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Application of HVOF Thermal Spraying to Solve Corrosion Problems in the Petroleum Industry—An Industrial Note

L.N. Moskowitz

Commercially available thermal spray coatings have seen limited use in corrosion applications due to the presence of interconnecting porosity and oxide networks. Use of vacuum chambers or post-treatments can eliminate most defects, but these methods are costly and impractical on a large scale. The ability to produce such high-quality coatings by thermal spraying in atmosphere and without post-treatments would offer important advantages as a means of building and repairing process equipment. A modified HVOF process using unique inert gas shrouding has resulted in highly dense, low-oxide coatings of metallic alloys. These coatings were extensively evaluated for severe petroleum industry corrosion applications in laboratory and plant testing, with exposures as long as 5 years. Coatings of corrosion-resistant alloys, such as type 316L stainless steel and Hastelloy C-276, were shown to act as true corrosion barriers. They were protective to underlying base metals in severe environments and in most cases exhibited corrosion resistance comparable to the corresponding wrought alloy. The process was scaled up for on-site plant use and successfully applied to numerous corrosion problems in petroleum industry plant equipment. Significant technical and economic advantages can be realized by use of thermal spray coatings to solve plant equipment problems.

1. Introduction

CORROSION of process equipment has always been a costly but unavoidable part of plant operations in the petroleum industry. Liquid and gaseous corrosives, ranging from strong acids to caustics and often at elevated temperatures and pressures, are prevalent. With the processing of higher sulfur crudes in recent years, corrosion problems have intensified. These "sour" crudes have also led to increasing susceptibility to several corrosion-based cracking phenomena. Problems of this nature are usually associated with hard metal areas and residual stresses, particularly in welds and heat-affected zones. This has necessitated more stringent controls on materials and extensive use of post-weld heat treatments on new fabrications and field repairs.

Designing around these corrosion problems is expensive. Material selection is governed by a combination of cost, fabricability, strength, and corrosion resistance. Often, less expensive carbon and low-alloy pressure vessel steels are used for new equipment, and repairs or replacement are planned on a frequent basis. Another option is to use very expensive corrosion-resistant alloys and bear the cost up front. A third approach is to build with the cheaper steels, but overlay or clad them with more chemically resistant materials. Weld overlaying, roll bonding, and explosion bonding are common methods. Whichever design approach is used, however, it is often the case in service that process variables or operating limits change, and the original design proves inadequate. This leads to unexpectedly severe corrosion and costly repair or replacement situations.

Keywords: applications, corrosion barrier, Hastelloy, high velocity oxygen fuel process (HVOF), petroleum industry, stainless steel

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Equipment and plant unit shutdowns, both planned and unplanned, are extremely costly. For this reason, relatively fast and effective repair methods can be very valuable. Repair options include partial or full replacement, weld overlaying, and strip lining (laying in corrosion-resistant sheet and welding the seams). Each has its advantages and drawbacks, but all involve welding. Usually this requires that the repairs be post-weld heat treated, which adds greatly to the equipment downtime and overall cost of the repair.

Thermal spray processes have long offered attractive potential solutions to many of these problems due to the speed, portability, and low heat input involved with the technique. Also, the advantages of a thinner coating without base metal dilution or heat-affected zones are obvious. In practice, though, thermal spray coatings have not lived up to their expectations. Experience with thermal spraying to solve problems in the process industries has been poor due to the inability of the coatings to effectively protect against harsh corrosive environments. The porosity and oxide networks inherent in conventional thermal spray coatings have limited their usefulness in applications involving corrosion. Sealants have been used to obtain corrosion protection in some applications, but they quickly degrade in temperatures above about 200 °C (390 °F) or in the more aggressive corrosive environments. Amoco Corporation has periodically evaluated state-of-the-art thermal spray coatings for use in applications involving corrosion. Results have consistently showed that these coatings were not suitable for corrosion service.

Current coating literature contains numerous examples of advances that have been made in coating quality by use of vacuum (or controlled atmosphere) chamber plasma spraying.[1-3] Similar high-quality coatings have long been produced by using post-treatments, such as fusing (of self-fluxing alloys), diffusion heat treatments, or laser consolidation.[4,5] These methods are, however, impractical for use on a large scale and for use on equipment located in the field. It was the goal of this work, therefore, to overcome these deficiencies and produce thermal spray coatings of sufficient quality to be capable of providing cost-effective solutions to corrosion problems in the petroleum industry. The intent of this article is to describe in-depth examples of plant applications that have successfully been addressed. Coating microstructures, details of the coating process, and laboratory testing will be only described briefly in the next section.

