Quick Insight Brief:
Cold Spray Deposition Process

RESEARCH QUESTION

What applications exist in the current nuclear power station fleet or advanced reactor concepts, including small modular reactors and Generation IV reactors, that can benefit from cold spray processing?

KEY TAKEAWAYS

Cold spray is a unique metallic coating method that can potentially be used to preemptively mitigate or repair corrosion damage in high-value nuclear assets. The process can be incorporated into manufacturing operations during new component fabrication or used on legacy components to improve/extend service life.

KEY POINTS

- Cold spray uses supersonic particle velocities to deposit a dense layer of metallic powder on the surface of components.
- Low process temperatures permit the application of metals that are metallurgically difficult to apply with traditional means.
- Cold spray can be used for surface property modification (corrosion and/or wear resistance), repair, surface restoration, or refurbishment.
- Cold spray applications can be performed in a shop setting or in the field, giving the process applicability to new component fabrication or legacy component repair/modification.
- Cold spray systems are commercially available, and the process has been widely used by other industries.

WHAT IS COLD SPRAY?

Cold spray is a solid-state coating technology used to deposit metallic or composite powders onto a metallic substrate. Many terms have been used to identify cold spray processing technologies, including *cold gas dynamic spray, kinetic metallization,* and *supersonic particle deposition*. However, each of these synonymous terms describes the same underlying process. The cold spray process is schematically depicted in Figure 1. Microscale powder particles are accelerated to supersonic speeds through an electrically heated carrier gas stream and directed to a target substrate. The powder particles then collide with the target substrate or previously deposited powder and adhere to create a surface coating. Typical cold spray applications include property modification (such as corrosion resistance or wear resistance), repair, or surface restoration/refurbishment of metallic components [1].

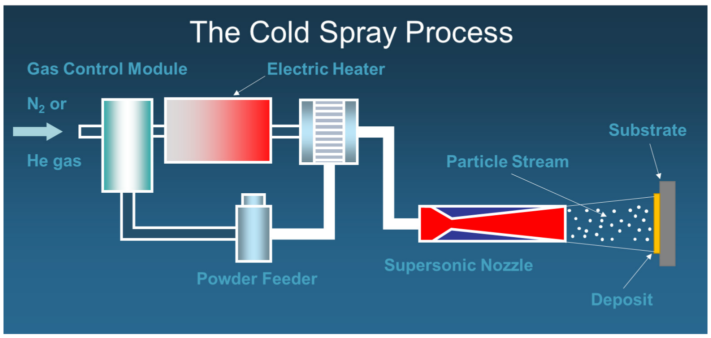

Figure 1. Schematic of the cold spray process
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ADVANTAGES OF THE COLD SPRAY PROCESS

A distinguishing feature of the cold spray process is that the powder particles never melt during application. This differs significantly from other metallic thermal spray coating techniques such as plasma or high-velocity oxygen fuel, where high process temperatures cause melting. The low process temperatures associated with cold spray offer the advantages of being able to apply coatings that are inherently temperature sensitive, limit substrate heating, and create dissimilar material combinations that are not metallurgically compatible through traditional means. Unlike other techniques that involve high process temperatures and melting (that is, weld cladding, high-temperature thermal spray processes, and so forth), no heat-affected zone forms within the substrate and no dilution occurs between the substrate and deposit materials. The low-temperature solid-state characteristic of cold spray also provides the added benefit of developing minimal, or even compressive, residual stresses in the coating and at the substrate surface reducing potential degradation mechanisms.

Cold spray deposits are generally highly dense (<1% porosity achievable) and exhibit excellent mechanical properties. Examples of atomized 304L stainless steel powder before application and a representative cold spray deposit cross section are shown in Figure 2. As can be seen, the 304L stainless steel deposit is highly dense and uniform in thickness. The bonding that is achieved during application is both mechanical and metallurgical in nature. The strength of cold spray deposits often exceeds that of comparable wrought materials, although ductility is often lower. Post-processing heat treatments can be used to restore ductility to the deposit; however, this is often unnecessary and depends on the final service requirements for the material.

