enables joining dissimilar materials that cannot be welded together by conventional means, supporting the fabrication of multi-material components. ShAPE™ can deliver copper and aluminum composites with higher conductivity, extrude brittle materials such as high-iron aluminum alloys and thermoelectric materials, and co-extrude 6000- and 7000-series aluminum alloys.

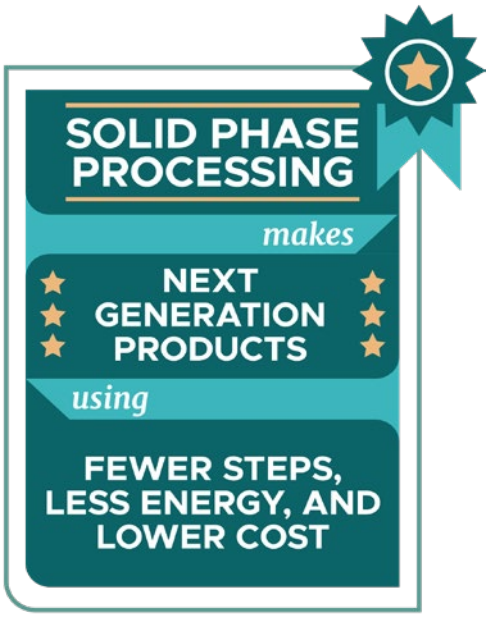
From scraps to high-performance materials

In collaboration with industry partner Magna International, PNNL demonstrated the direct conversion of 100% aluminum scrap into high-performance tubing via ShAPE™. In addition to lowering materials costs by recycling scrap, this process is estimated to use 30% less energy and reduce 90% of greenhouse gas emissions relative to the same tubing produced from primary aluminum.

To learn more about the suite of SPP approaches, visit ***https://www.pnnl.gov/solid-phase-processing***.

BE ON THE LEADING EDGE OF ADVANCED MANUFACTURING WITH SPP@PNNL

Leveraging innovation, expertise, and fundamental scientific understanding in SPP, PNNL scientists and engineers are working with industry partners to develop and demonstrate scalable, affordable, and green manufacturing approaches for a variety of metal alloys and applications. Translating these innovative approaches in metals manufacturing to commercial use will provide a significant competitive advantage to the domestic manufacturing sector, create thousands of new, high-quality jobs, and establish the United States as the global source for the best metals components.



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Shear Assisted Processing and Extrusion (ShAPE)

Shaping greener manufacturing

BETTER, FASTER, AND MORE AFFORDABLE

ShAPE™, a technology developed by Pacific Northwest National Laboratory (PNNL), is a green manufacturing pathway to high-performance metals. ShAPE is an efficient, solid phase process that extrudes high-quality materials with superior properties—all while generating time, energy, and cost savings.

ShAPE can extrude aluminum alloy 7075 at rates up to 10 times faster than conventional extrusion processing with equivalent or better product properties. ShAPE's ability to process unhomogenized secondary scrap into aluminum alloy 6063 products has enabled a 50 percent reduction in energy usage compared to conventional extrusion. This avoids the need for primary aluminum additions and reduces carbon emissions by 92 percent during manufacturing. Winner of multiple manufacturing awards, ShAPE is a low-carbon manufacturing approach that enables applications across multiple industries—from automotive to aerospace to national security.

SHAPE ADVANTAGES

ShAPE is a solid phase process that induces severe plastic deformation and mixes materials more than conventional manufacturing to result in many benefits. When ShAPE is used, the combination of extreme deformation at elevated temperature alters the structure of materials on a microscopic level, creating microstructures that are more refined, homogenous, and stable; this translates to unique material properties, like increased strength and ductility. By eliminating the need for separate heat treatment steps, ShAPE increases processing speed and energy efficiency while extruding superior products compared to conventional methods.

ShAPE produces better materials and does so faster, greener, and more affordably. (Photo by Andrea Starr | Pacific Northwest National Laboratory)