2. Corrosion Barrier HVOF Coatings

Typical commercially available thermal spray coatings contain varying degrees of porosity and oxide scales, both isolated and interconnecting. Unmelted and partially melted particles are also common. The concentration of these defects also varies throughout the coating, particularly when it is applied by hand

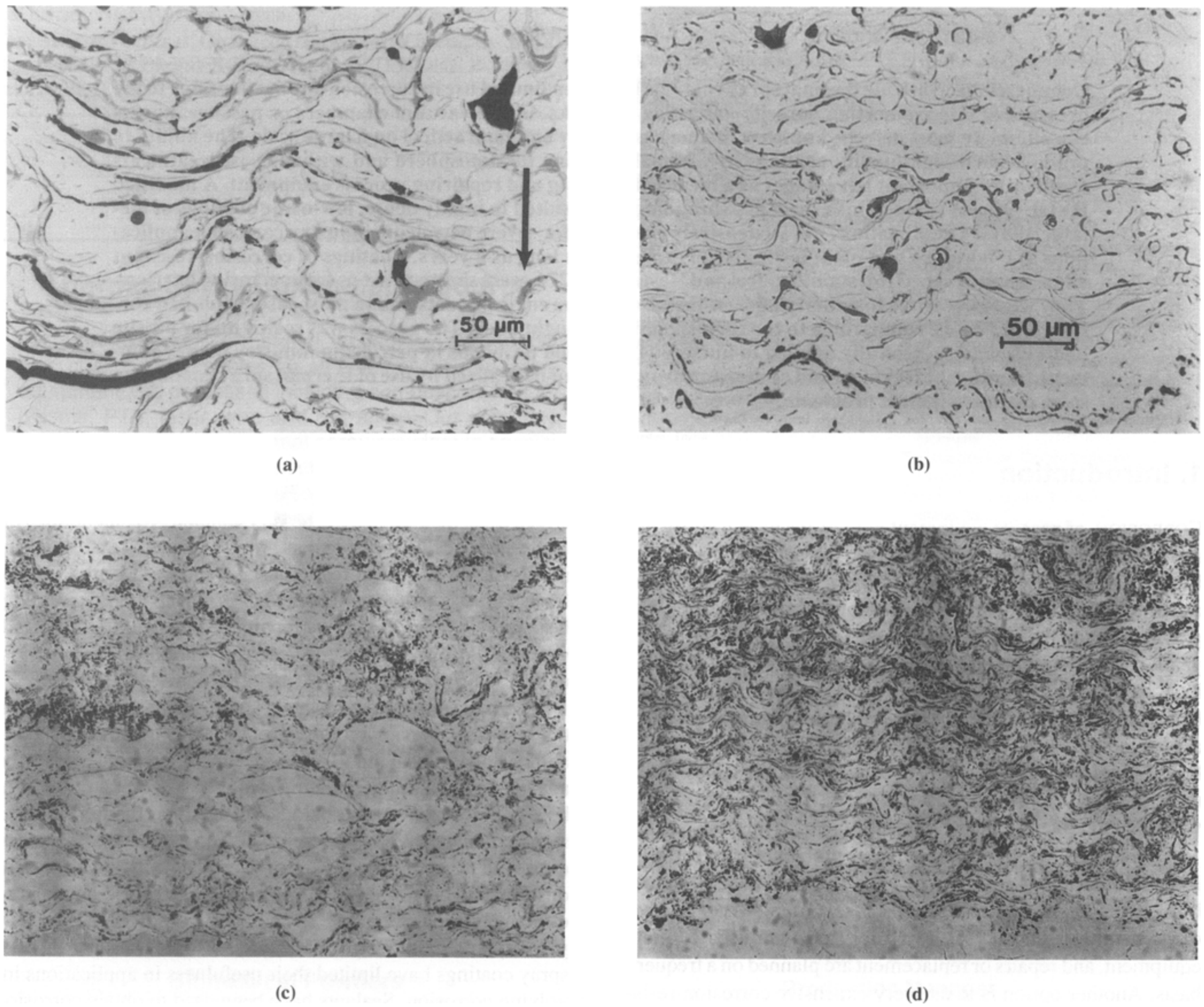


Fig. 1 Polished cross sections of typical commercially obtained Hastelloy C-276 coatings obtained by (a) flame spraying, (b) plasma spraying, (c) HVOF (method A), and (d) HVOF (method B). All micrographs were taken at the same magnification.

(without gun motion control devices). Examples of these defects are shown in the photomicrographs of Fig. 1.

All these specimens are examples of the best commercially available Hastelloy C-276 coatings by various processes, produced by different reputable commercial spray vendors. Results with type 316L stainless steel coatings look almost identical to these. The coatings in Fig. 1 are all transverse sections, photographed at similar magnifications, and oriented with the substrate at the bottom. All are in the as-polished condition, using polishing procedures that were optimized for this alloy to minimize

tions. These tests showed that Ultracoat coatings on carbon steel samples could survive test durations of several months without breakthrough to the substrate. In contrast, all samples with conventionally sprayed flame, wire, plasma, and HVOF coatings failed in a matter of hours or days. This routine failure of conventionally sprayed coatings is not surprising. There is little discussion of corrosion testing on thermal spray coatings in the literature. Where it is found,[1] testing usually is done on vacuum plasma sprayed or post-treated coatings. Even then, corrosion tests are often performed on the coating layer itself, and the abilmize pull-out.

Figure 1(a) shows a typical result of flame spraying, and Fig. 1(b) shows that of a high-quality plasma spray coating. Figures 1(c) and (d) are results from two different commercial HVOF techniques using hydrogen fuel gas. With HVOF techniques, it is possible to get good particle deformation and high densities in metallic alloys (particularly when hydrogen is used as the fuel gas). However, oxide scales with these metallic alloys are severe and continuous. Individual powder particle surfaces are clearly outlined by oxide layers, and interparticle bonding is obviously affected. Also, for all processes, the degree of parameter optimization varies greatly, and the uniformity of the microstructure is poor when applied manually.

