IDEA

Innovations Deserving
Exploratory Analysis Programs

NCHRP IDEA Program

Stainless Steel Coated Rebar for Chloride Resistant Concrete Highway and Bridges

Final Report for
NCHRP IDEA Project 240

Prepared by:
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NATIONAL ACADEMIES Sciences Engineering Medicine

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- The Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).

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IDEA Project NCHRP-240

Prepared for

The NCHRP IDEA Program
Transportation Research Board
National Academies of Sciences, Engineering, and Medicine

by

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Allium Engineering, Inc.

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Prof. Michael Short	**Massachusetts Institute of Technology**
Mr. Michael Sock	**Rhode Island Department of Transportation**
Mr. Gary Figgallo	**Durisol US**
Dr. Timothy Barrett	**Federal Highway Administration**
Mr. Jim Wild	**Vermont Agency of Transportation**

The project team would like to acknowledge the excitement the panel has had in helping navigate the project.

Glossary

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BCC	Body-Centered Cubic
CRSI	Concrete Reinforcing Steel Institute
DOT	Department of Transportation
EDX	Energy-dispersive X-ray Spectroscopy
FCC	Face-Centered Cubic
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
LCC	Life Cycle Cost
SEM	Scanning Electron Microscope
VDOT	Virginia Department of Transportation

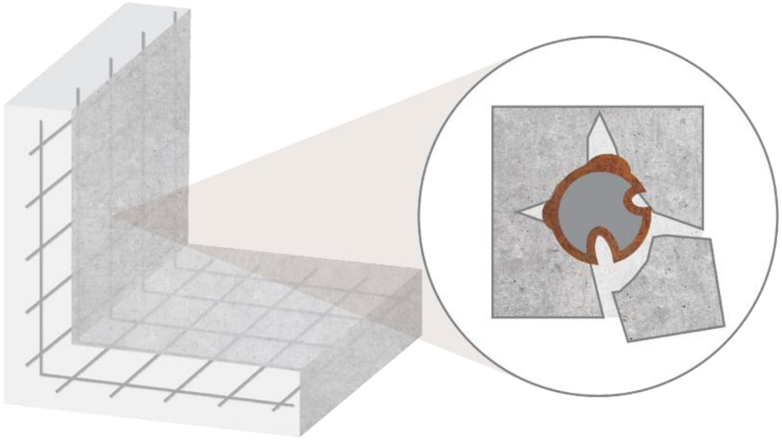
EXECUTIVE SUMMARY

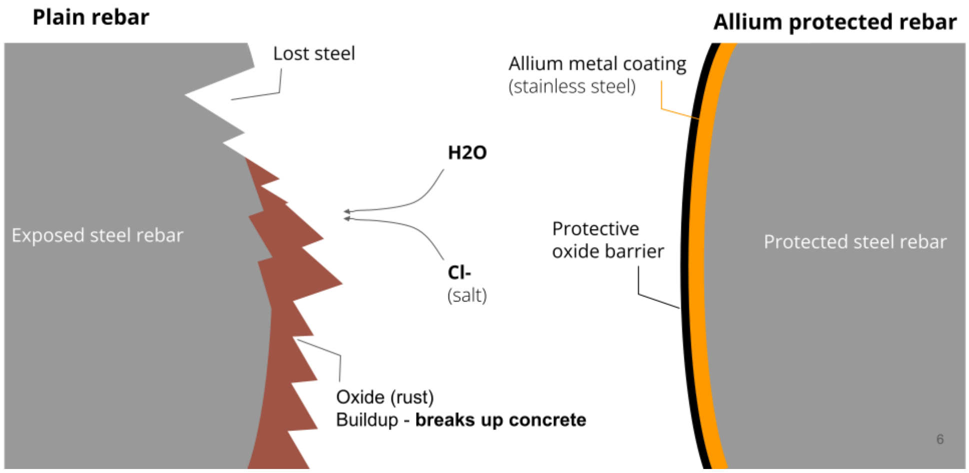
This NCHRP IDEA project focused on a novel material approach to solving the reinforcement corrosion problem, using a stainless steel coating to create a metallic multilayer composite steel bar which is highly cost-effective and corrosion resistant. By providing a solution to the rebar corrosion problem, this concept has the ability to enable transportation infrastructure to last for 100 years or longer in corrosive environments. The resulting IDEA product is a refined reinforcement bar and manufacturing process which can integrate with existing steelmaking processes and create a composite bar with four-times greater corrosion resistance than conventional rebar. At the end of the project, a 1500-pound batch of stainless coated reinforcement was produced, indicating that this process has meaningful scalability to serve transportation infrastructure projects.

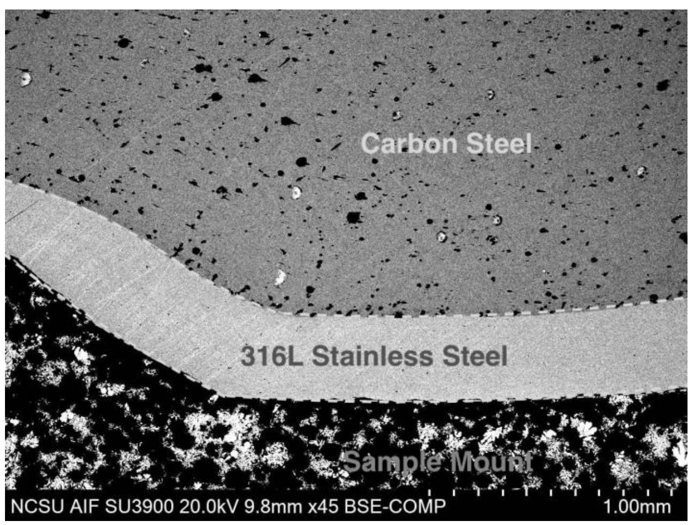
In addition to being much more corrosion resistant than conventional steel rebar, testing throughout the course of this project demonstrated that the stainless coated rebar can be bent just like conventional rebar without cracking or breaking off. It is also highly durable, and testing during the course of this project demonstrated much more resistance to damage from impact than conventional coating technologies such as fusion bonded epoxy coating which is beneficial to the contractors utilizing this material in the field. In addition, it was also demonstrated over the course of this project that the coating does not have any negative impact on the bond strength between the rebar and concrete.

If this IDEA is successfully commercialized, it has the potential to provide the transportation industry with a cost-effective solution to the rebar corrosion problem which would lead to roads, bridges, tunnels, and other structures to have significantly longer lifetimes, while also being more safe, sustainable, and affordable to maintain. Because this product can be produced with methods that can integrate into the existing process for making steel rebar, this technology has potential to be rapidly scaled. This IDEA product serves as a drop-in replacement for conventional uncoated or epoxy-coated rebar to drastically enhance the performance of transportation infrastructure.

Along with the technical development enabled by this project, over the course of this IDEA project significant progress has been made in commercializing the technology. First of all, a strong relationship with a major steel producer has been formed which enabled the production of a pilot batch of the IDEA product. Second, a strong relationship has also been formed with a rebar fabricator who can provide user feedback as well as a distribution channel once production is scaled up. Finally, the initial market within Virginia transportation projects has been identified and there is a clear market need for this technology and IDEA product.







Executive Summary Figures: (top) diagram of macroscale rebar corrosion degradation (middle) diagram of microscale rebar corrosion (bottom) microscope image of material resulting from this research project.

IDEA PRODUCT

The resulting product from this NCHRP IDEA project is a new type of steel reinforcing bar (rebar) material in which the external surface of the bar is composed of corrosion-resistant stainless steel while the bar core is composed of the low-cost carbon steel which makes up conventional rebar. There is a distinct metallurgical bond between the stainless outer layer and the carbon steel core, which allows the bar to be bent without cracking or delamination of the outer cladding layer. This new product can serve as a drop-in replacement for conventional reinforcement such as black rebar or epoxy-coated rebar, and enable reinforced concrete structures to experience far longer operational lifetimes (100-200 years) than those with conventional reinforcement (50 years). This product will also be cost-effective since the majority of the volume of the bar remains low-cost carbon steel, and is expected to be cost-competitive with other methods such as galvanization once the product is commercialized at scale. This IDEA product can greatly improve the safety, longevity, and durability of transportation infrastructure such as roads, bridges, and tunnels. Transportation infrastructure which utilizes this IDEA product is not only expected to achieve a much longer operational lifetime, but also incur much lower lifetime costs related to maintenance and repair as well. In addition, for infrastructure in near-coastal areas, usage of this IDEA product will enhance the durability and resiliency of this infrastructure to the effects of climate change.

Concept and Innovation

The use of reinforcing steel within concrete to create reinforced concrete is pivotal as it imparts tensile strength to concrete which would otherwise be very strong in compression but very weak and prone to cracking in tension. Because reinforced concrete has the ability to sustain significant tensile and compressive stresses while being very low cost, reinforced concrete is by far the most popular structural material in the world and forms the basis for the vast majority of critical transportation infrastructure such as highways, bridges, and tunnels. Steel reinforcement is in many ways the basis of this transportation infrastructure. Yet, the corrosion-driven degradation of this steel reinforcement is also the primary factor which limits the lifetime of reinforced concrete structures to several decades. When steel undergoes corrosion, metal oxide corrosion products form at the surface of the bar and cause a significant volumetric expansion, which creates internal stresses within the concrete and eventually leads to widespread cracking and spalling of concrete where entire pieces of concrete become detached. Finding a cost-effective solution to this steel corrosion challenge could lead to vastly improved infrastructure safety, durability, and longevity while also drastically reducing the life-cycle cost (LCC) of transportation infrastructure due to lower maintenance and repair.

The fundamental innovation, which was further refined during the course of this project, involves the use of a corrosion-resistant stainless steel coating or cladding applied to the outer layer of the rebar to form a metallic multilayer composite steel reinforcement bar, which should in principle have greatly improved corrosion resistance compared to conventional rebar while being cost-effective as it is only applied to the outer layer of material. The stainless steel outer layer contains elements such as Cr which have the ability to form passivating nanoscale oxide films, such as Cr_2O_3, under corrosive conditions and drastically reduce corrosion. Because the corrosion-resistant outer metal layer is a metallic material with significant toughness, the durability of the bar to damage is much higher than for organic coatings such as epoxy. This is a major benefit as rebar undergoes significant wear-and-tear just during transportation via rail and flatbed trucks as well as during handling on construction job sites.

The innovation includes not just the final product itself and its application in concrete reinforcing, but also the manufacturing approach being implemented in order to make the product. This manufacturing approach was refined significantly over the course of the project. The initial manufacturing concept explored within the scope of this project utilized cold spray as the method of applying the stainless steel coating to the finished rebar. By the conclusion of the project, it was concluded that a more advantageous approach to manufacturing is to apply the stainless steel coating to a steel billet which is then reheated and hot rolled into the finished rebar product. This approach not only has technical benefits for the final product performance, but also provides a more simple, less capital-intensive pathway to establish and scale-up commercial production of the IDEA product. A key aspect of this innovation is that it is designed to directly integrate with current established steel mill processes to allow production to scale rapidly.

In principle, this innovation should be easy for the construction industry to adopt once further development and production scale-up is achieved. The product can be specified through an American Association of State Highway and Transportation Officials (AASHTO) performance specification, and in the future it is intended that an American Society for Testing and Materials (ASTM) performance specification will be established as well. Once a network of fabricators and distributors is established, transportation agencies will be able to specify this innovative product in their construction projects. It is expected that at-scale this IDEA product will be highly cost-effective, increasing the upfront costs of a given construction project by 1-2% but drastically reducing the life cycle costs and increasing the operational value of the project.

INVESTIGATION

INITIAL PROTOTYPING

The first step in the project was to conduct prototype manufacturing to validate the coating application approach and address initial issues with the method of production for the IDEA product. For the initial prototype manufacturing conducted in this project, cold spray was used to apply a stainless steel coating onto a carbon steel rebar substrate. For the initial prototyping, several possible stainless steel grades were used for the coating material. In the first set of coating trials, 430 stainless steel with a body-centered cubic (BCC) crystal structure, and 316 stainless steel with a face-centered cubic (FCC) crystal structure were used as the coating materials.

430SS Cold Sprayed Rebar

316SS Cold Sprayed Rebar

Figure 1 Photographs of the first cold spray prototypes produced in this project.

Salt spray testing according to ASTM B117 was used to rapidly assess the corrosion performance of the prototypes. It should be noted that the corrosive environment in ASTM B117 is much more aggressive than the environment within concrete, so the test is not totally reflective of the target service environment but the test does give very rapid feedback regarding corrosion performance. The corrosion performance can be assessed qualitatively using visual inspection of the samples over time, and quantitatively using a mass loss measurement approach following oxide stripping from the corroded specimens. The 316-coated rebar showed a 38% reduction in the corrosion rate compared to black bar, while 430-coated rebar showed a 16% reduction in corrosion rate compared to black bar. A plot of the corrosion performance quantified using the mass loss rate is shown in FIGURE 2, and photographs of the test specimens at different time points within the salt spray test are shown in FIGURE 3. Although these results provided a promising initial proof of concept, the corrosion performance was not as good as expected and indicated room for improvement in the coating process itself. So, effort was made to develop an improved coating process with better corrosion performance.