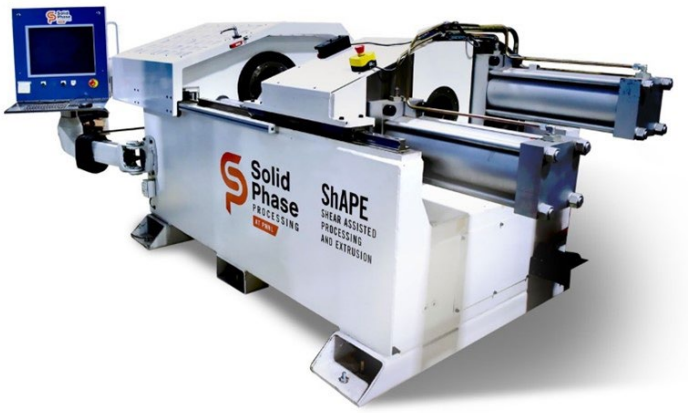
Gas-atomized powders can be directly processed using ShAPE to avoid multiple energy-intensive manufacturing steps. Exotic alloys can be extruded faster because the improved microstructure produced by ShAPE prevents surface cracking. ShAPE can even use scrap

metals to create components with complex shapes and geometries without the addition of virgin feedstock—a game changer in aluminum recycling. PNNL partners with a major producer of automotive parts to demonstrate manufacturing of complex structural components for vehicles.

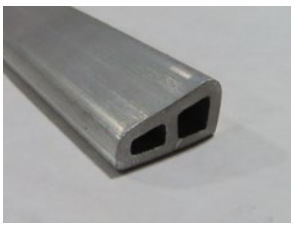
SHAPE APPLICATIONS

Because of these advantages, ShAPE is being used to enable a wide range of applications, including:

- Fabrication of copper-carbon and aluminum-carbon composites with enhanced electrical conductivity;
- Single-step processing of direct reduced iron pellets into high performance, oxide dispersion strengthened steels;
- Production of corrosion resistant magnesium and high-performance aluminum alloys, which can be used to make energy efficient lightweight vehicles; and
- Recycling secondary aluminum scraps directly into automotive components to reduce the demand for raw materials.



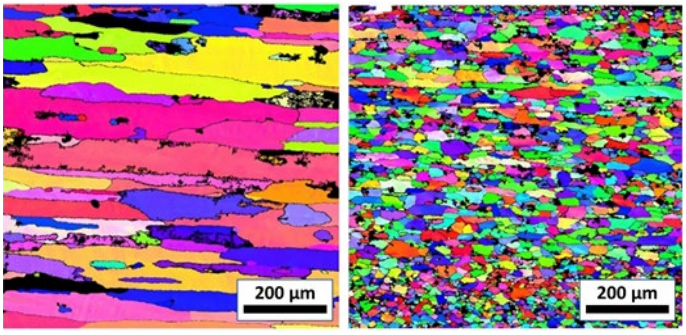
Developed by Pacific Northwest National Laboratory and designed and Manufactured by BOND Technologies, the ShAPE machine lowers speeds the process by up to 10 times, uses up to 50 percent less energy, and reduces emissions by up to 92 percent compared to conventional manufacturing. (Photo by Scott Whalen | Pacific Northwest National Laboratory)



A multi-cell, non-circular metal alloy extruded from scrap aluminum using ShAPE is approximately 1 inch in width. (Photo by Scott Whalen | Pacific Northwest National Laboratory)

SHAPE AT PNNL

Winner of a 2020 R&D 100 Award for Advanced Manufacturing and the 2021 Association of Washington Business Green Manufacturing Award, ShAPE is recognized as a revolutionary, low-carbon manufacturing approach that produces next-generation materials and supports a greener future. Intellectual property for the ShAPE technology is protected under 20 United States and international patents, and PNNL and has licensed the technology to the automotive industry to help deliver next-generation electric vehicles. Now, PNNL is investing in ShAPE 2.0—a larger machine that will demonstrate industry scalability of this revolutionary approach to manufacturing.



The combination of extreme deformation at elevated temperature during ShAPE alters a feedstock material's structure (left) on a microscopic level, creating microstructures that are more refined, homogenous, and stable (right). This translates to unique material properties like increased strength and ductility. (Microscopy images by Joshua Silverstein | Pacific Northwest National Laboratory)

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SPP technologies available for licensing at PNNL

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Friction Stir Joining and Processing

Friction stir lowers manufacturing energy needs and enables more efficient products

SOLID-PHASE JOINING AND PROCESSING

Solid-phase joining and processing techniques—including friction stir welding—could revolutionize the $20 billion, conventional, melt-based fusion welding industry. Because friction stir welding uses only about 16 percent of the energy required for fusion welding, even a modest adoption of friction stir joining and welding approaches by the domestic manufacturing industry (10 percent market penetration) could eliminate 700 million pounds of carbon dioxide emissions and generate an economic benefit of $6.5 billion per year for the United States.