With the high densities that are possible using HVOF equipment, refinements to the process were developed in an attempt to eliminate the remaining interconnecting porosity and to greatly reduce oxide formation. These refinements included the use of hydrogen fuel, optimized gas pressures and ratios, and controlled starting powder particle size distribution and gas content. Additionally, attempts were made to use inert gas shrouding to further reduce oxygen pickup from the environment surrounding the spray stream. Conventional coaxial-type shrouding attachments[6] led to little improvement in coatings, due in part to the high velocity of the spray stream and degree of resulting turbulence. A unique shrouding device was developed, however, that overcame these problems and greatly reduced oxide levels in coatings.[7-9] This device produces a high-pressure, helical flowing inert gas stream around the high-speed particle/gas effluent from the gun.

Coatings of metallic alloys that were optimized around these refinements showed virtually no porosity and extremely low oxide levels. Clean powder interfaces and homogeneous, uniform structures were obtained throughout the coatings. Along with these improved microstructural features, it was found that the deposit efficiency, buildup rate, and allowable thicknesses of the coatings were greatly improved. An example of the as-polished microstructure of a Hastelloy C-276 coating produced by this refined method is shown in Fig. 2. The coating was metallographically prepared in an identical manner to those in Fig. 1, and the magnification of the photomicrograph is similar. The as-polished microstructure is almost featureless. Similar clean, dense results have been obtained with type 316L stainless steel, Hastelloy B, Stellite 6, and Stellite 21. Other comparable alloys also can be produced by this method to the same level of quality. The name "Ultracoat" was used within Amoco Corporation to refer to this process and the resultant coatings, and for convenience, this name will similarly be used in this article.

The potential for a coating of this quality to act as a corrosion barrier was first evaluated through immersion tests in acid soluity of the coating to act as a corrosion barrier to the substrate is not even evaluated.

With these positive initial results, a more comprehensive laboratory test program was carried out to explore the potential use of Ultracoat coatings in specific key problem areas within Amoco's operations. This included corrosion testing, by immersion and electrochemical methods, as well as some mechanical and thermal cycling tests. The main focus of the testing was on Hastelloy C-276 and type 316L stainless steel because one or both of these alloys will perform well in most of these anticipated applications. Examples of environments evaluated include acetic, sulfuric, hydrochloric, hydrofluoric, and carbonic acids, molten sulfur, hydrogen sulfide, and sodium hydroxide. In general, the laboratory tests showed the Hastelloy C-276 and type 316L stainless steel Ultracoat coatings to be effective corrosion barriers and to exhibit corrosion resistance equal to or slightly inferior to the performance of their wrought counterpart. In several solutions, however, the type 316L stainless steel coating exhibited somewhat higher than expected corrosion rates (weight losses). This is believed to be due to the presence of high ferrite levels at the particle boundaries, because significant amounts of ferrite were measured on the surfaces of all atomized type 316L powders used. The Ultracoat coatings also were tested for downhole production applications involving cavitation erosion.[10] Erosion rates similar to those of the corresponding solid alloy were demonstrated.

In addition to these laboratory tests, an extensive program of field evaluations in plant applications was conducted. Numerous applications, with exposures as long as 5 years, have been addressed with good success. Equipment such as pressure vessels, drums, rail cars, heat exchangers, valves, etc., encompassing a broad range of harsh plant environments has been included. To do this, equipment and techniques had to be developed to apply Ultracoat coatings in the field and over large areas. In corrosion applications, the uniformity of the microstructure over these large areas is critical. For this reason, control and automation of process variables and gun motion were used to various extents in these applications. On a smaller scale, the use of coatings on mechanical components, where severe corrosion along with wear or erosion are involved, also was successfully demonstrated. This included severe downhole gas production environments.

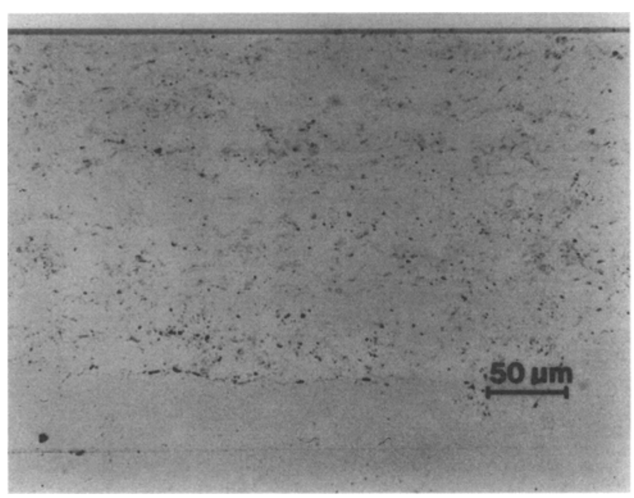
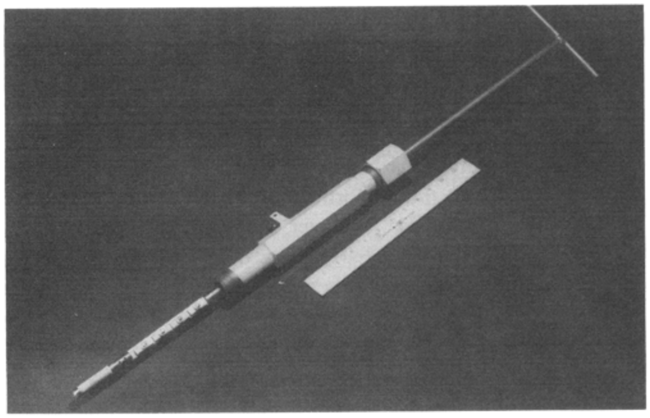
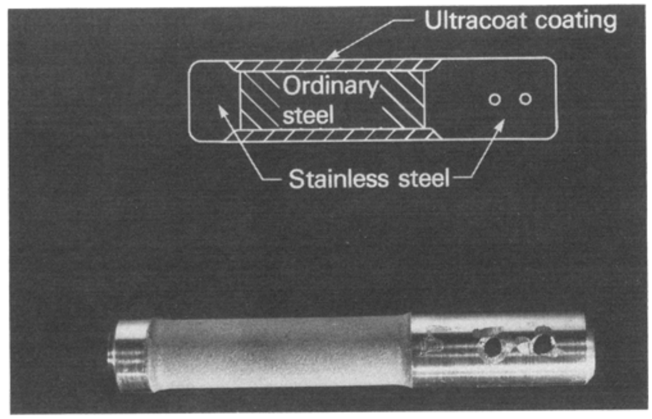