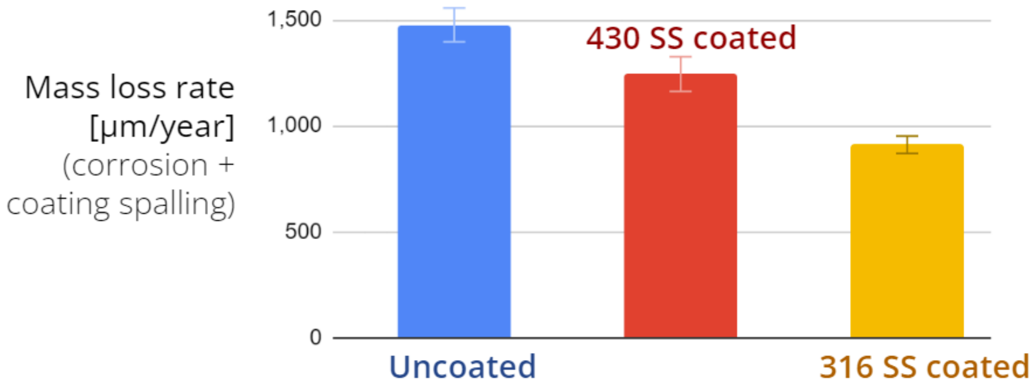
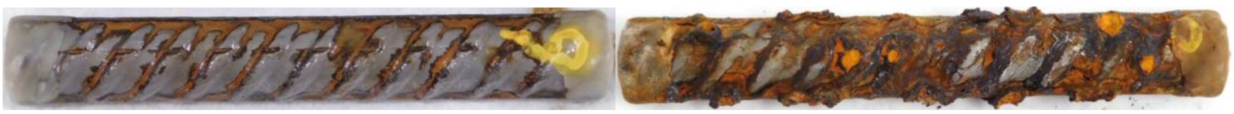


FIGURE 2 Average corrosion rate of different test specimens with error bars indicating uncertainty from 3 measurements. Note that the corrosion rates of the coated bars are inflated by delamination and spalling of the coating itself.

316SS Cold Spray

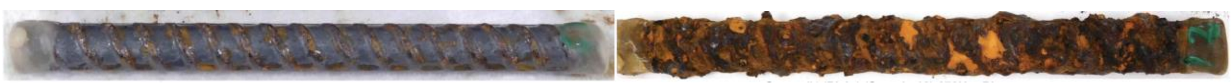
9 hours **672 hours**

430SS Cold Spray



9 hours **672 hours**

Plain Carbon Steel



9 hours **672 hours**

FIGURE 3 Photographs of cold spray coated rebar samples after 9 hours (left) and 672 hours (right) of salt spray testing (ASTM B117). Note the corrosion attack emanating out from the top and bottom ridges of the coated rebar.

COLD SPRAY COATING PROCESS DEVELOPMENT

The first step in improving the cold spray coating process was to revisit the surface preparation procedure. Micrographs revealed some oxide present underneath the stainless steel coating, indicating cleaning the rebar with a metal wire brush before cold spray coating was insufficient, so grit blasting was explored as an alternative for surface preparation. Grit blasting was shown to be a much better method for pre-coating surface preparation. In addition to surface preparation, the spray process path was also revisited. In the 9 hour salt spray test images shown on the left side of FIGURE 3, it is apparent that the initial corrosive attack begins along the ridge running along the length of the bar as well as one side of the diagonal rib deformations. This indicates that the coating is not achieving sufficient bonding or coverage at these locations. So, instead of rotating the bar, the sprayer was moved along the length without rotation during spray, sequentially covering the surface of the bar. In addition to eliminating rotation of the bar during the spray process, the nozzle was oriented at an angle relative to the surface of the bar (roughly 20 degree tilt) in order to properly spray the surface features (the ridges and ribs). After one angled pass along the length of the bar, the nozzle was tilted in the other direction and moved along the same track along the length of the bar to ensure symmetric coverage.

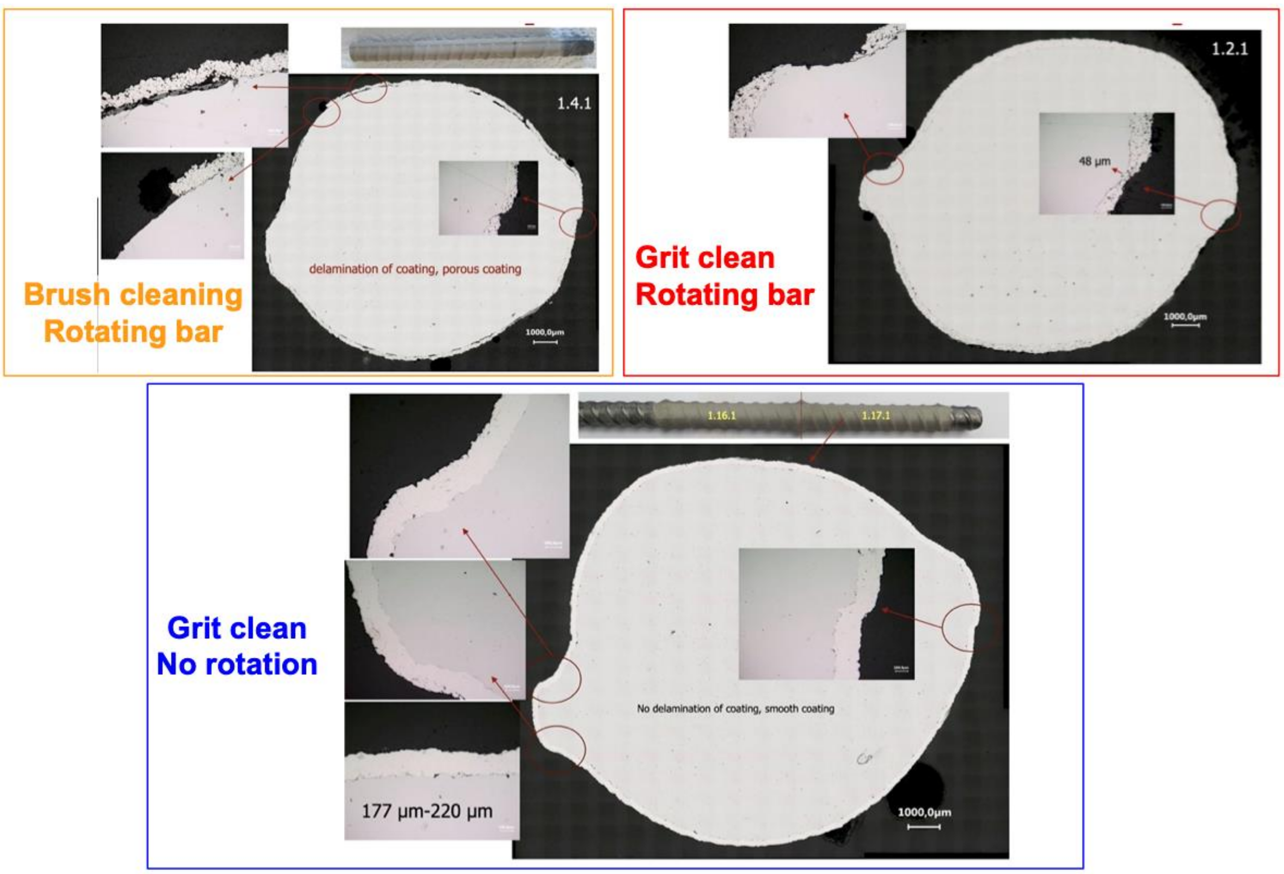


FIGURE 4 Optical micrographs of coated rebar under different spray process conditions

Following the second round of improved prototyping, salt spray testing was conducted on 316 coated rebar in order to understand the influence of the improved spray coating process on corrosion performance.

The rebar coated with the improved cold spray process using 316 produced roughly ¼ the corrosion of black rebar, corresponding to a 4x increase in the expected lifetime in comparison to black rebar. This corrosion rate is superior to ChromX (ASTM 1035), a high-price, high-Cr alloy steel. This demonstrates that the improved coating process leads to greatly improved corrosion resistance.

During the second round of prototyping during the cold spray coating process development and improvement, attempts were made to also use 2205 stainless steel powder as a coating material. Powder was purchased to achieve this goal, but unfortunately significant powder quality challenges were encountered. This was a major lesson learned as part of the project and will be discussed in the following section.

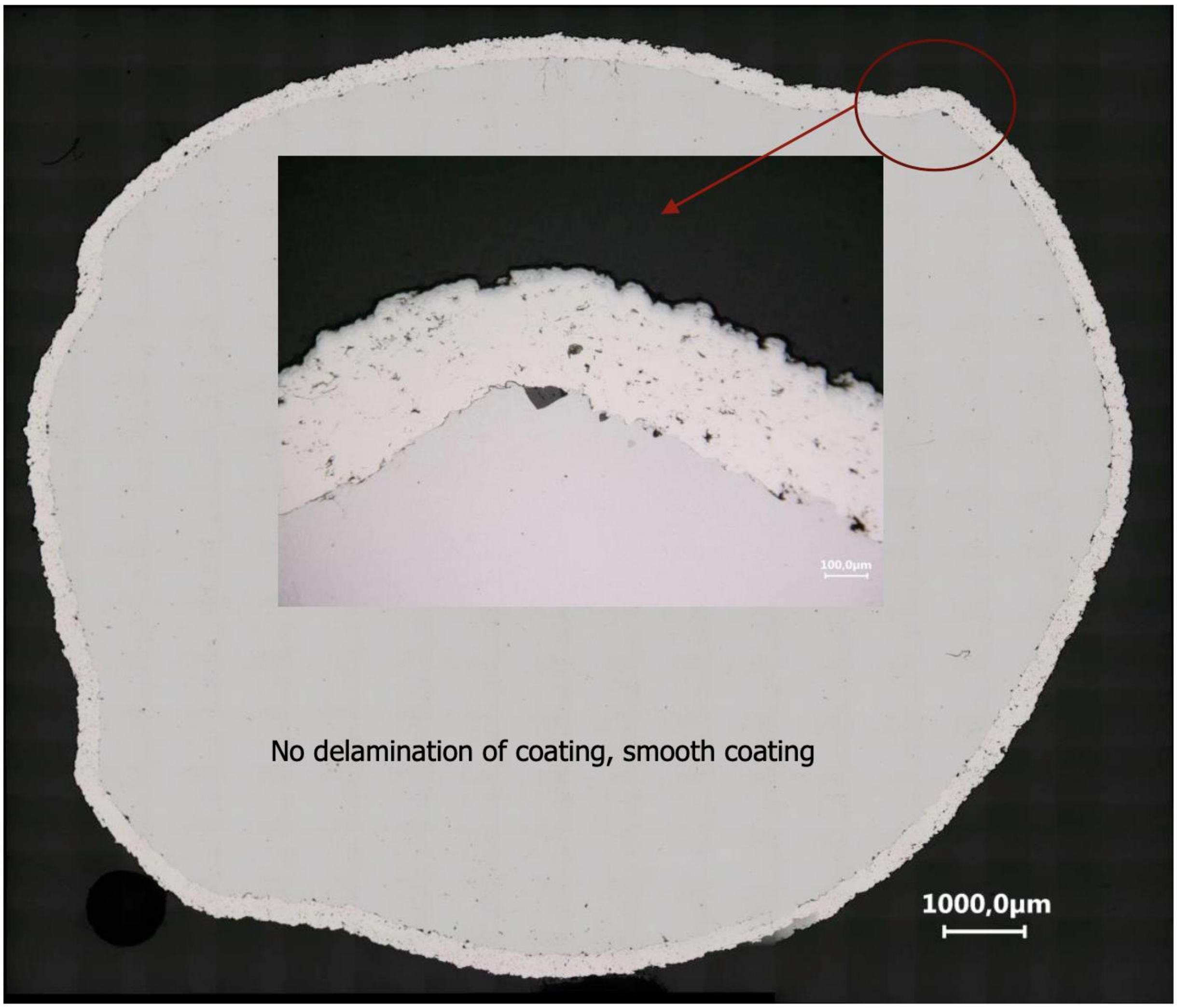


FIGURE 5 optical micrograph of rebar coated using the improved cold spray process. The coating fully covers the surface with a dense, continuous coating. In this case, there is a slight degree of porosity in the coating likely due to the water atomization process used to make the coating powder.