In addition to lowering energy consumption and direct emissions from manufacturing processes, solid-phase joining and processing can enable energy efficiency in manufactured products. For example, friction stir welding can join dissimilar lightweight materials that cannot be joined by other methods, enabling the manufacture of lighter, more efficient vehicles. Friction stir welding can also be used to fabricate industrial assemblies like heat exchangers in high temperature thermal power systems, such as solar collectors or boilers. When fabricated using friction stir processes, these assemblies are more durable and can withstand temperatures 50 – 100 °C higher than assemblies fabricated by fusion welding. This makes them up to seven

Solid-phase joining and processing saves energy and reduces carbon emissions during manufacturing in addition to enabling materials that make it easier to fabricate energy efficient products. (Photo by Andrea Starr | Pacific Northwest National Laboratory)

percent more efficient, reducing carbon emissions from fossil energy power systems by 30 percent.

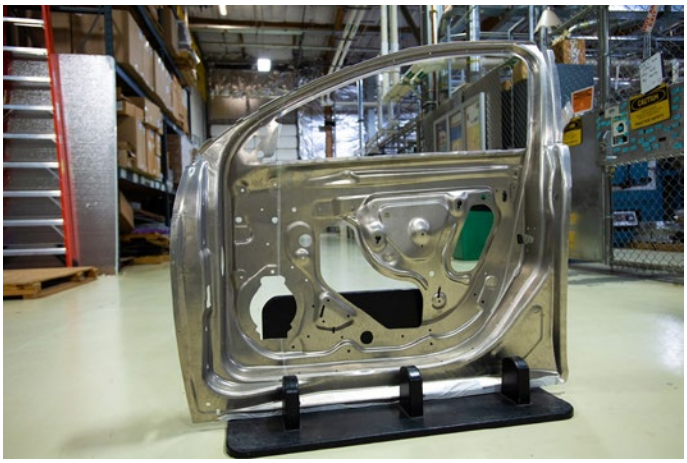
FRICTION STIR PROCESSES

Friction stir is a group of solid-phase processing techniques that can join materials or modify metals for improved performance—all without melting. These approaches and processes leverage the power of friction to join and mix materials. During friction stir processing, a rotating tool is plunged into

a material and moved along a joint line, or along the material's surface, to physically stir the metal around the tool. This leaves behind a unique, high-performance surface or can create a fully joined bond when used as a welding technique. Friction stir approaches are faster, more energy efficient, and able to produce welds that are impossible with conventional methods.

FRICTION STIR AT PNNL

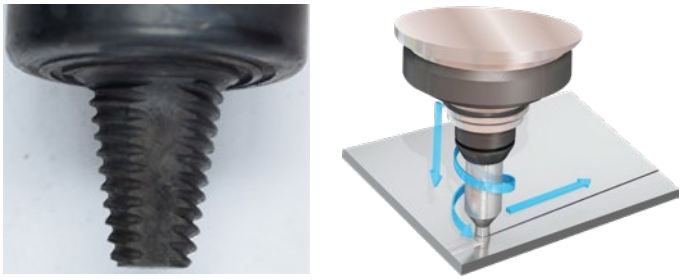
Pacific Northwest National Laboratory (PNNL) has improved various friction stir-based processing methods by adding tools and inventing new ways to 'stir' materials. Friction stir welding, dovetailing, the scribe, and riveting are just some of the techniques developed at PNNL to join materials in new ways to allow for greater energy efficiency. These processes are faster than conventional fusion welding and eliminate the need for adhesives and fasteners that increase cost and manufacturing steps and can weigh materials down. Using these processes, manufacturers are able to incorporate new materials and designs into lighter components without sacrificing strength or durability.



In a process called tailor welded blanking, friction stir welding can join aluminum sheets of different thickness to produce lighter car doors like the one shown here.(Photos by Piyush Upadhyay | Pacific Northwest National Laboratory)

LIGHTER COMPONENTS WITH FRICTION STIR

In partnership with General Motors, Alcoa, and TWB Company LLC, PNNL researchers developed a new friction stir welding technique able to join aluminum sheets of varying thicknesses at rapid speeds in a method called tailor welded blanking. This approach produced a car door panel that was 62 percent lighter, while still retaining strength where it was most needed. The PNNL-developed technique is ten times faster than previous friction stir welding techniques, so it can better meet the needs of high-volume manufacturing assemblies. Today, these friction stir welded blanks are used across the automotive industry, especially in aluminum intensive cars.