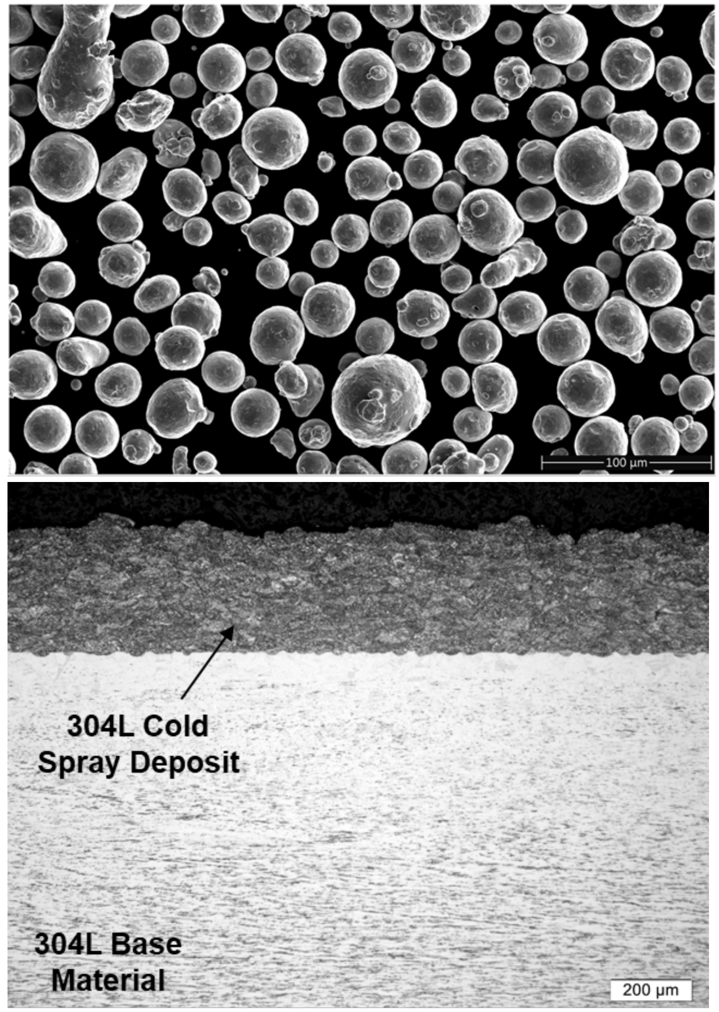

Figure 2. Stainless steel powder metal (top); cross section of 304L stainless steel cold spray deposit (bottom)

Another advantage of cold spray is the maturity of the process. Cold spray systems are commercially available from a variety of vendors spanning from automated robotic workstations in shop-based environments to field-deployable handheld solutions for manual operation. An example of a manual cold spray application is presented in Figure 3. Although the utilization of cold spray technologies has been widely adopted in other industrial sectors (particularly aeronautic and defense), applications within the nuclear power generation industry have been much more limited. Examples of successful applications outside the nuclear power generation industry include dimensional restoration of corroded, mechanically damaged, or worn Al components [2, 3]; corrosion protection and repair of Mg components [4, 5]; and repair of machining errors in cast Fe [1]. Many other application examples can be found by referencing the meeting materials from the Cold Spray Action Team workshops that have been held annually since 2011 [6].

Figure 3. Example of a manual cold spray application
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TECHNICAL CHALLENGES

As mentioned previously, some residual porosity can exist in cold spray deposits. The extent and interconnectivity of porosity must be considered for the given application. An example where residual porosity might be a concern is for metallic deposits that rely on surface passivity to maintain corrosion resistance in wetted environments. In this scenario, surface-connected porosity could serve as an occluded region where localized corrosion attack may occur. However, porosity can be minimized through the development of optimized processing parameters and/or by modifying the feedstock powder itself.

Additionally, much like other manufacturing processes that use powder metal feedstock (that is, laser powder bed fusion additive manufacturing, powder metallurgy and hot isostatic pressing, and so forth), care must be taken to ensure that the powder metal is of sufficient quality to achieve success. This encompasses factors such as powder size distribution, powder morphology, and propensity for oxidation that can influence powder flow characteristics, deposition efficiency, and properties of the final cold spray deposit. Manufacturer-to-manufacturer and heat-to-heat powder variability can cause a stable processing window to become unstable for a given alloy. Furthermore, care must be taken to properly handle and store the metal powders to prevent unwanted surface oxidation.

Surface preparation of the target component must also be addressed. The removal of surface oil, grease, oxides, and other surface contaminants is necessary to maximize surface adhesion during cold spray. This is often achieved by mechanical preparation—that is, surface grinding or grit blasting—of the target substrate immediately prior to cold spray application. Care must be taken to ensure that grinding or blasting media are not embedded in the substrate surface. It is generally recommended to use new abrasives or blasting media to avoid surface contamination from previous cleaning operations.

Special tooling and delivery systems must be developed for scenarios where accessibility is limited. The success of the cold spray process is reliant upon heating and accelerating the powder particles to a temperature and velocity that is favorable for particle adhesion. Customized equipment designs will be necessary in tight spaces where a traditional cold spray nozzle cannot be used or an appropriate standoff distance is unobtainable and in scenarios where the cold spray nozzle is exceptionally far from the heating and powder feeding units.

Lastly, powder containment and cleanup during a cold spray application must be considered. The deposition efficiency of the cold spray process is less than 100%, and not all powder particles will adhere to the target substrate. In a controlled manufacturing environment, this can be managed by performing cold spray applications on a downdraft table or by using a vacuum system to collect dust and powder particles that are generated. Applications outside a controlled manufacturing environment require a dust and powder collection strategy to prevent contamination of the build and surrounding environment.