Coating Powder Quality Control

In order to initiate prototype manufacturing of a 2205 stainless steel cold spray coated rebar, powder was purchased online labeled as “S220” which had a nominal composition listed online which matches 2205, and had a listed particle-size distribution sufficient for cold spray coating. Powder was purchased and sent directly to the development partner conducting the cold spray coating under the implicit assumption that the information provided by the vendor was valid and trustworthy. After receiving the cold spray coated rebars and conducting salt spray testing, scanning electron microscopy (SEM) was conducted on some of the samples. This is when irregularities were identified using composition analysis of the coating, and it was concluded by further investigation of several powders provided by the same powder supplier that the actual composition was more consistent with 316 stainless steel. Two different powder batches with different particle size distributions were purchased and both batches had compositions consistent with 316 stainless steel. SEM and energy-dispersive X-ray (EDX) chemical composition analysis of the powder received from the supplier are shown in FIGURE 6:

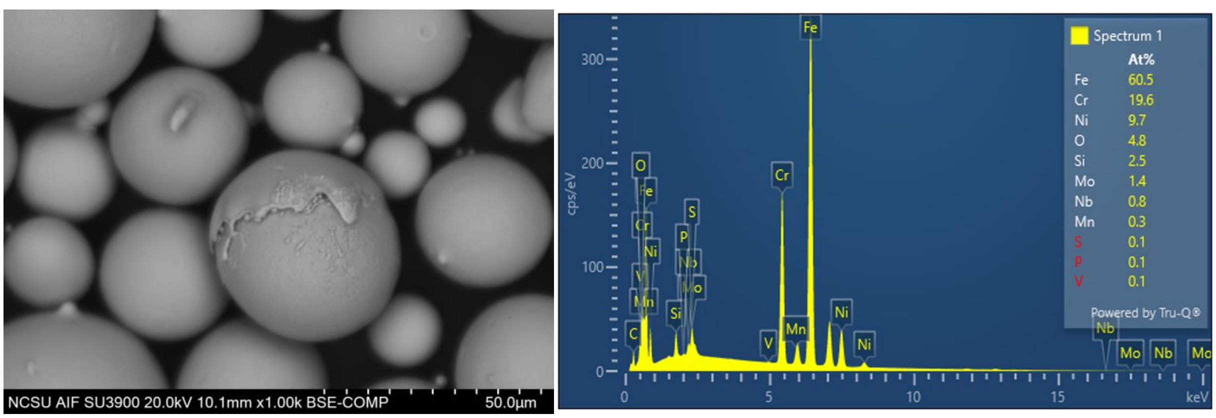


FIGURE 6 (Left) Scanning electron micrograph of S220 powder purchased (Right) EDX results showing the chemical composition of the powder, showing Cr and Mo content too low and Ni content too high to be consistent with 2205 stainless steel.

This challenge necessitated the development of stricter quality control measures internally, and identification of different powder suppliers. Ultimately, there was not a sufficient source identified for 2205 powder, but a significant quantity of 2507 stainless steel powder was purchased, which has a similar composition to 2205 but with slightly higher Cr, Ni, and Mo concentrations. This powder was purchased from Sandvik Osprey based in the United Kingdom and much more robust quality assurance documentation was provided, although based on the previous experience the powder was still verified internally.

Stainless Steel Coating Composition

During the first stage of the project, several different coating compositions were explored. Due to some of the powder quality control challenges mentioned in the previous section, the coatings ultimately used were adjusted slightly, but significant conclusions can still be drawn from this work. The essential idea of the different coating grades which were selected for this work was to understand the possible effect of different crystal structures as well as the effect of chemical composition and the presence of molybdenum in the coating alloy for this application. Shown below in TABLE 1 is the general concept of the different types of coatings explored, and then in TABLE 2 the commercial grades initially intended are shown. Finally, in TABLE 3 the coating grades which were actually used during the course of the project are shown.

TABLE 1 Matrix of stainless steels based on crystal structure and Mo content

Austenitic, No Molybdenum	Ferritic or Duplex, No Molybdenum
Austenitic, Contains Molybdenum	Ferritic or Duplex, Contains Molybdenum

TABLE 2 Matrix of stainless steels grades originally intended for this project

304	430
316	2205

TABLE 3 Matrix of stainless steels grades actually used in this project for cold spray coating

304	430
316	2507

The high-level result of the investigation into the effect of coating composition within this project is that the composition of the coating is not the only important factor for corrosion performance but also the coating microstructure itself which is a complex function of powder morphology, cold spray coating process parameters, etc. Furthermore, heat treatment after cold spray coating can significantly improve the corrosion performance as shown in FIGURE 7, indicating that indeed microstructure of the coating is likely equally as important for corrosion performance as the composition of the coating itself.

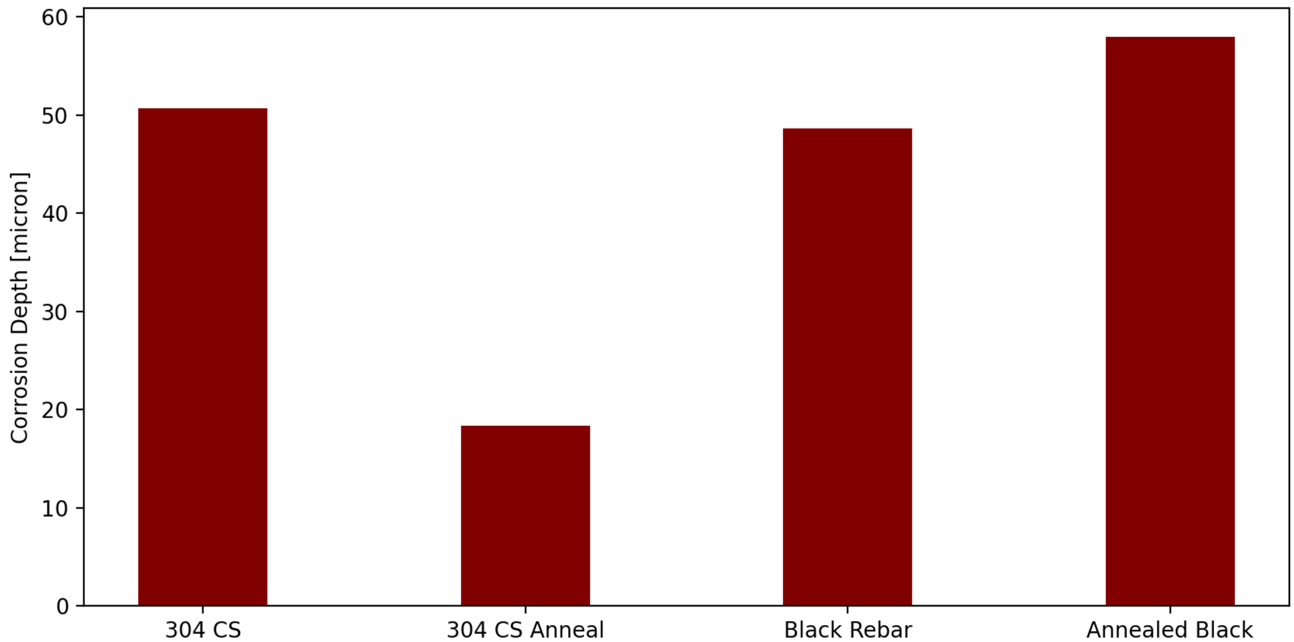


FIGURE 7 Corrosion depth from salt spray testing of cold sprayed 304 stainless steel. In the as-sprayed condition the performance is comparable to black rebar while the coating corrosion resistance significantly improves after annealing for 1 hour at 1100^{o}C.

REBAR BEND TESTING AND DEVELOPMENT

One of the most important characteristics of any solution to the rebar corrosion challenge is the ability of the rebar to bend without the corrosion solution cracking or undergoing delamination. Rebar is frequently bent up to 180 degrees during the fabrication process and on job sites. The ability of the stainless steel cladding to hold up, maintain corrosion protection, and not crack and delaminate from the core is a necessary outcome for large scale adoption of this technology. It is noteworthy that epoxy-coating, hot dip galvanization, and glass-fiber reinforced polymer (GFRP) rebars all have potential problems in bending.

Bend testing was conducted using an electric rebar bender with bending pin diameters in compliance with relevant ASTM and CRSI standards.The bendability of the coated rebar is directly related to the ductility of the cold spray coating. The cold spray process is known to significantly reduce the ductility of sprayed materials, especially for steels, so this is a major concern in our product development. The results quickly demonstrated that for all stainless steel cold spray coatings tested in this project, in the as-sprayed condition they were extremely brittle and prone to cracking during rebar bending. In the field, rebar is often bent during the fabrication process, so solving this challenge was an important goal for this project.

FIGURE 8 430-coated rebar after 90 degree bend test showing periodic cracking along the diagonal ribs (left) and along the long ridge of the rebar (right). The results indicate minimal coating ductility in the as-sprayed state.

In order to address the bending failure demonstrated above, thermal treatment was developed in order to restore ductility to the coating. Cold sprayed bars were annealed for 1 hour at **1100^{o}C** followed by water quenching to rapidly cool the bars, followed by tempering for 1 hour at 600^{o}**C**. It should be noted that the initial annealing step allows the cold spray coating to recover ductility, while the quenching and tempering is performed only to achieve the original strength and ductility of the underlying black rebar substrate . This annealing-quenching-tempering thermal treatment proved effective in restoring sufficient ductility to the coating to allow rebar bending without cracking of the coating, as demonstrated in **Figure 9**.

FIGURE 9 S220 coated and thermally treated rebar after 90 degree bend testing. Note that the slight dark discoloration is due to high temperature oxidation during the thermal treatment. The bar is able to bend without any perceivable cracking in the coating.

Another question which was raised by the IDEA advisor Dr. Parkany concerned the effect of bending itself on the corrosion resistance of the cold spray coated bars. Bars were bent using different mandrel sizes after annealing the cold spray coated bars using the anneal-quench-temper procedure previously described. The larger mandrel size, 5 inch diameter, represents a less severe bend while the smaller mandrel size, 2 inch diameter, represents a more severe bend. Salt spray test results from these bent bars are shown in FIGURE 10. The degree of corrosion for both coated and uncoated bars increases with an increasing degree of bending, but the relative amount of corrosion for coated bars in comparison to uncoated bars does not increase for the bent bars in comparison to the straight bars. Therefore, utilizing the annealing approach taken to enable bending, the bent bars have sufficient corrosion performance.

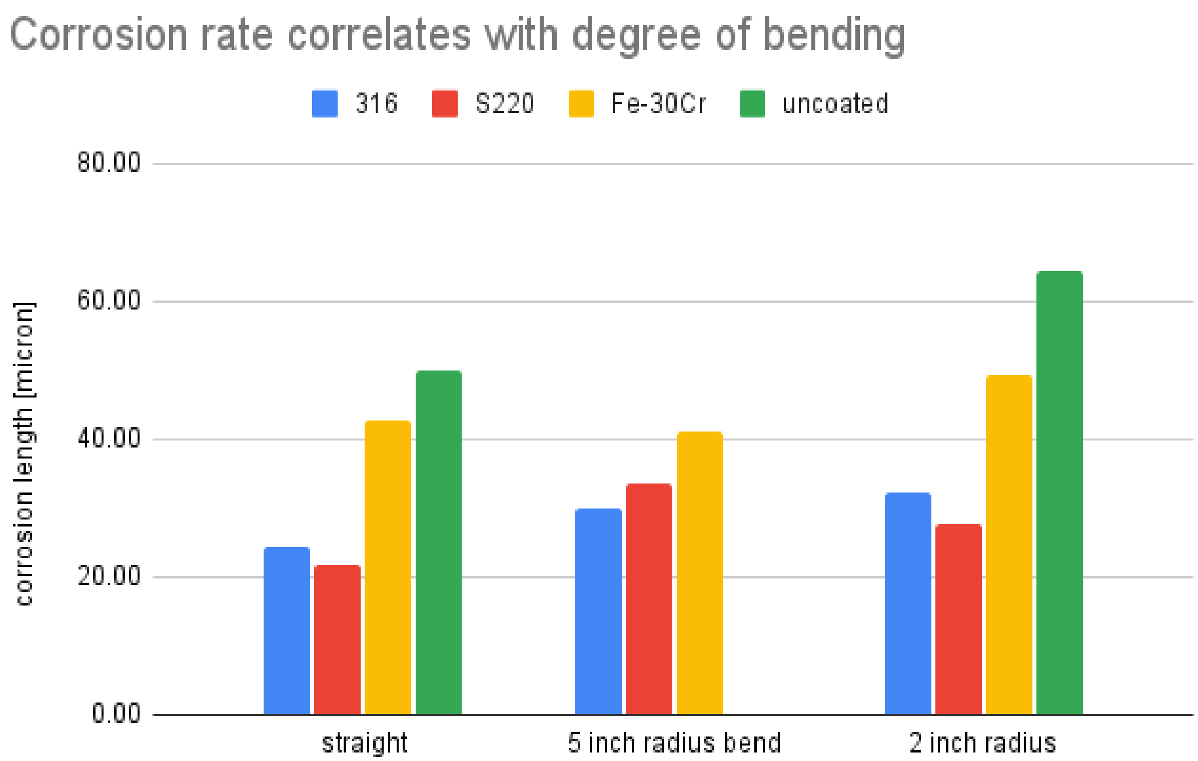


FIGURE 10 Data from salt spray testing after bending samples shows bending does increase the amount of corrosion, but this also occurs in uncoated black rebar. The extent of corrosion increases for the more severe bend.