Fig. 2 Polished cross section of Hastelloy C-276 coating produced by the Ultracoat HVOF technique.



(a)



(b)

Fig. 3 (a) Retractable coupon probe. (b) Probe tip corrosion sample for coating evaluation.

3. Application Examples

In this section, specific examples of problem areas that were addressed with this thermal spray coating technology will be discussed in detail. These examples were chosen to show the wide range of potential applications in petroleum industry operations and the benefits that are possible.

3.1. *Solvent Extraction Unit*

A refinery solvent extraction unit experienced unexpectedly severe corrosion of carbon steel equipment due to the presence of organic acids. To evaluate the potential of Ultracoat type 316L stainless steel coatings to withstand this environment and to protect carbon steel, seven areas were probed with a special device called a retractable coupon probe. This probe, shown in Fig. 3(a), can be inserted through a small gate valve while the unit is running to test various materials in an actual process stream. The flat metal coupons are mounted on the front of the probe, along with a special cylindrical coated sample at the tip. This cylindrical sample was designed, as shown in Fig. 3(b), to

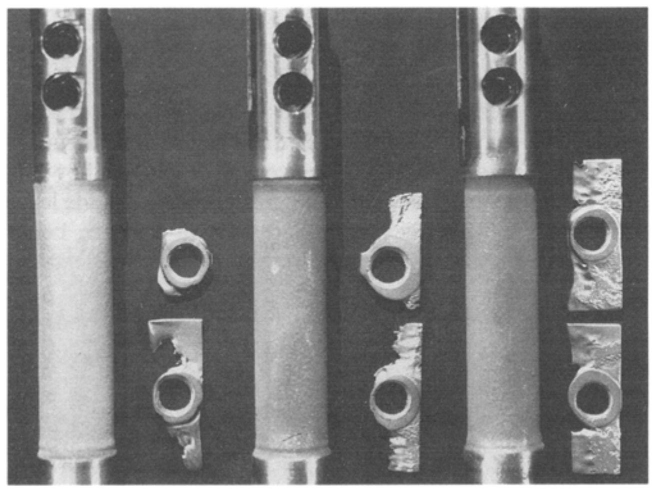
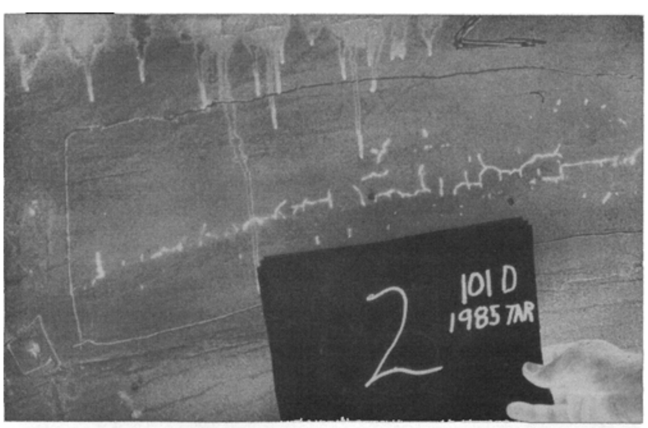


Fig. 4 Exposed Ultracoat coated samples (the long rods) alongside corresponding carbon steel coupons (in pieces) from three locations in a solvent extraction unit.



(a)

(b)

Fig. 5 Dye-penetrant inspection photographs of areas in the bottom of a hydrocracker reactor showing (a) a crack network in the original overlay and (b) new cracks emanating from weld repair of previously existing cracks.

evaluate the ability of the coating to protect carbon steel. The sample is made of stainless steel to ensure its integrity, but it contains an undercut center area with a carbon steel sleeve. The coating is applied over the carbon steel and onto the undercut edges of the stainless coupon ends, thereby completely encapsulating the carbon steel.

Seven probes were inserted in various areas of the process stream where corrosion was most severe. Each probe had a coating sample along with several carbon steel control coupons. The probes were left in place for a 3-month period. Temperatures in some areas were as high as 315 °C (600 °F). After removal, all of the Ultracoated samples were found to be in excellent condition. On all of the probes, the coatings showed no signs of attack and had protected the underlying carbon steel base metal. The steel control coupons on the other hand were heavily corroded. Figure 4 shows coating samples from three probes alongside two carbon steel coupons from the corresponding probe. In some locations, the carbon steel corroded at rates of 1.8 mm/year (0.07 in./year).

