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EFFECTS OF COLD SPRAY REPAIRS ON THE MECHANICAL PROPERTIES OF A COMPONENT

EXECUTIVE SUMMARY

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Project Summary
Cold dynamic gas spray, better known as cold spray, has generated much interest for repairing metallic components and depositing protective metal coatings. Naval shipyards recognize the potential of this technology to provide rapid repair and manufacturing capability and to replace welding as the state-of-the-art for metal joining and repairs. As cold spray evolves into a mature technology, there is a need to understand the mechanical behavior of widely used engineering alloys such as the cupronickel alloys. This study investigates the mechanical behavior of Cu-38Ni coatings cold sprayed onto Cu-10Ni substrates with and without an annealing heat treatment. The cold sprayed coated specimens undergo uniaxial tensile tests to study the durability of the cold sprayed coating layer and its effects on the overall mechanical behavior of the coated substrate. Annealing at 650 °C is found to enhance both the ductility and strength of the coating material. The annealed coating specimen experiences an elongation to failure of ~13.7%, while the as-sprayed specimen only experienced ~3.9% elongation. Adhesion tests show that annealing leads to a large increase in adhesion strength of the coating to the substrate due to solid state diffusion across the interface during the heat treatment. Annealing further leads to a reduction in pores, intersplat cracks and porosity, and a more ductile and tough material due to recrystallized grains. Nanoindentation reveals that the cold as-sprayed material is the hardest, but also the most brittle, exhibiting plasticity of only 81%, as compared to 89-90% for the annealed coating and the substrates.

Keywords: *cold spray, heat treatment, copper nickel, protection, repair*

Background
The Navy is interested in developing and implementing technologies that can be used for repair and protection operations at the site of need, such as naval shipyards or ships at sea. Cold spray is an emerging technology utilizing relatively low temperatures (compared to welding and other conventional metal working techniques) to deposit metallic deposits or coatings. The process requires a metallic feedstock (e.g., metallic powder particulates) and a high pressure gas to accelerate the metallic particulates to supersonic speeds, which enables them to impact the surface with sufficient kinetic energy to adhere onto the material and form a continuous deposit, layer by layer. Such coatings can be used to provide protection from wear and corrosion. Similarly, cold sprayed deposits can be used in the same manner as conventional welds, to repair and join metallic structures. Welded deposits often cause damage to the underlying metal. The relatively low temperatures used in cold spray allows temperature sensitive substrates (e.g., steel, magnesium, Cu-Ni alloys) to be sprayed without damage to the substrate. The cold sprayed deposits themselves exhibit excellent mechanical properties because of the strengthening imparted by the severe plastic deformation (i.e., work hardening) that the metallic powder particulates undergo during the deposition process.

However, what is still poorly understood is the nature of interfacial strength of the cold sprayed coating with the substrate and any possible effects (e.g., residual stresses, localized hardening) on the substrate material. Furthermore, while cold sprayed deposits often possess good strength, without additional heat treatments, they may have insufficient or even poor ductility. If a substrate has sufficient ductility to undergo a graceful failure, it would be desirable for the coating not to fail at such a critical point. As such, the cold sprayed coating should have good ductility as well. The mechanical behavior of load bearing components with relatively thick cold sprayed deposits (300-700 μm) is still largely unexplored but critical to transitioning cold spray repairs onto the structural and load bearing arena. The objective of this study is to quantify the adhesion strength of cold sprayed Cu-Ni coatings on Cu-Ni substrates and investigate the effects of the cold sprayed deposits on the tensile strength and fatigue resistance of Cu-Ni.

This work investigated the mechanical behavior of Cu-38Ni coatings that were cold sprayed onto Cu-10Ni substrates and evaluated their mechanical behavior in the as-sprayed state, as well as after an annealing heat treatment. In this study the tensile mechanical behavior of a Cu-38Ni coating was evaluated, where the coating was about 9% of the substrate thickness. This type of test is more realistic to the actual application of cold spray, where a coating or cladding layer would be deposited on an existing substrate being repaired. Most studies to analyze the tensile strength of cold sprayed coatings have been on stand-alone coatings that are less likely to be representative of the actual conditions in which cold spray will be used.

Findings and Conclusions

Annealing was able to endow the coating with both enhanced ductility and strength. The heat treatment induced solid-state diffusion within the coating that reduced porosity and bridged intersplat cracks and pores, thereby enhancing strength. At the interface, diffusion between the substrate and coating was evident ,and this led to a large increase in coating adhesion strength, from ~17 MPa to beyond ~46 MPa, the limit of the adhesive used. Annealing led to the expected increase in ductility and evidence of finer recrystallized sub-grain structures within splats was observed via optical and scanning electron microscopy. Nanoindentation studies confirmed that the annealed coating experienced 89% plastic deformation (on par with substrate), in contrast to only 81% plastic for the as-sprayed coating. The elongation of the coating at failure increased by over a factor of three, from ~3.9% to ~13.7%. This enabled the annealed coating to survive well beyond the yield strength of the coated substrate. This is a critical benchmark for utilizing cold spray coatings in a structural application as it ensures the coating would be able to participate in load bearing and undergo plastic deformation prior to failing. In practice, most structural design is based on never reaching the yield strength and hence survival of the coating past the yield point of the substrate is critical.

These findings provide two critical pieces of information for the implementation of cold sprayed coatings for use in structural repairs: 1) cold sprayed Cu-Ni coatings can be robust enough to survive past the yield stress of a Cu-Ni substrate, and 2) heat treatments can be utilized to enhance adhesion, tensile strength, and ductility of cold sprayed coatings. Cu-Ni is widely used on shipboard components such as pipes and heat exchangers. These parts typically have minimal requirements for tensile yield strength. The current findings show that cold spray could be used to repair failed Cu-Ni parts without compromising the tensile strength properties of the substrate. In fact, a Cu-Ni coating could be sprayed with nitrogen, which is much cheaper than helium, and heat treated to ensure it will not fail prior to the yield point. The heat treatment process would be limited only by the size of the component to be repaired and the corresponding size of the furnace at the shipyard. It is hence recommended that Cu-Ni parts repaired using cold spray be heat treated if the parts are load bearing or otherwise have minimal tensile strength requirements.

Recommendations for Further Research

Future studies may consider the use of helium as carrier gas (nitrogen was used in this study). The use of helium could further improve the as-sprayed coating's mechanical behavior as the coating particles would possess more energy to enhance metallurgical bonding. This might be a viable alternative to heat treatment, which constrains in-field applications due to the need to place the component in a controlled and enclosed furnace environment. Future studies should consider alternate spray parameters to achieve desired thick coating in one pass or resolve porosity between layers. Future studies should investigate other ways to enhance the adhesion, tensile strength, and ductility of cold sprayed Cu-Ni, such as by utilizing secondary reinforcements to yield a composite coating. Lastly, future studies are needed to investigate the fatigue performance of both the as-sprayed coating and the heat treated coatings.