RE-ENGINEERED MANUFACTURING APPROACH

During the course of the project it became clear that the annealing step was critical to improve the ductility of the coating and promote the ability for the bar to bend without the stainless steel layer cracking. Furthermore, the corrosion data demonstrated in FIGURE 7 suggests the annealing step may also have benefits to the corrosion resistance of the stainless steel layer as well. These considerations encouraged the idea of applying the stainless steel layer earlier in the steelmaking process. In the modern manufacturing process used to make rebar, large billets (typically 6-7" square bars, 20-40' long) are reheated for several hours (typically 5-6) around 1200^{o}C before going through many hot rolling stands (typically 10-15 rolling stands) to reduce the cross-section and create the characteristic reinforcement deformations. The potential benefits of this approach are that the reheating process will also anneal the stainless steel layer, and the hot rolling is carried out at high temperature so the coating layer should be in a highly ductile state, and this could be achieved without the need to install coating equipment within the mill at the end of the production line. The risk or potential drawback of this approach is the potential for the hot rolling/deformation process to cause breaks in the stainless steel coating, along with general non-uniformity of the coating thickness around the outer surface of the bar. To test the idea, a small-scale trial was devised in which a smaller but still representative 3” square bar, 18” long was coated with 316 stainless steel using laser cladding at Oerlikon Metco in Huntersville, NC. Then, this small billet was hot rolled using the Birdsboro rolling mill at the Technology Processing Center (TPC) pilot facility operated by Special Metals in Huntington, WV. Images of the bar being coated using laser cladding, during the intermediate stage of the hot rolling process, and finished are shown below in Figure 10. The 3” square bars were hot rolled into 0.644” diameter rough round bars. After hot rolling, the bars were indeed able to be bent around a 2” diameter mandrel without any visible cracking.

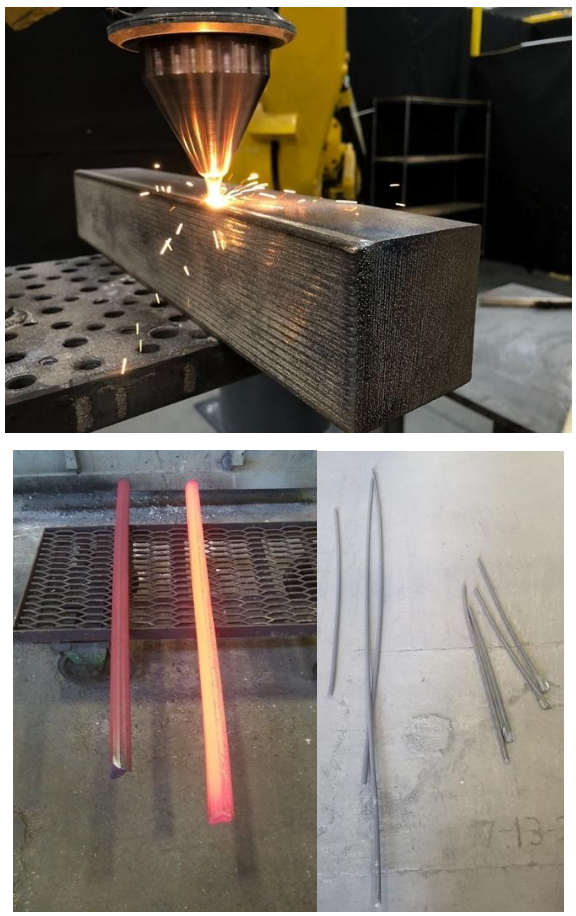


FIGURE 11 (Top) laser cladding of 316SS onto square bar (Bottom Left) during hot rolling (Bottom Right) after completion of the hot rolling process.

The stainless steel outer layer remained intact around the surface for the most part but there were some isolated breaches in the coating that were identified. Factors specific to the pilot mill used in this small-scale study are suspected to be responsible for these breaches, so overall the results of this initial study are encouraging. Accelerated corrosion testing of the hot rolled cladded bars indicate that the corrosion performance is comparable or better than the corrosion performance achieved by the improved cold spray coated bars described earlier in this report.

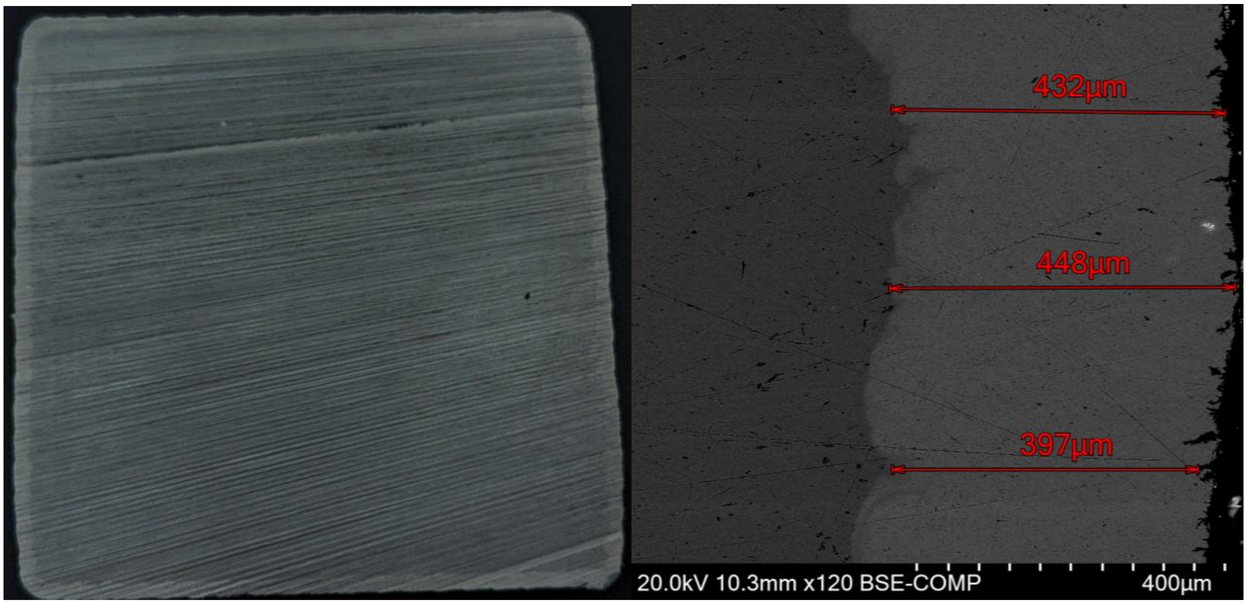


FIGURE 12 (Left) cross-sectional image of cladded square bar with stainless steel outer layer visible (Right) SEM image of polished cross-section of 0.644" diameter hot rolled bar, where the target final cladding thickness was 400 micron. Uniformity and metallurgical bonding are present in the multilayer metallic microstructure.

Based on these promising results, in consultation with the IDEA expert panel it was concluded that in the second stage of this project the focus would shift to this manufacturing method and comparing the performance and scalability to the cold spray coating approach. A commercial partner was identified in order to facilitate the production of actual deformed reinforcement bars at a larger scale than the initial feasibility study mentioned above.

A 7" x 7" square, 26 foot long steel billet was obtained and laser cladding was performed at the Oerlikon Metco additive manufacturing facility located in Huntersville, NC. Photos of the billet after the laser cladding process are shown below in Figure 13:

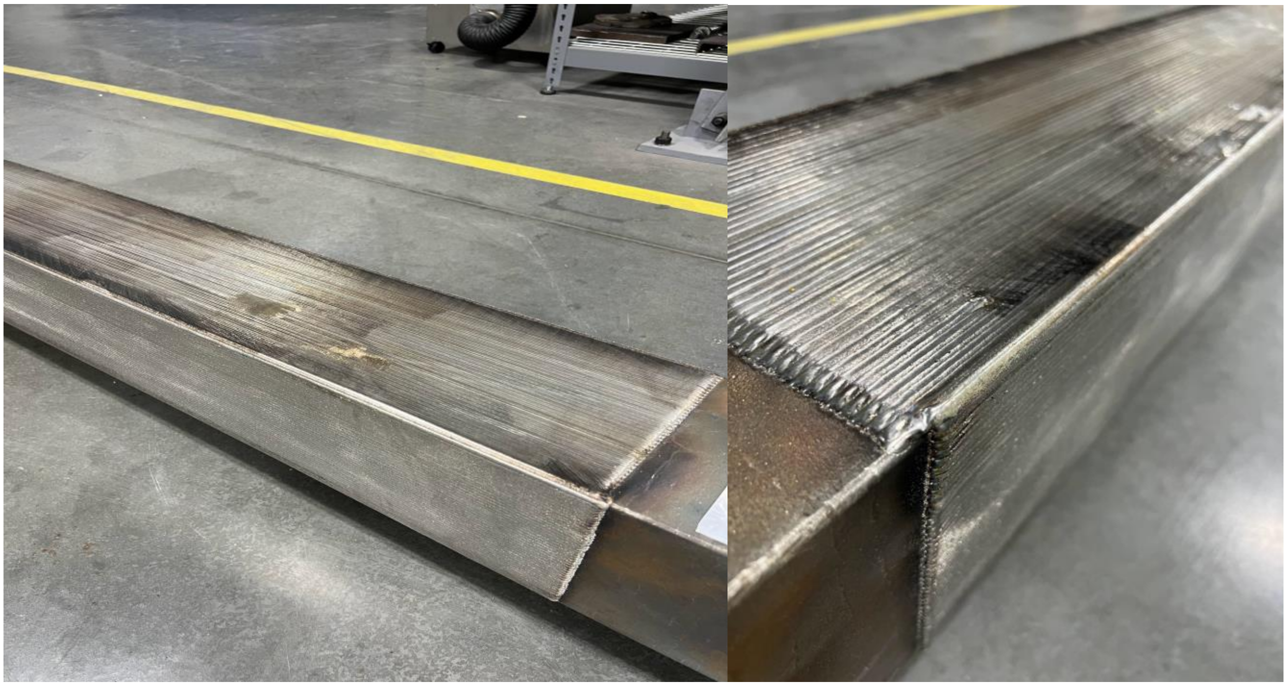


Figure 13: Pictures of the laser cladded billet, note that only the middle 10 feet of the 26 foot long billet were cladded. The cladding is approximately ⅛” thick.

After laser cladding at the Oerlikon facility, the cladded billet was shipped via flatbed truck to the Steel Dynamics, Inc (SDI) Structural and Rail Division mill located in Columbia City, IN. This mill is a mini-mill, where steel scrap is melted in large electric arc furnaces (EAF) and cast into billets. These billets are then reheated in a large natural gas-fired reheat furnace before hot rolling into finished products such as beams, rebar, and rail.

The cladded billet was successfully processed through the reheat furnace and rolling mill to produce a spool of #5 (⅝” diameter) rebar in which the middle portion of the spool contained approximately 1500 lbs of cladded rebar. Photos of the Allium founding team with the first spool produced along with a picture of the produced bar are shown in Figure 14. Overall the initial pilot batch was a success, but there were some areas for improvement that became clear after processing, and are the focus of a second pilot batch described later in this report. One example of an issue observed was rollover as shown on the left side of Figure 15, along with uneven cladding on both sides on the right side.

FIGURE 14: (Left) Allium co-founders with first large-scale batch (Right) Produced bar after abrasive blast cleaning

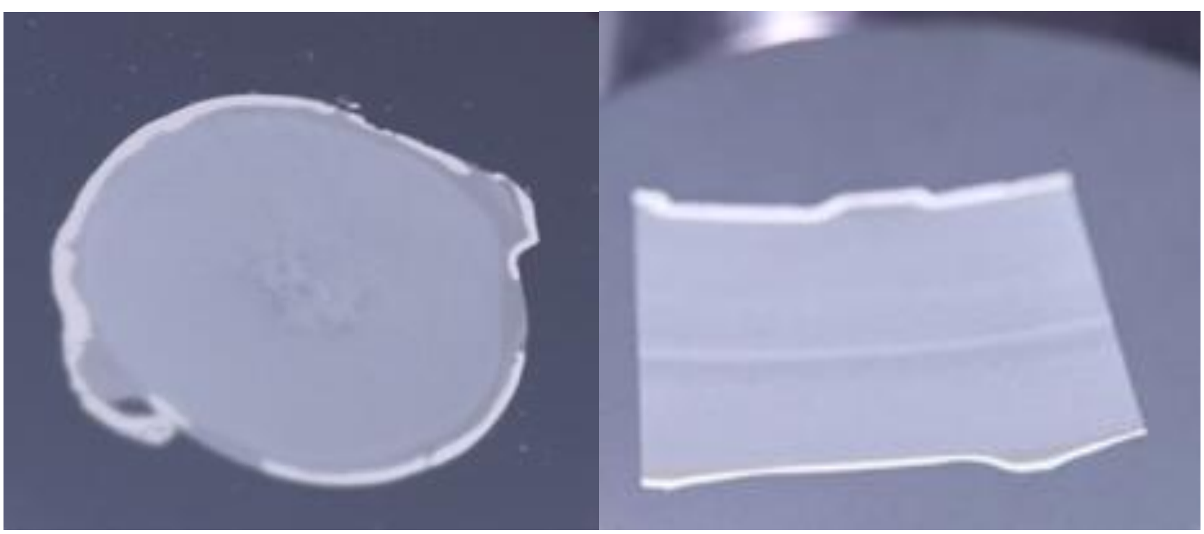


FIGURE 15 Sectioned, polished and etched samples showing (Left) cross-section (Right) longitudinal section. These bar pieces are approximately 0.625" diameter.