3.2. *Hydrocracker Reactor*

Hydrocracker reactors are typically as tall as 21.3 m (70 ft) with a diameter of about 3 m (10 ft). Due to the high pressures and temperatures (greater than 13,800 kPa, or 2000 psi, and 427 °C, or 800 °F) contained in these vessels, the wall thickness is usually on the order of 15.25 cm (6 in.). The presence of high-pressure hydrogen requires that the vessels be made from a 2.25Cr-1Mo steel, and the presence of H_2S calls for a corrosion-resistant weld overlaid lining of an austenitic stainless steel.

One problem that can be experienced in this type of equipment is cracking in the stainless steel overlay. Cracking in an overlay can have several causes. In a particular problem experienced by some refineries, the δ ferrite in the stainless steel overlay converts to a brittle σ phase as a result of improper control of heat treatment during fabrication. When the unit starts up, the high-temperature cycling during operation then leads to the formation of crack networks in the overlay such as those shown after dye-penetrant inspection in Fig. 5(a). Cracks such as these would normally be repaired by welding, but in this instance, the heat input from the repair welding causes additional cracking in the embrittled overlay. An example of this is shown in Fig. 5(b). Repeated attempts have been made to find a suitable weld repair method, but all have been unsuccessful. Because the crack networks grow and deepen with each operating cycle of the reactor, the lack of a suitable repair method means the vessels have to be replaced when the crack depth in the overlay nears the base metal. This is a very costly undertaking, particularly considering the expense associated with the equipment downtime.

An effort was made to determine whether a thermal spray coating could be used to repair the overlay in several hydrocracker vessels showing the above phenomenon. Because thermal spraying could be performed without imparting much heat to the surrounding embrittled overlay, it could conceivably be used to protect the exposed base metal after the cracks are ground out of the overlay, as shown in Fig. 6. The thermal spray deposit, however, would have to be able to withstand the severe, high-temperature environment, as well as protect the base metal from attack.

This concept was tested in several series of test exposures over a 2-year period in a hydrocracker reactor. Many conventional type 316L stainless steel coatings were evaluated along with the Ultracoat coatings. Two types of tests were performed—flat coupon evaluations and simulated crack repairs. In the first type, flat carbon steel coupons were welded on their edges to a stainless steel plate using stainless weld metal. Thermal spray coatings were then applied over the carbon steel coupons and onto the stainless welds to encapsulate the carbon steel. For the crack repair simulations, large overlaid plates of the actual vessel materials and thicknesses were prepared. The weld overlay was heat treated to the same embrittled condition, and 0.95-cm (3/8-in.) deep grooves were ground through the overlay exposing the base metal. These grooves were shaped with 45° angles on the sides, 0.635-cm (1/4-in.) radii at the bottom corners and 0.635-cm (1/4-in.) bottom widths. Coatings were then applied to these grooves in a simulation of the actual repair of ground out cracks. Conventional coatings used in the evaluations were applied to the test plate grooves by several commercial vendors using flame, wire-arc, plasma, and HVOF (Jet-Kote) techniques. Ultracoat type 316L stainless steel coatings were also applied. Duplicate sets of test plates were placed inside the reactor during its annual shutdown and exposed for 1- and 2-year periods.

The results of all of these test exposures showed that only the Ultracoat coatings had successfully survived the test. The Ultracoat coatings stayed in place and protected the underlying base metal from attack. All commercially applied coatings either fell out due to the stresses from the thermal cycling, or, for those

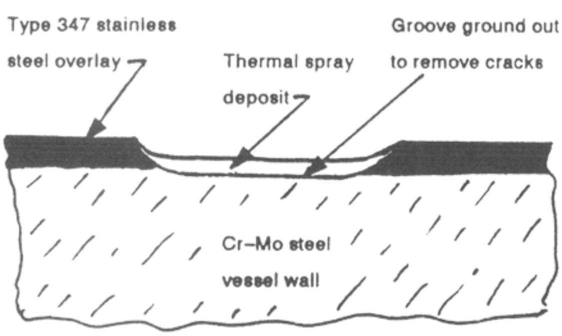


Fig. 6 Schematic of overlay crack repair concept.

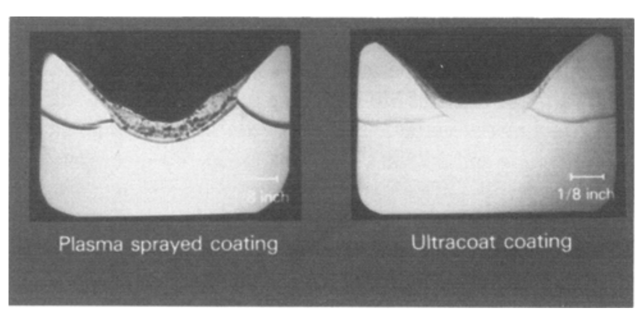


Fig. 7 Polished cross sections of two crack-repair test samples following 1 year exposure in a hydrocracker reactor.