Friction stir is a solid phase processing approach that can produce joins that are impossible to achieve with conventional methods and enable lighter components in multiple industries. On the left is a newly developed friction stir welding tool used to join thick aluminum plates, and on the right is a schematic of friction stir. (Photo by Piyush Upadhyay | Pacific Northwest National Laboratory)

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Robotic High Pressure Cold Spray

An innovative solid-phase coating process

FOR MATERIAL REPAIRS AND IMPROVEMENTS

Cold spray is a solid-phase metal deposition process used for coating or additive manufacturing (AM). Cold spray can be used for repairs—to return a component to its original shape after wear and tear—or to improve a component's corrosion resistance, wear resistance, and other properties. It is capable of high deposition rates that deliver an improved surface finish compared to many other metal coating or AM processes. Powders used in cold spray can also be easily customized to create coatings and components with unique properties.

Cold spray is a solid-phase metal deposition process used to create coatings that can be used to improve component performance. The image shown here is a nickel coating on aluminum. (Photo by Kenneth Ross | Pacific Northwest National Laboratory)

OPTIMAL PERFORMANCE, LOWER COSTS

Because deposits are made in the solid phase, cold spray can deliver superior results for many applications compared to melt-based coating and AM processes. Cold spray also enables engineers to design multi-material components to optimize performance and reduce costs.

During the cold spray process, powder is injected into a heated, pressurized carrier gas stream as it enters a nozzle. The gas and powder are accelerated to supersonic speeds as they exit the nozzle. When the powder makes contact with the material being processed, the particles undergo extreme deformation which causes the powder to adhere to the substrate. Powder particles build up and create a high-density coating or three-dimensional structure.

COLD SPRAY AT PNNL

Pacific Northwest National Laboratory (PNNL) has a state-of-the-art, robotic cold spray system which can be used for application development and prototype part fabrication. The system can be used in manual and robotic-based applications, as well as

applications that require portability and limited access. PNNL also has a suite of characterization equipment to optimize cold spray processing for different applications.

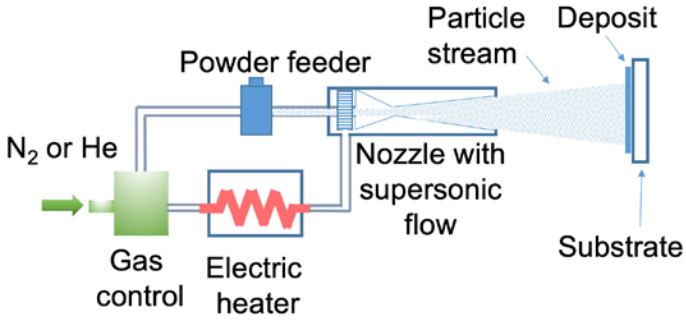
LONGER-LASTING TURBINES

PNNL has demonstrated that cold spray coatings improve cavitation resistance—improved resistance to wear and tear from fast-moving water—by a factor of five or more versus the current repair method. This has potential to reduce cavitation damage rates in hydropower turbines so they can last longer. Now, PNNL is developing a portable cold spray process to repair hydropower components. This would dramatically reduce the frequency at which turbines are taken offline for cavitation damage repairs, while significantly lowering maintenance costs and lost revenue associated with the downtime for repairs.

Cold spray can increase corrosion resistance and limit cavitation damage caused by fast-moving water, like the cavitation damage shown in this close-up photo of a hydropower turbine. (Image by Kenneth Ross | Pacific Northwest National Laboratory)

REPAIR OF SPENT NUCLEAR FUEL STORAGE

An additional use for cold spray technology is the repair of spent nuclear fuel dry storage containers. PNNL researchers are investigating ways to use cold spray to make sure dry cask storage system canisters maintain their structural integrity beyond their originally intended licensing period. Cold spray allows coatings to be deposited and bonded to materials for added functions. Coatings can protect the environment or, in the case of ceramic coatings, create materials that can be used at higher temperatures than originally intended.



A schematic of the cold spray process. (Drawing by Hellen Jiang | Pacific Northwest National Laboratory)

Learn more about cold spray at PNNL

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Manufacturing a Cleaner Future

Reducing the carbon footprint of metals manufacturing

GREENER MANUFACTURING

Achieving a net-zero economy will require greener products from start to finish—including new, environmentally-conscious manufacturing methods. Pacific Northwest National Laboratory (PNNL) is advancing low-carbon manufacturing approaches that produce next-generation materials while dramatically reducing carbon emissions. Using solid-phase processing approaches, researchers are increasing throughput, reducing processing steps, and recycling scrap directly into products. From electric vehicle battery trays to aircraft hydraulic tubing, a cleaner tomorrow can be built using the materials and processes PNNL is developing today.