Microstructural Characterization of Clad Rebar

The clad rebar produced from the first large scale production batch was prepared for microstructural analysis by sectioning/cutting, mounting, and polishing using metallographic polishing paper and suspensions. These polished samples were then evaluated using the Hitachi SU3900 Variable-Pressure SEM located at North Carolina State University. An example of an SEM image showing a surface deformation and cladding interface is shown in FIGURE 16. One consistent observation from this first batch of cladded rebar is that the surface deformations lead to an uneven coating thickness along the surface of the bar. In the case of the region shown in FIGURE 16, this is not problematic as there is sufficient coating and continuous coverage so as to maintain corrosion resistance. An elemental composition map collected using energy-dispersive x-ray spectroscopy (EDX) is shown in FIGURE 17 demonstrating the metallic multilayer composite structure of the bar.

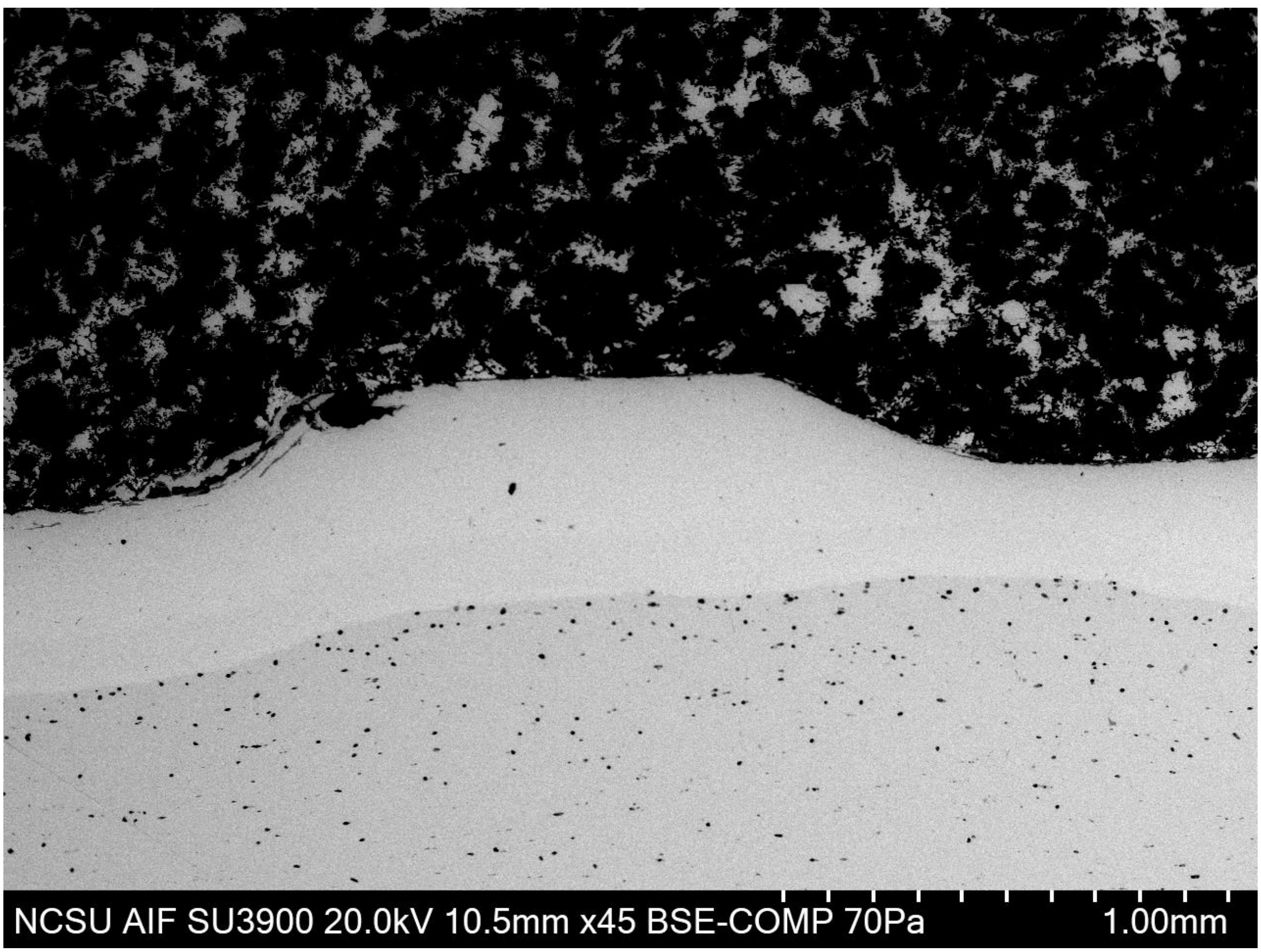


FIGURE 16 SEM image of cladded rebar produced from first large scale batch.

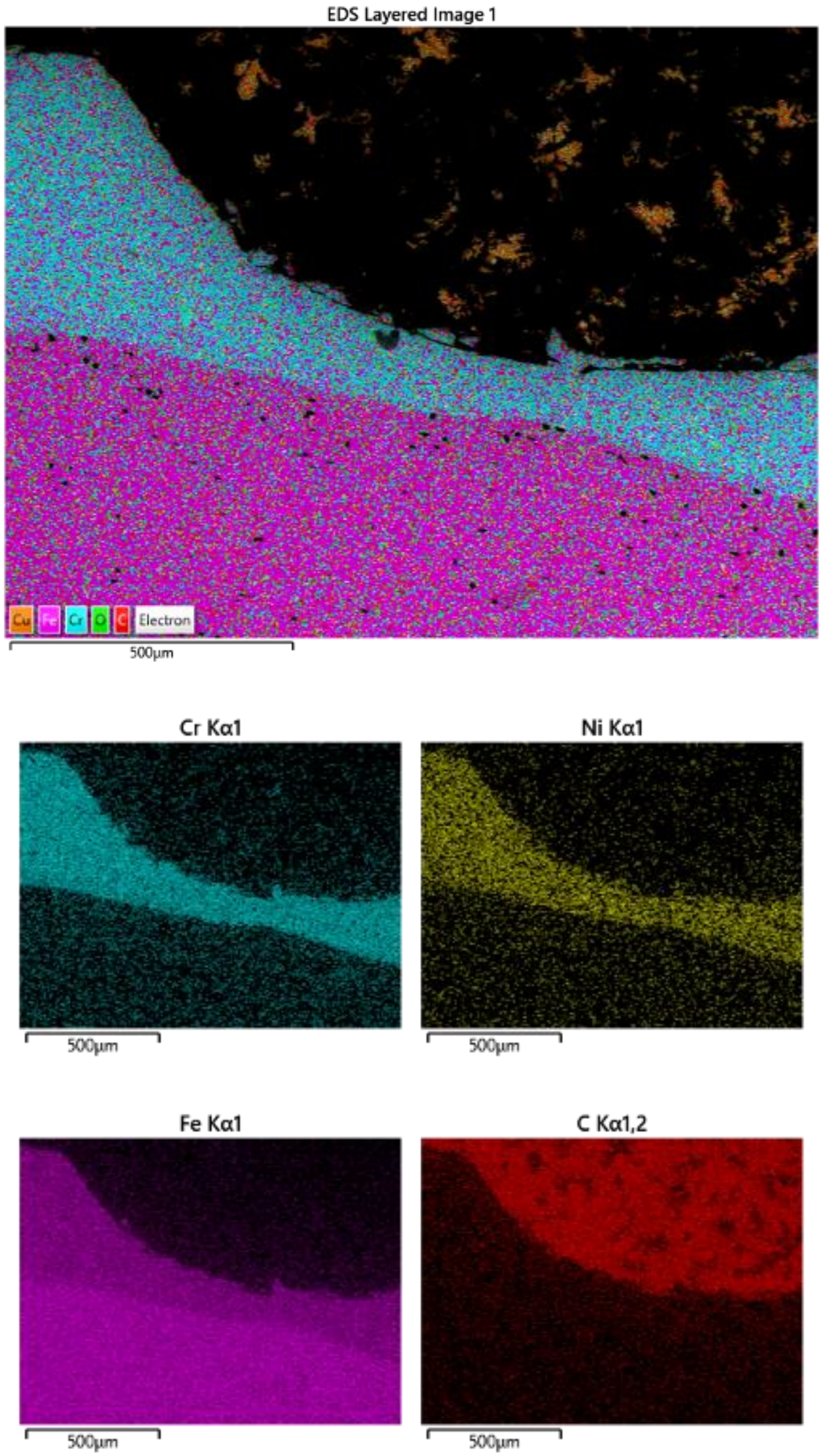


FIGURE 17 composite and elemental EDX maps of the stainless-clad rebar.

A more problematic situation is shown in FIGURE 18 below, where a microcrack has formed within the cladding layer at the thin point of the cladding. This is likely caused by the shear forces imparted on the bar by the deformation hot rolling step at the end of the hot rolling process. This crack has not entirely penetrated the cladding layer in this case, so some degree of corrosion resistance should be retained, but this could lead to crevice corrosion of the cladding along with potential for crack growth during an operation such as bending which could expose the core carbon steel underneath the cladding.

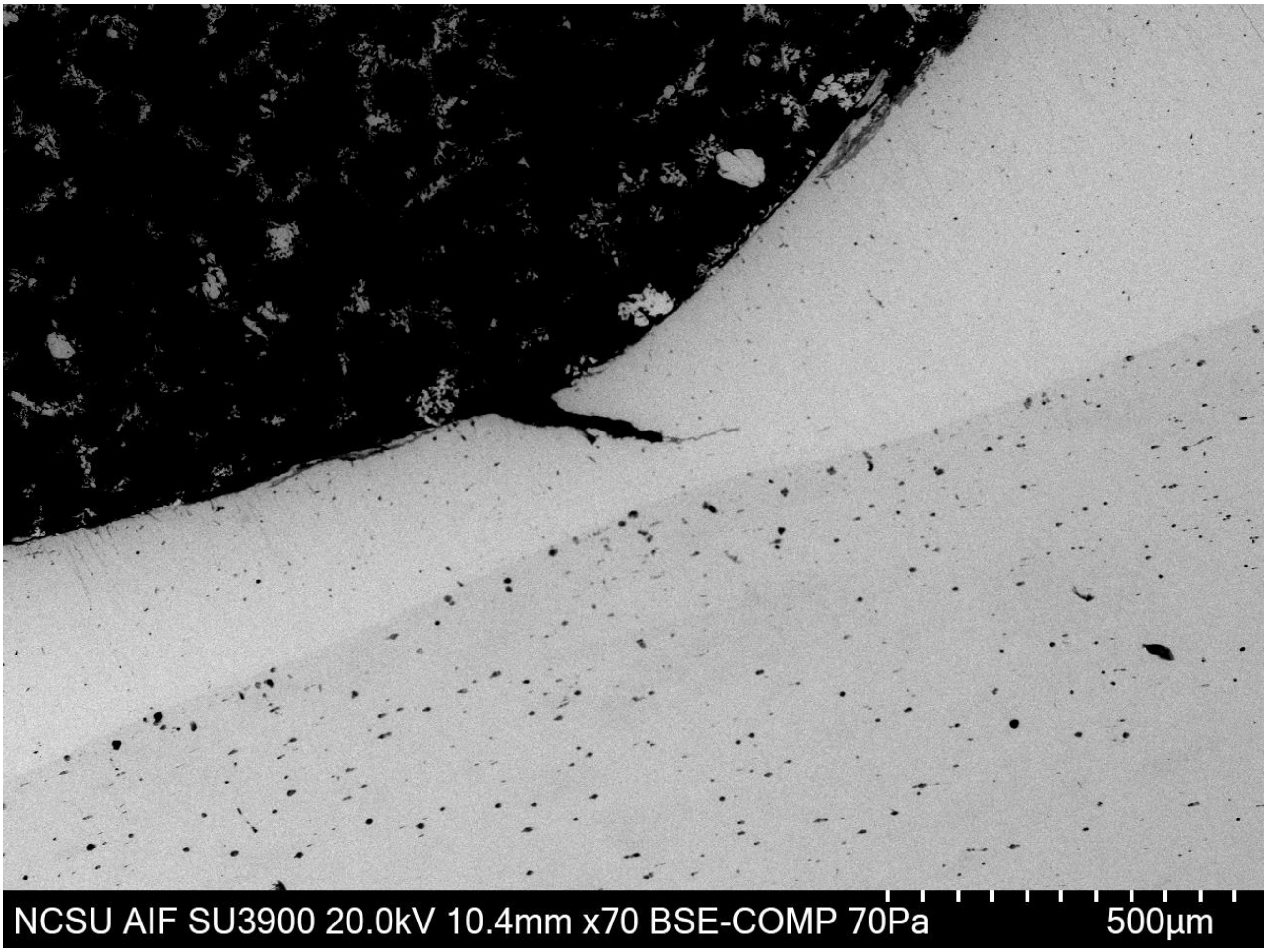


FIGURE 18 SEM image of a microcrack formed within the stainless cladding layer.