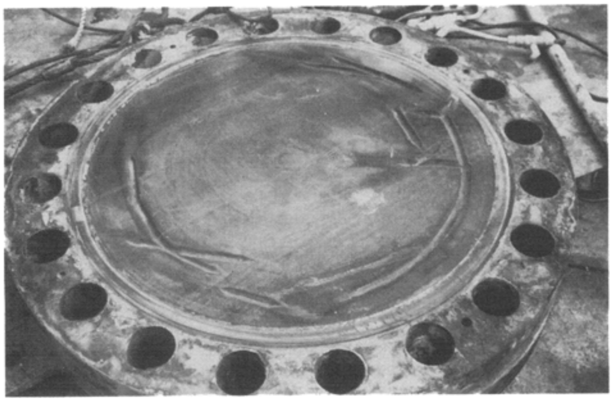


Fig. 8 Heat exchanger channel cover with overlay crack repairs after 2-year exposure in a hydrocracker unit.

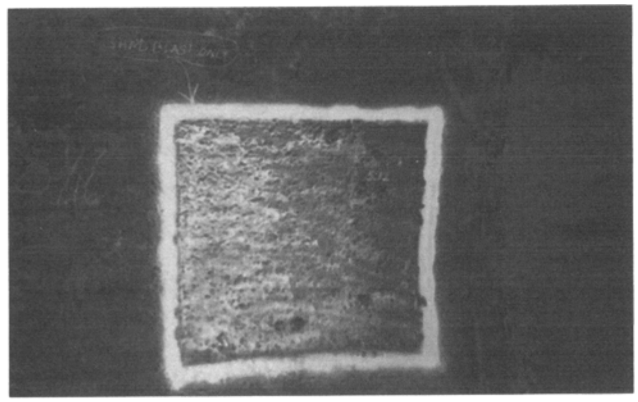


Fig. 9 Corroded area of internal high-pressure separator vessel wall after blasting and prior to spraying.

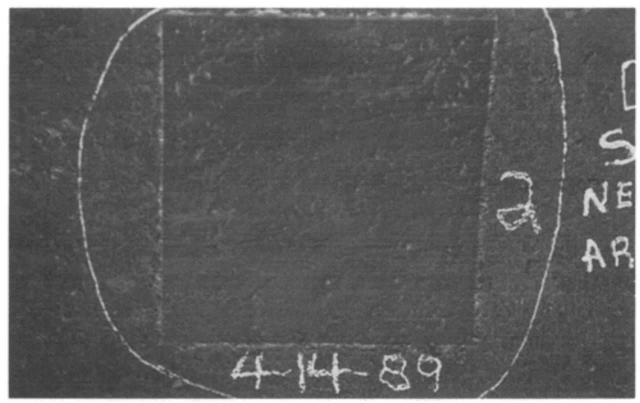


Fig. 10 Coated area of internal vessel wall after 2-year exposure.

coatings still adhering, failed to protect the base metal from attack.

Figure 7 shows micrographs of a conventional plasma sprayed type 316L stainless steel coating with a nickel-aluminum bond coat and a type 316L Ultracoat coating, in crack repair simulation grooves after 1-year exposure. The photomicrograph of the plasma sprayed coating shows the plasma sprayed deposit to be completely sulfidized, with attack in the underlying steel. The Ultracoat coating has a sulfide scale of only about 0.025 mm (0.001 in.) on its surface and no corrosion of the steel base metal.

With these encouraging test results, further evaluations of this crack repair concept were performed on actual plant equipment. A large heat exchanger channel cover from one of the many heat exchangers adjacent to the hydrocracker reactors was selected for testing. The channel covers are 4 ft in diameter, and because they see the same process conditions as the reactors, they are the same thickness and made of the same materials. Various test patterns were machined through the overlay (exposing the base metal) on one channel cover. Ultracoat type 316L coatings were applied to all of these areas. Another channel cover was found that had actual crack networks in the overlay that resembled those in the reactors. These cracks were ground out and repaired by this thermal spray method. Both channel covers were placed back in service on their heat exchangers. Inspections after 2 years of exposure showed the coatings on both parts to be working successfully. Figure 8 shows one of the channel covers with the successful crack repairs after 2 years of exposure.

3.3. *High-Pressure Separator Vessel*

A high-pressure separator vessel in a refinery hydrotreater unit was made from 0.5Mo-carbon steel and left unprotected (no interior lining or overlay). This horizontal vessel was about 12.2 m (40 ft) long and 2.75 m (9 ft) in diameter. The necessary wall thickness (in this case 12.7 cm, or 5 in.) was determined from the process conditions and includes a "corrosion allowance" based on the expected corrosion rate of the vessel.

In service, however, the corrosion that has been experienced in this vessel and other associated equipment is more severe than originally expected. The high-temperature sulfur and ammonia environment causes both a general corrosion of the interior walls and the formation of pits. Vessel replacement or weld overlaying will be required when the corrosion allowance is gone. If a thermal spray coating could be used to protect the interior walls from further corrosion, it would have a significant advantage in cost over these two options. This is because weld overlaying would require pre- and post-weld heat treatment. This is time consuming and adds to downtime costs due to the lengthy unit outage. Thermal spraying, on the other hand, can be applied relatively quickly and would not require vessel heat treatment.