EMERGING COLD SPRAY TECHNOLOGIES

Extended Storage of Spent Nuclear Fuel

Recent inspection developments for dry cask storage systems have prompted a need for repair and mitigation technologies for stainless steel spent nuclear fuel canisters [7]. A concern exists regarding chloride-induced degradation of the canisters during extended storage conditions. Cold spray is currently being explored as a potential solution to mitigate or repair these structures [8]. The cold spray process is capable of remotely delivering a thin corrosion resistant metallic coating at a low temperature. Furthermore, the deposited corrosion resistant coating can improve the residual stress profile on the outer diameter of the canister where corrosion may occur. Current efforts are focused on assessing candidate alloys (304L, 316L, 625, CP Ni, and so forth), process development, quantifying the corrosion resistance of cold spray deposits, and developing remote delivery techniques. This is a highly collaborative research area with active engagement with many utility, industry, national laboratory, and university partners. EPRI's Welding and Repair Technology Center (WRTC) Program and the Extended Storage Collaboration Program (ESCP) are actively engaged in this effort.

NEUP/EPRI Collaboration for Cold Spray Evaluation

EPRI's WRTC Program and ESCP are engaged with universities around the United States that are investigating candidate repair processes for spent nuclear fuel canisters. The participating universities, in collaboration with vendor and national laboratory partners, are funded through the U.S. Department of Energy's Nuclear Energy University Program (NEUP). Many of the universities are investigating cold spray technologies as a part of their efforts. Evaluations include pitting and stress corrosion cracking resistance of cold spray deposits, residual stress evolution of cold spray deposits over corrosion-susceptible materials, metallurgical characterization, and feasibility assessments for repairs. EPRI's role in these collaborations is to provide technical feedback, encourage industrial relevance, foster collaboration among the participating university teams, and offer a conduit between researchers and industry.

Residual Stress Modification of Weldments

One of the most intriguing characteristics of cold spray is that it can be used to locally modify the residual stress distribution of a component. Thick-section weldments generally contain relatively high residual tensile stresses in the weld metal and heat-affected zones following fabrication. If left in this condition, the weld-induced tensile stresses can serve as a mechanical driving force for stress corrosion crack propagation in wetted components. Efforts are currently underway to understand how cold spray could be used to locally modify the residual stress distribution of nuclear weldments. An example is provided in Figure 4, where residual stresses within a high restraint gas tungsten arc weld mockup have been characterized before and after cold spray. As can be seen, the residual stress fields at the top surface of the mockup shift from highly tensile in an as-welded condition to compressive following cold spray application. It is believed that the cold spray technique could be used to preemptively mitigate stress corrosion cracking through residual stress modification during component fabrication or be applied to in-service components. EPRI's WRTC Program is currently leading this research effort for weldments in nuclear components.

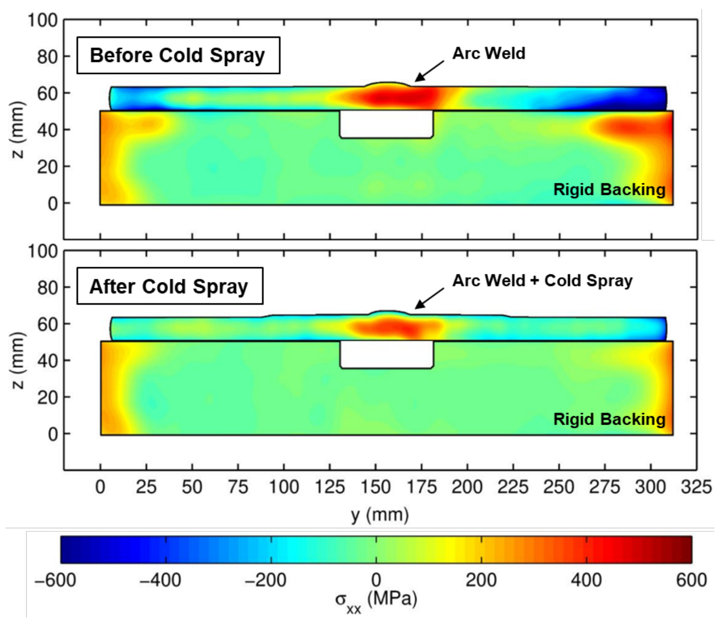

Figure 4. Residual stress measurements from a high restraint arc weld mockup (304L base material, 308L filler material) before and after the application of a 304L cold spray deposit

NEXT STEPS/ONGOING EPRI WORK

The nuclear power generation industry is in the early stages of extending the cold spray process into the areas of component manufacturing, mitigation, and repair. Extensive experience in other industrial sectors has built the technical basis for cold spray and provides an opportunity to adopt this emerging technology to address specific challenges in the nuclear industry. Current and near-term efforts for cold spray should focus on identifying candidate application areas, characterizing and optimizing deposits that are relevant to nuclear environments, and performance demonstrations.

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Advanced Nuclear Technology

Note

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