Another example of some of the problematic regions identified in the initial batch of stainless clad rebar is shown in FIGURE 19. In this case, there is a small breach located on the side of a spine deformation, the deep longitudinal deformations running the length of the rebar. Due to the oxides present around the breach it is highly likely this breach occurred at some point toward the end of the hot rolling process. A series of EDX maps of this region is shown in FIGURE 20, which make it easier to observe that the breached region forms a relatively small section of the surface. A set of EDX line scans for Fe, Cr, and Ni is shown in FIGURE 21, showing the composition across the interface and the 3-5 micron wide compositional gradient layer which naturally forms during the reheat and hot rolling process.

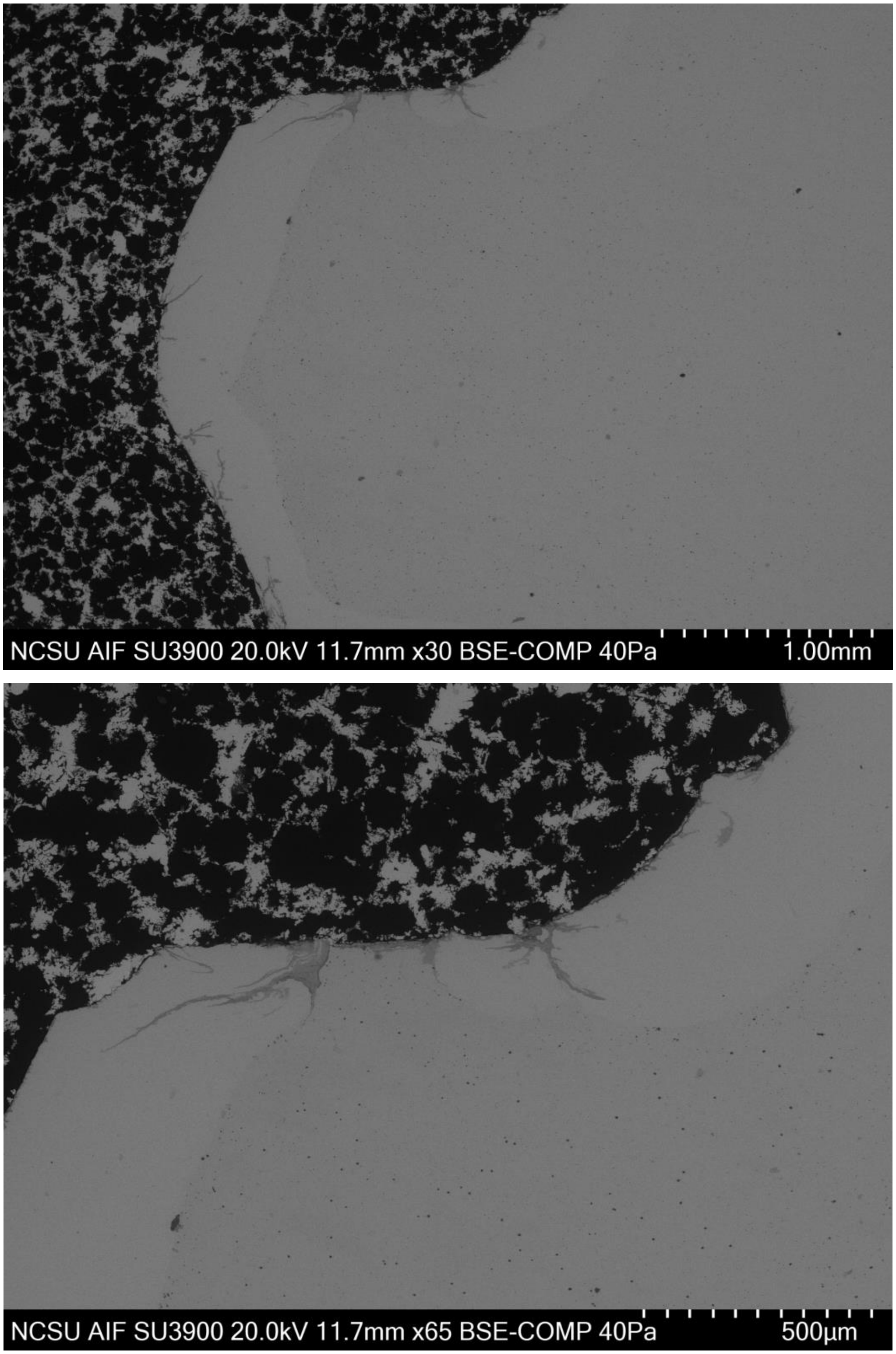


FIGURE 19 (Top) SEM image of spine deformation and (Bottom) zoom-in image showing small breach on the side of the spine deformation. Due to the visible oxide (darker material) it is likely this breach occurred towards the end of the hot rolling process.

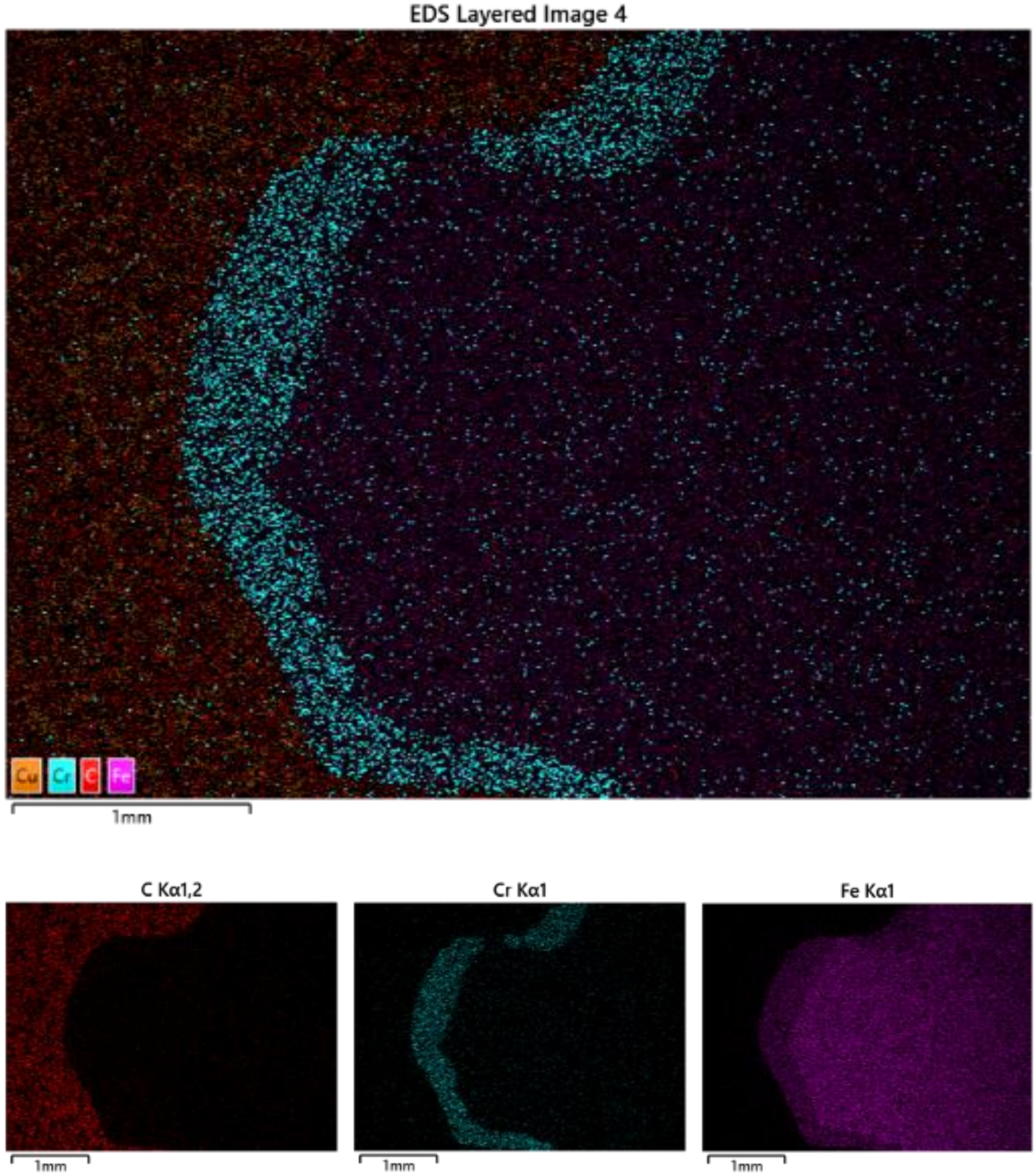


FIGURE 20 EDX composite and elemental maps of the small spine deformation cladding breach

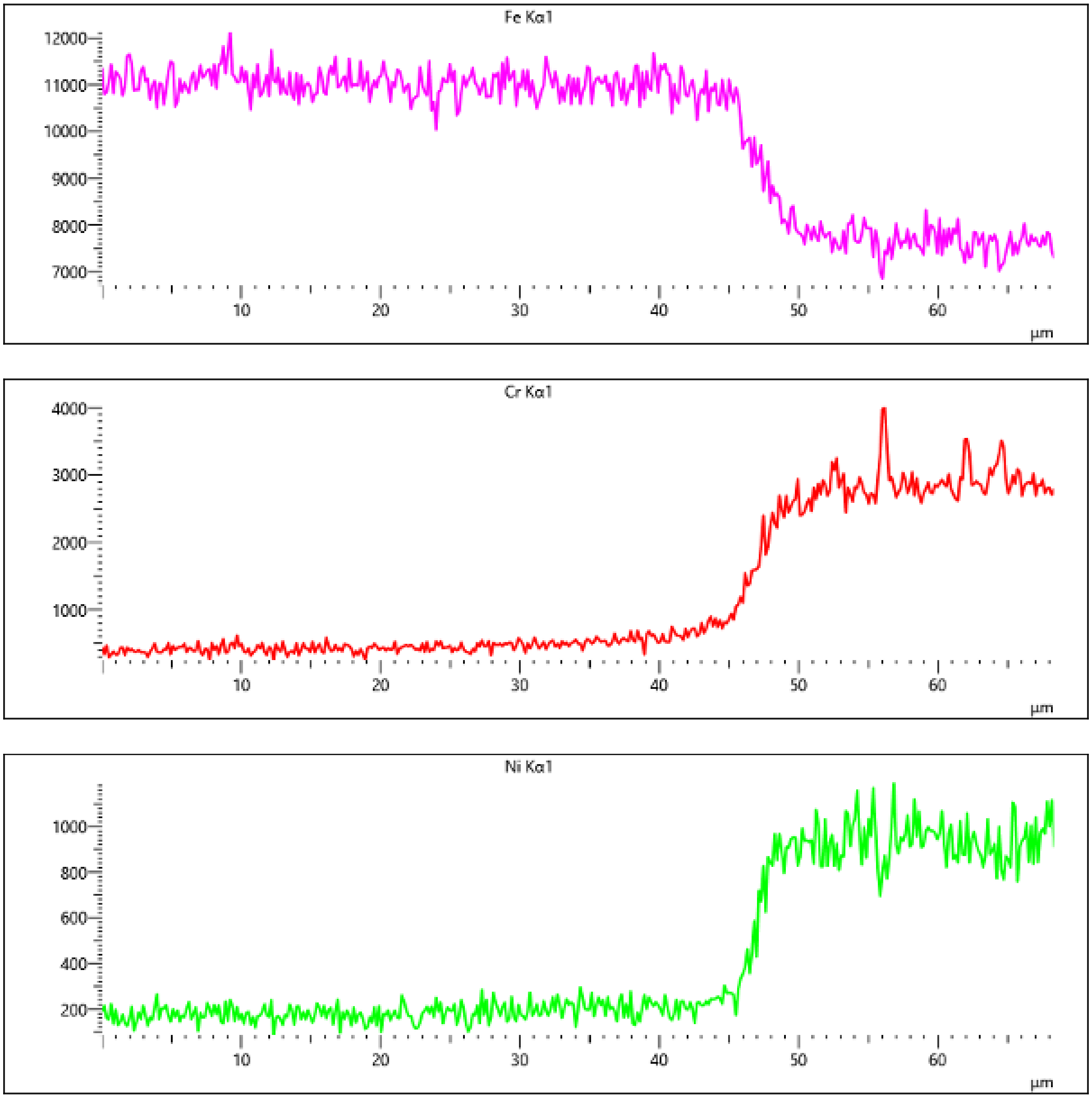


FIGURE 21 EDX linescan showing the composition gradient across the interface.

Second Stainless-Clad Rebar Manufacturing Batch

In order to address some of the issues described above in the first batch of stainless-clad rebar manufacturing, a second manufacturing attempt was made with a clad billet.

PULLOUT AND REBAR/CONCRETE BOND TESTING

Another aspect of steel reinforcement which was investigated in this project is the bonding between the stainless coated rebar and concrete. Based on characteristics and surface roughness of the coating, it was expected that the rebar/concrete bond strength should be essentially unaffected but testing was performed in order to ensure this is the case. In order to conduct pullout testing, which measures the tensile stress required to pull an concrete-encased rebar until the rebar/concrete bond is broken, 6-inch cube concrete specimens were produced using 4,000 PSI Quikrete mix. Each cube had a piece of rebar embedded 3 inches into the concrete cube. After a minimum of 72 hours of curing time after concrete mixing and casting, tests were performed using a hydraulic jack with a pressure gauge to measure the pullout strength. A pulling head along with wedges which are threaded on the inside were used to couple the hydraulic jack to the rebar. Images of the pullout test setup are shown on the top of Figure 22 below, along with marks left from threaded wedges after testing.