Testing of the Ultracoat type 316L coating was performed on two areas (each about 930 cm^2, or 1 ft^2, in size) inside the vessel during a planned unit shutdown. Figure 9 shows one of the two areas of the wall prior to coating. The rough surface and deep pitting resulting from corrosion are evident. The areas were prepared by blasting with chilled steel grit. Access to vessels of this type is through a small 40.6-cm (16-in.) diameter manway. To automate movement of the torch during spraying, a track-mounted motor system was assembled inside the vessel and attached to curve rails that were magnetically mounted on the walls. The coatings applied were approximately 0.76 mm (0.03 in.) in thickness.

After 2 years of operation, the vessel was again opened and the coatings inspected. Both areas were found to be in excellent condition. The coatings were intact, no attack to the coating surface or edges had occurred, and the underlying base metal had not corroded further. Figure 10 shows one of the coated areas after the 2-year exposure.

3.4. *Sulfur Rail Cars*

Rail cars that are used to ship sulfur have steam coils under the insulated outside jacket to liquefy the sulfur. Although liquid sulfur is not normally corrosive to steel, certain cars have been found to be prone to localized attack. This attack occurs in areas of these cars where moisture contacts the residue remaining after the sulfur is unloaded. The cause of this attack is believed to be the formation of sulfurous acid. One such area is shown in Fig. 11. Because the wall thickness is only 1.3 cm (0.5 in.) to begin with, not much corrosion of this sort can be tolerated.

In an effort to see if Ultracoat coatings could repair these areas and prevent any further corrosion, tests were conducted using two liquid sulfur rail cars showing this attack. Three affected areas were coated in each car. The areas ranged in size from 930 to 3720 cm^2 (1 to 4 ft^2). Both Hastelloy C-276 and type 316L stainless steel coatings were applied by the Ultracoat process inside the rail cars using the same track-mounted motor system mentioned in the previous example. Following the coating application, both cars were returned to normal service and then reexamined after an 18-month period. At that time, all six coated areas were found to be in excellent condition, and no further corrosion had occurred in the steel. Figure 12 shows a photograph of one of the repaired areas after the 18-month exposure.

3.5. *Sulfur Condenser Head*

Numerous carbon steel condenser heads from a new sulfur-producing plant are being scrapped after only 3 or 4 years of service. These 2.1-m (7-ft) diameter heads are flanged to the ends of long sulfur-processing trains, but were being severely attacked by the process stream. The attack occurs in two places—the heat-affected zone of the head seam weld and the impingement area opposite the process stream inlet. The corrosion observed in this application is unexpectedly severe. It is caused by a combination of sulfuric and sulfurous acids.

Because the alternative is to fabricate new heads from solid stainless steel, an attempt was made to repair and protect a condenser head that had not yet corroded through. Type 316L stainless steel is known to be immune to this environment. Therefore, the Ultracoat process was used to apply type 316L stainless steel to those areas of the condenser head experiencing the attack—the weld heat-affected zone and the impingement area. Figure 13 shows the interior of the condenser head after the coating was applied. Approximately 2.33 m^2 (25 ft^2) of coating, comprising 0.64 mm (0.025 in.) in thickness, was used. The coating was applied using a special robotic positioner to control the motion of the torch. This sulfur-processing unit was inspected after 18 months of service, and the coating on both the weld and the impingement areas of the condenser head were in excellent condition.

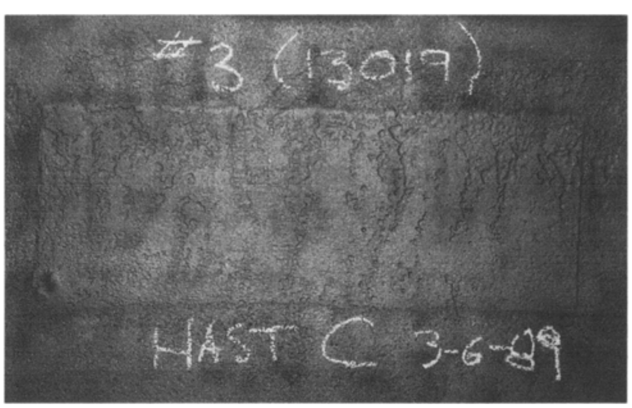


Fig. 12 Coated area inside sulfur rail car after 18 months of service.

3.6. *Reformer Valve Stems*

Failures of large, motor-operated valve stems in reformer units had been occurring on a frequent basis. The failures were due to leakage between the packing and the stem, resulting from a combination of galling wear and corrosion. The stems are made from type 410 stainless steel. Galling occurs from contact with the stuffing box bushing or gland follower. Corrosion is due to hydrochloric acid (generated in the process from chlorine in the catalyst). These stems are subject to large cycles in temperature, from about 66 °C (150 °F) to over 454 °C (850 °F). Because

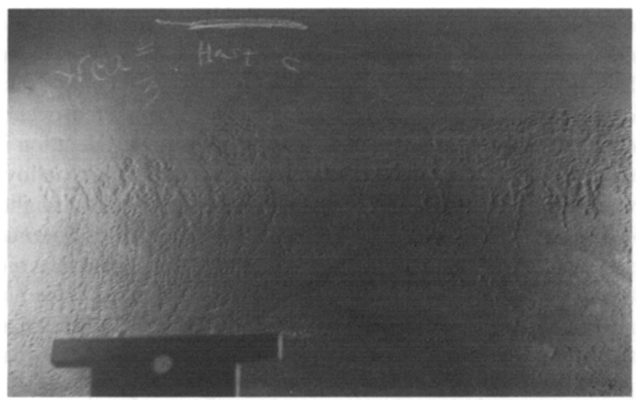


Fig. 11 Localized corrosive attack found in areas of certain liquid sulfur rail cars.