Pacific Northwest National Laboratory researchers are developing low-carbon manufacturing approaches for a greener future. (Photo by Andrea Starr | Pacific Northwest National Laboratory)

LOW-CARBON MANUFACTURING AT PNNL

Lowering carbon emissions during manufacturing is key to developing greener processes. PNNL-developed Shear Assisted Processing and Extrusion (ShAPE™) has been shown to efficiently extrude 100 percent recycled high-strength aluminum alloy 6063, reducing carbon emissions by up to 92 percent over the manufacturing lifecycle—from ore to final material. ShAPE also eliminates heating steps—speeding up the extrusion of high-strength aluminum alloy 7075 as much as 10 times. ShAPE is being used to directly produce high-performance steel alloys using less energy consumption than conventional manufacturing.

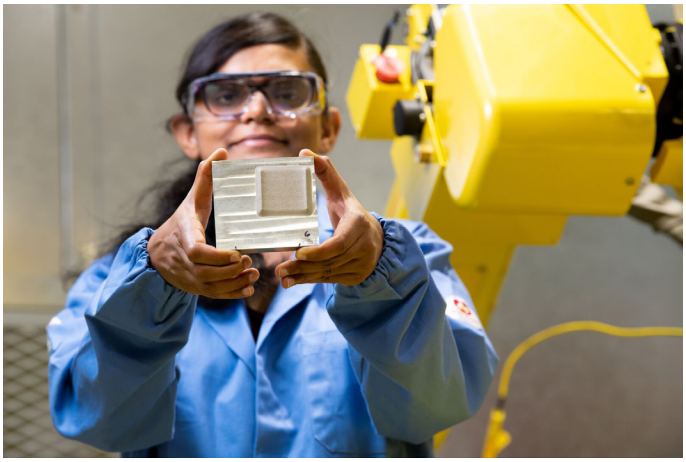
In addition to lowering direct emissions, reducing the carbon footprint of metals manufacturing involves reusing and recycling materials. PNNL is advancing manufacturing processes that can be used to limit material wear and tear to keep products usable for longer. Novel manufacturing approaches applied to existing technologies emit fewer greenhouse gases compared to conven-

tional alternatives and even recycle scrap metal into usable components—a method that's been licensed by the automotive industry.

FROM TRASH TO TREASURE

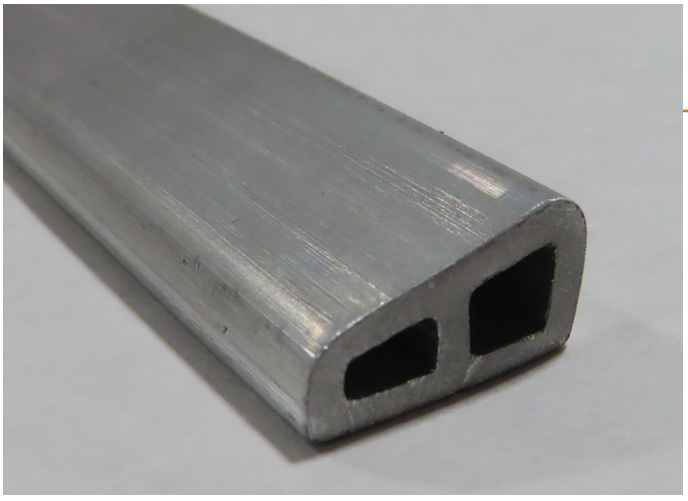
Recycling secondary scrap metal to produce material components uses less energy and lowers carbon emissions. That's why PNNL is partnering with Magna International to turn aluminum scrap into battery trays for electric vehicles using ShAPE.

With scrap aluminum trimmings reclaimed from Magna's manufacturing floor, PNNL demonstrated that ShAPE can extrude materials with similar configurations and mechanical properties as current automotive components. In fact, products extruded from scrap using ShAPE exceeded industry performance standards for virgin material. Now, PNNL researchers are exploring the use of less pure-scrap metal as feedstock because ShAPE-processed products can tolerate higher iron content than conventional extrusion products.



Low-carbon manufacturing methods developed at Pacific Northwest National Laboratory are being used to help repair and recycle materials, reducing the energy and emissions associated with manufacturing. Cold spray has been demonstrated to improve the durability of hydropower turbines. (Photo by Andrea Starr | Pacific Northwest National Laboratory)

This work was funded by the Department of Energy's Vehicles Technologies Office Lightweight Materials Consortium. ShAPE technology has been licensed to Magna for production of lightweight automotive components.



Low-carbon manufacturing processes developed at Pacific Northwest National Laboratory, including ShAPE, are being licensed by industry to produce greener automotive components like this non-circular extruded metal alloy that is approximately 1 inch in width. (Photo by Scott Whalen | Pacific Northwest National Laboratory)

Solid phase processing technologies available for licensing at PNNL

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