FIGURE 22 (Top Left) Pullout test of rebar coated with stainless steel using cold spray coating (Top Right) Pullout test of epoxy-coated rebar (Bottom Left) Threading marks left on cold spray coating after pullout testing (Bottom Right) Epoxy-coating removal and damage due to threaded wedges used during pullout testing.

FIGURE 23 (Left) Black rebar specimen being cast in 6-inch cube reusable steel mold. (Right) Characteristic damage after pullout failure.

The black rebar generally had a pullout failure stress of 1500 psi, the stainless steel cold spray coated bars had a pullout failure stress of 1300-1500 psi, and the epoxy-coated bars had a pullout failure stress of 1100-1200 psi. In the future specimens will be tested using lap-splice beam testing which is a more involved and expensive test setup but provides a more realistic stress state on the embedded rebar.

IMPACT DAMAGE AND DURABILITY TESTING

The coating damage testing has been conducted using a load guillotine approach adapted from that used by Frosch and Sim in their 2014 report (1). In this way, equal damage conditions can be imposed on different coatings to understand their robustness and response to damage. A custom weighted channel bar was fabricated for use in testing. A load guillotine was made from wood and constructed to facilitate a 4-foot drop of the weighted channel bar. A comparison of cold sprayed stainless steel coated rebar damage to damage of epoxy-coated rebar damage under the same conditions is shown below in FIGURE 25. Under the same damage impact conditions, the cold spray coated bars are much more resilient and show much lower visible damage than epoxy-coated rebar.

Figure 24: (Left) Custom weighted channel bar used for creating damage (Right) example of damage level caused by drop onto 2x4 piece of wood.

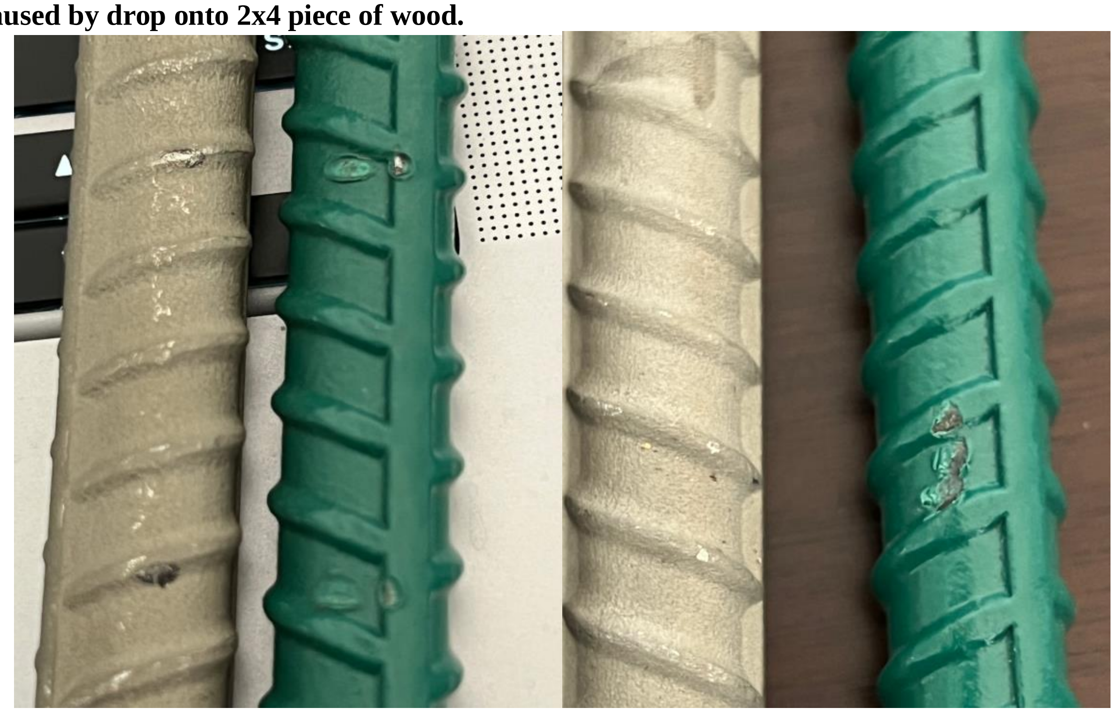


Figure 25: (Left) Damage comparison on primary impact side showing superficial marking on cold spray coating while the epoxy coating is punctured. (Right) bottom side of bars showing additional epoxy-coating damage due to impact friction with the support surface, while the bottom surface of the cold spray bar is hardly marked at all. Cold spray coated bars are on the left side of the photos and epoxy-coated bars are on the right side of the photos.

Non-destructive thickness measurement and quality control

Another point which was raised by our expert advisory panel was techniques to identify breaches and measure thickness along the length of the bar in a simplistic way. A magnetic probe approach was identified which can be used for this purpose in general for non-magnetic coatings. Because austenitic steels are non-magnetic, this is an effective approach when the coating is 304 or 316 stainless steel, but duplex and ferritic steels are magnetic so the probe will not work in those cases. But, 316 has been the most dependable cladding/coating composition so this is still a meaningful development. The hand-held magnetic gauge can be seen below in FIGURE 26. The spot-size for the measurement is approximately 1 mm diameter so the analog gauge will read out the average coating thickness across a 1 mm diameter circle on the surface. The device can measure down to the micron-scale coating thickness. Cladding breaches can also be identified because they will read out as zero on the gauge.

FIGURE 26 A hand-held magnetic gauge which can measure average coating thickness within a ~1mm diameter measurement spot, and can also identify cladding/coating breaches in non-magnetic stainless steel coatings.

Macrocell Corrosion Results

During the initial phase of the project the corrosion testing was executed using ASTM B117 salt spray testing which provided rapid corrosion results but not in an environment representative within concrete and also the corrosion data obtained using this approach is not highly quantitative. In order to overcome this shortcoming, in recent months rapid macrocell corrosion testing has been performed on both cold spray and cladded-hot rolled stainless clad rebar along with black carbon steel rebar in order to more accurately quantify the corrosion rates within an environment designed to chemically simulate concrete. This experimental approach is adapted from ASTM A955 and is shown schematically in FIGURE 27 below. The quantitative results of this testing are shown in FIGURE 28 on the following page.

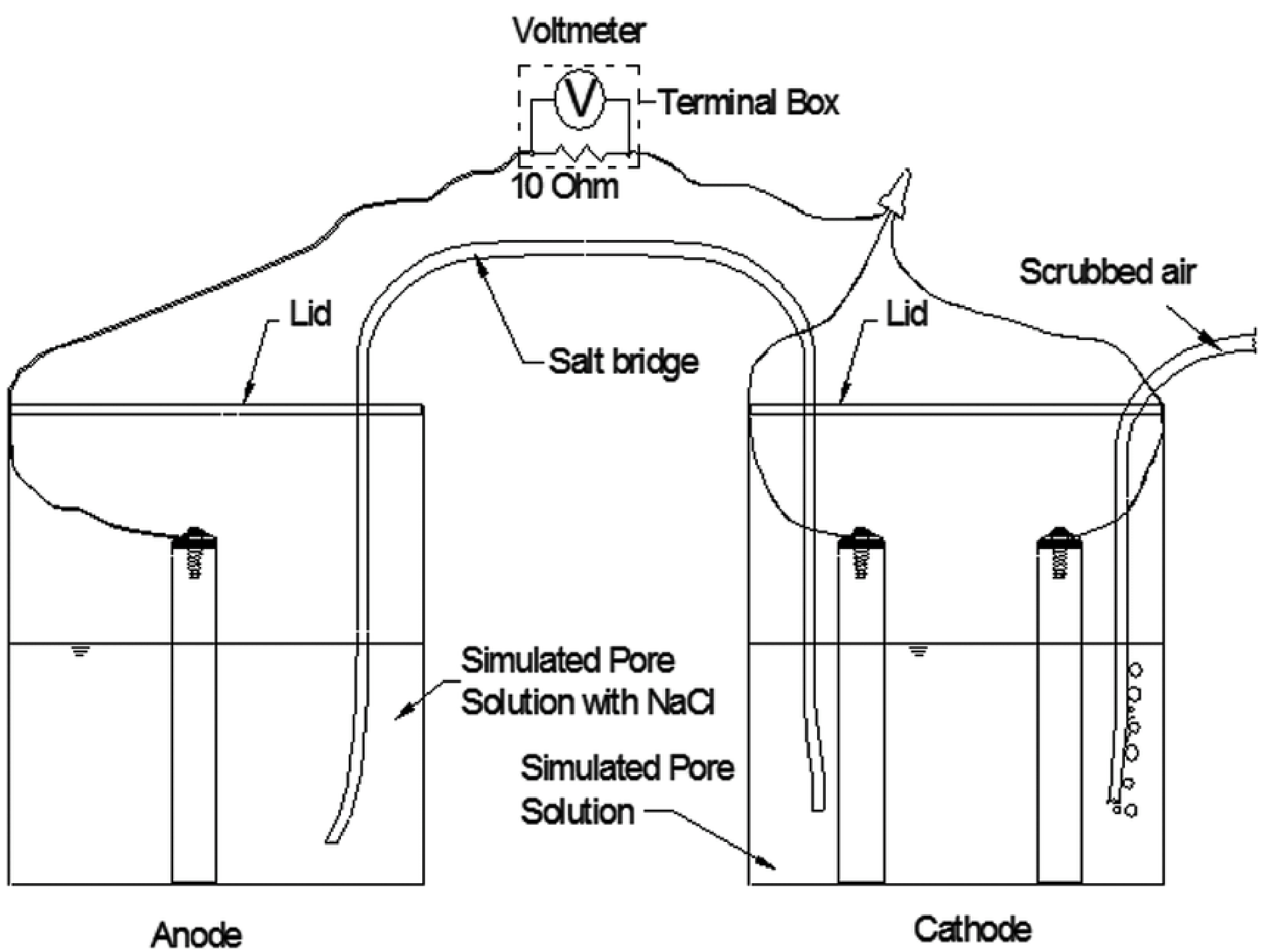


FIGURE 27 A schematic diagram of the rapid macrocell corrosion test setup.

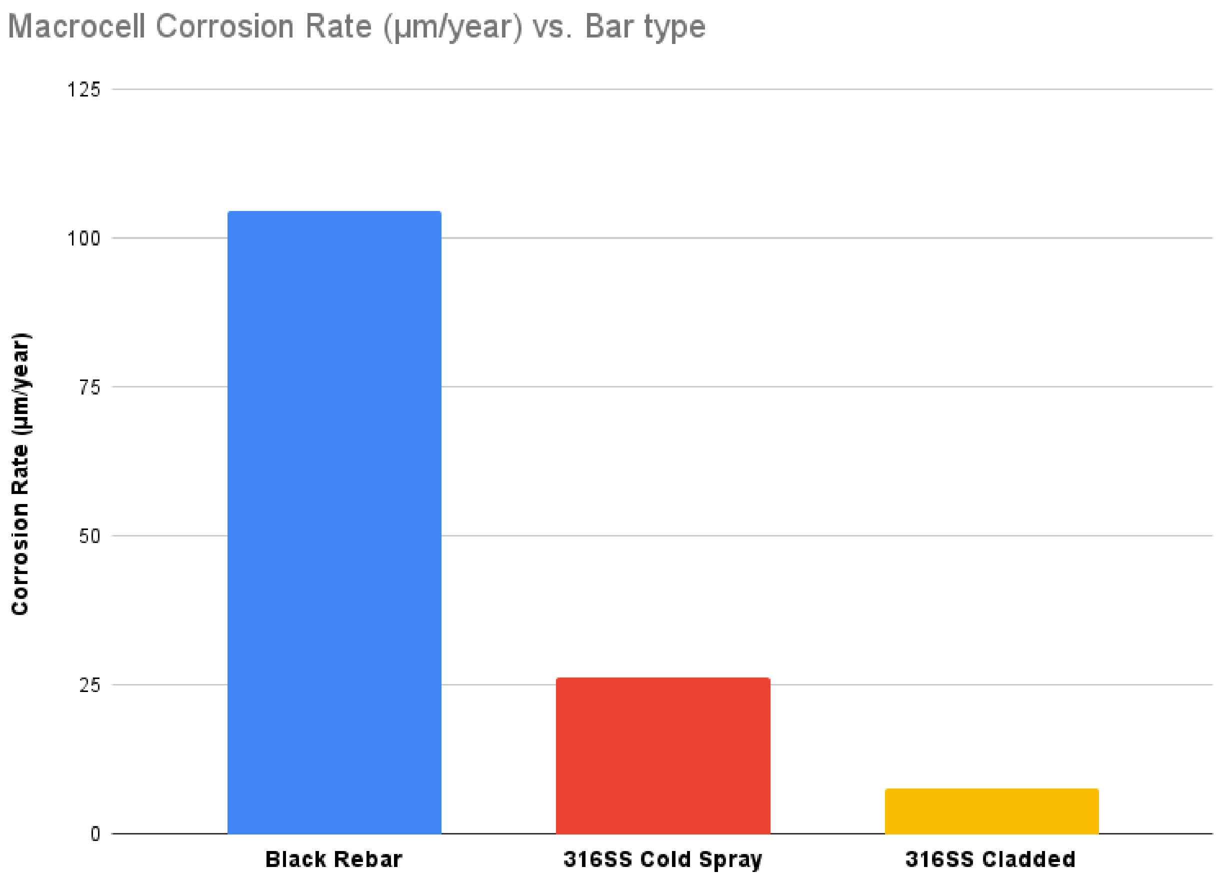


FIGURE 28 Electrochemically-measured corrosion rates using rapid macrocell testing. Cold spray coating enables a 4-fold reduction in corrosion rate while the cladding approach enables a 10-fold or more reduction in corrosion rate.

The macrocell tests revealed even far superior performance in corrosion resistance for the stainless-clad rebar in comparison to the cold spray coated rebar. The black carbon steel rebar had a corrosion rate of 104.7 micron/year, the 316 cold spray coated rebar had a corrosion rate of 26.2 micron/year, and 316 stainless clad and hot rolled rebar had a corrosion rate of 7.63 micron/year.

Mechanical Behavior of Cladded Rebars

Another important property to measure on the cladded rebars is the tensile behavior, namely performing a uniaxial tensile test along with 180-degree bend testing. Size #5 stainless-clad reinforcement was bend tested using a 2” diameter mandrel and passed 3 separate bend tests at different points in the batch. Tensile tests were also performed, using a load frame and digital image-based strain gauge. Tensile test data in the elastic-plastic transition region is shown FIGURE 29 below, and numerical tensile test results are shown in TABLE 4 below.

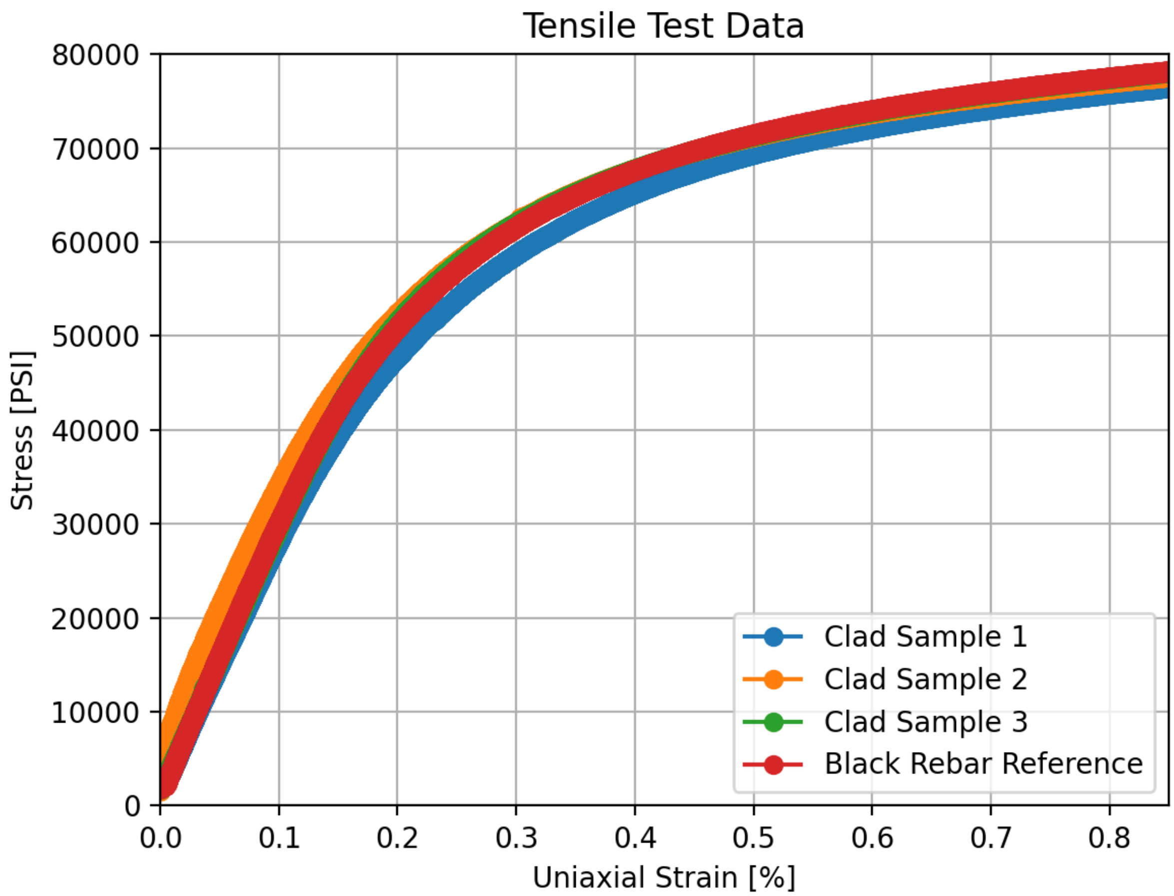


FIGURE 29 Tensile test data demonstrating no decrease in yield strength for stainless-clad reinforcement.

TABLE 4 Tensile test results for 3 stainless-clad samples along with carbon steel rebar reference.

Sample	Ultimate Tensile Strength [PSI]	Yield Strength [PSI]	Total Elongation [%]
SS Clad 1	94,761	68,204	13.71
SS Clad 2	93,843	69,327	12.15
SS Clad 3	96,263	69,659	13.69
A615 Bar	95,457	69,722	13.49

PLANS FOR IMPLEMENTATION

The first step in implementing this IDEA product in transportation infrastructure is to obtain support from state Departments of Transportation (DOT) as they are the key stakeholder and owners of transportation infrastructure. In general, state DOTs recognize the rebar corrosion problem that this technology addresses. In the early stages this mostly has to do with engagement with individual DOTs as well as appropriate AASHTO committees and potential funding and execution of pilot projects and installations, while in the later stages this would center on state DOTs establishing policy specifying the use of this IDEA product in certain applications. Initially, this will be achieved through an existing AASHTO specification, AASHTO M329 which is a performance specification for stainless-clad rebar.

VIRGINIA DOT: INITIAL TRANSPORTATION INFRASTRUCTURE MARKET

State DOTs in Virginia (VDOT) and Florida (FDOT) have established policies ending the use of epoxy-coated rebar indicating these states have identified the need for more corrosion resistant technology within transportation infrastructure. VDOT has established a 3-class system of Corrosion Resistant Reinforcement (CRR) in which ChromX (ASTM 1035) constitutes CRR Class I, stainless-clad rebar (AASHTO M329) which would encompass the technology in this project constitutes CRR Class II, and pure stainless steel rebar (ASTM 955) is CRR Class III. The original VDOT policy when the CRR 3-class system was established is shown in FIGURE 30 below. A commercial supply of CRR Class II was never established so in practice only Class I and Class III are currently used. But, in principle, once a commercial supply is established, stainless clad rebar should be used for rural and urban minor arterial roads and bridges. In addition, CRR Class II could be substituted in any application which would otherwise use CRR Class I.

Functional Classification	Low Carbon / Higher Chromium	Stainless Clad	Solid Stainless
Freeway			X
Rural Principal Arterial			X
Rural Minor Arterial		X	
Rural Collector Road	X		
Rural Local Road	X		
Urban Principal Arterial			X
Urban Minor Arterial		X	
Urban Collector Street	X		
Urban Local Street	X		

FIGURE 30 Chart showing VDOT policy for corrosion resistant reinforcement identifying areas where different classes of rebar should be specified.

In efforts to commercialize this IDEA product, conversations have taken place with VDOT engineers to understand how to begin entering the market and providing CRR Class II. The conclusion was once Allium can produce 5-10 tons of reinforcement meeting AASHTO M329 then a pilot installation such as a small bridge or precast component can move forward. Precast concrete in particular is an ideal early application. Allium has formed a strong relationship with a major steel producer and steel mill as described earlier in this report. Additionally, Allium has formed a strong relationship with a rebar fabricator located in the Hampton Roads region of Virginia, Tidewater Rebar. Allium intends to fabricate and distribute reinforcement for VDOT projects initially through Tidewater Rebar. After entering the VDOT market, Allium will pursue adoption by FDOT in addition to establishing pilot installations in additional states such as Michigan, Vermont, Rhode Island, and California.

CONCLUSIONS

This IDEA project established the proof-of-concept of the stainless cladding and metallic multilayer composite approach to solving the rebar corrosion challenge in a cost effective manner, while it also enabled significant refinement and development of the initial concept, including engineering of the manufacturing approach as well as work towards commercial implementation. The major conclusions from the project can be summarized as follows:

(1) Cold spray stainless steel coatings can impart corrosion resistance but in the as-sprayed state the coatings are highly brittle and require an annealing heat treatment to be bent without cracking.
(2) By applying the cladding to semi-finished billets, stainless clad rebar can be produced by hot rolling.
(3) Using the method described in (2) the cladding is highly ductile in the as-rolled state and can be bent without cracking or delamination.
(4) Stainless steel coatings produced via cold spray or method described in (2) are very tough and much more durable than epoxy coatings to impact damage, which is highly advantageous.
(5) The rebar/concrete bond strength for stainless steel coated rebar is comparable to the bond strength for conventional rebar as measured through pullout testing.
(6) The Virginia DOT market is the ideal initial market for this technology and IDEA product as it would qualify under AASHTO M329 as VDOT CRR Class II and can be used in rural and urban minor arterial roads, collector roads, and local roads in the VDOT market.
(7) Rapid macrocell corrosion testing demonstrated a 4-fold decrease in corrosion rate for cold spray 316 stainless steel coated reinforcement, while the manufacturing method developed during the project showed a greater than 10-fold decrease in corrosion rate, in comparison to black carbon steel rebar.

Investigators' Profiles

PRINCIPAL INVESTIGATOR

Samuel McAlpine, PhD

Educational Background

PhD Nuclear Science and Engineering Massachusetts Institute of Technology - November 2021

BS Nuclear Engineering/Materials Science and Engineering University of California, Berkeley - May 2015

Dr. McAlpine has an academic background centered at the interface between nuclear engineering and materials science. His doctoral research developing novel metallic multilayer composite materials for advanced nuclear energy applications has provided the ideal background experience and knowledge base for his current focus at Allium, developing advanced reinforcing steel materials that will enable transportation infrastructure like highways and bridges to last for centuries.

References

(1) R.J. Frosch, S. Labi, C. Sim, *Increasing bridge deck service life: Volume I—Technical evaluation*, 2014. https://doi.org/10.5703/1288284315516.

Appendix: Research Results

Sidebar Info

Program Steering Committee: NCHRP IDEA Program Committee

Month and Year: April 2023

Title: Stainless Steel Coated Rebar for Chloride Resistant Concrete Highway and Bridges

Project Number: NCHRP-240
Start Date: April 1, 2022
Completion Date: June 30, 2023

Product Category: Advanced Materials for Transportation Infrastructure

Principal Investigator:
Samuel McAlpine, PhD
Co-Founder & Chief Technology Officer
Allium Engineering, Inc.
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925-878-1173

TITLE

Stainless Steel Coated Rebar for 200 Year Bridges

SUBHEAD

New steel composite material provides a low-cost solution to corrosion which enables concrete transportation infrastructure like bridges and tunnels to last much longer

WHAT WAS THE NEED?

Across the United States, reinforced concrete serves as the basis for transportation infrastructure like highways and bridges, but corrosion of steel rebar within the concrete is a major problem which limits the lifetime of most infrastructure to 50 years or less. According to the Report Card for America's Infrastructure, there are 178 million trips taken each day over structurally deficient bridges. New technologies and materials are needed to ensure that the wave of investment in infrastructure in the United States pays dividends for generations to come. We need to improve the safety, sustainability, and durability of our infrastructure.

WHAT WAS OUR GOAL?

The goal of this project was to establish the proof-of-concept for a new approach to solving the rebar corrosion problem. The fundamental idea is that a metallic multilayer composite structure using a stainless steel coating on a carbon steel core can provide a cost-effective but robust solution to rebar corrosion.

WHAT DID WE DO?

In this project, prototype coatings were manufactured using cold spray and tested for both corrosion resistance and other characteristics. Tests were performed to understand and validate the corrosion resistance, mechanical durability, and bonding characteristics with concrete. An improved manufacturing approach was developed over the course of the project and resulted in a scalable solution which can be integrated with the existing steelmaking process used to make rebar.

WHAT WAS THE OUTCOME?

The concept of the project was conceptually proven out and shown to enable a four-fold increase in the expected lifetime of concrete. Furthermore, the stainless steel coating is highly durable and ductile which provides additional benefits in concrete reinforcement applications. This technology is a drop-in replacement for conventional rebar while greatly enhancing the expected lifetime for transportation infrastructure.

WHAT IS THE BENEFIT?

Bridges, tunnels, highways and other transportation infrastructure that is made from reinforced concrete will be expected to have a greatly increased operational lifetime by using this technology. In addition, this technology will lead to greatly reduced maintenance and repair costs over the lifetime of the infrastructure. This technology will be particularly beneficial in coastal regions and cold areas where de-icing salts are utilized as the presence of salt is a major driver of degradation from corrosion.

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