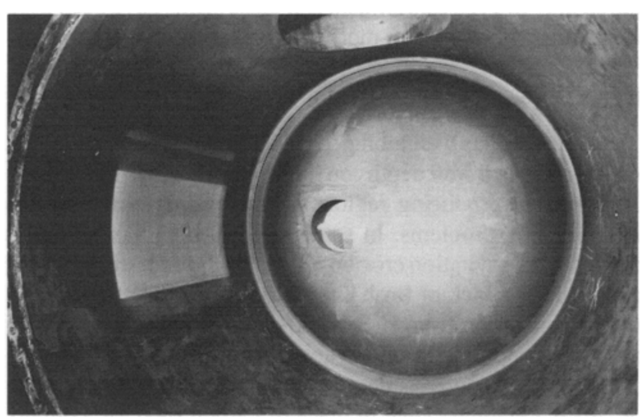


Fig. 13 Inside of condenser head from sulfur-producing unit showing Ultracoat coating applied to entire surface of corroded head seam weld heat-affected zone and to corroded/eroded impingement area.

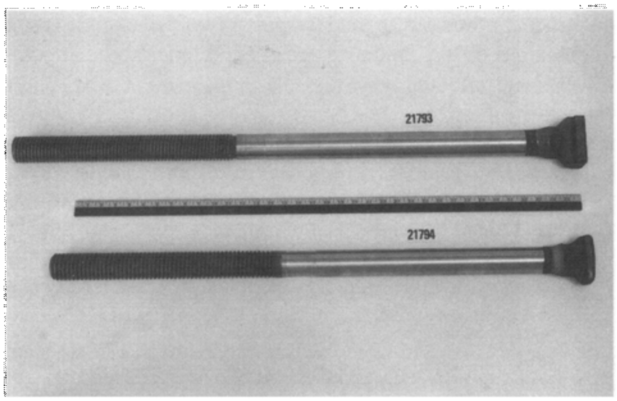


Fig. 14 Two large motor-operated valve stems from a refinery reformer unit. The packing area of each stem has been coated with Hastelloy C-276 by the Ultracoat process and ground to the required finish.

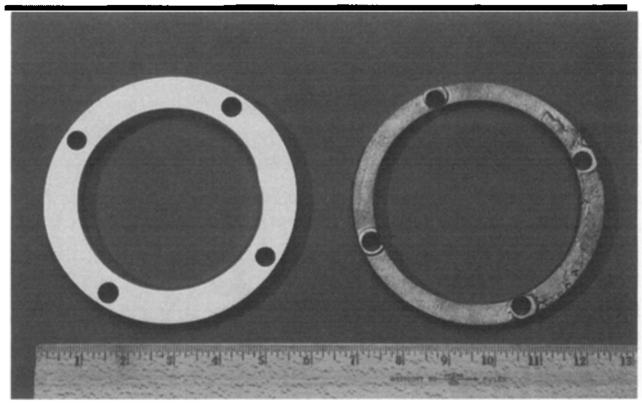


Fig. 15 Two ring samples after testing in a gas-producing well. The ring at left is coated with Hastelloy C-276 by the Ultracoat method and shows no attack.

few materials have the necessary mechanical and thermal expansion characteristics of the type 410 stainless steel, it was decided not to change materials but to correct the problem by protecting the affected area of the stems.

Weld overlays of nickel or cobalt alloys were used successfully for this application; however, many problems had to be overcome first. The type 410 stainless steel is martensitic and undergoes phase transformations during welding. These can lead to cracking of harder weld overlay materials. Once a successful overlay is applied, however, distortion of the stem occurs due to the high heat input. A difficult straightening operation is then required. Spray and fuse nickel-base self-fluxing alloys were also successfully tested, but they too require stem straightening due to the high heat input of the fusing step. Thermal sprayed chrome oxide and chromium oxide were tried to avoid the above heat-related problems, but these coatings were not able to prevent corrosion of the underlying stem. It was felt that the Ultracoat process could provide both the corrosion/wear protection and prevent the need for a straightening step.

Figure 14 shows two large reformer valve stems that were coated on their packing areas with Hastelloy C-276 by the Ultracoat process. Heat input was minimized, and no straightening operation was necessary. The coatings were ground to the required 0.41 μm (16 μin.) finish, and these stems have been used successfully in service for more than 3 years without problems.

3.7. *Downhole Gas Production*

Sections of gas well tubing, each 9.2 m (30 ft) in length, join together to reach well depths on the order of 3000 m (10,000 ft). Different gas-producing regions have differing environments and corrosion problems. In some regions, high gas velocities create severe cavitation erosion effects on the ends of the tubing partly due to a lack of flush connections. This, in combination with the corrosion from H_2S or CO_2, causes accelerated pitting on the tube ends and eventual tubing failure.

More corrosion-resistant alloys would solve this problem, i.e., a 13Cr stainless steel in place of carbon steel, or a duplex stainless alloy in place of the 13Cr stainless. The cost of upgrading the entire length of tubing, however, is extreme. Because the problem is isolated to the end of the tube, a preferable solution would be to use a coating to upgrade only the affected area. Due to the severity of the cavitation erosion and corrosion effects, however, extensive testing was required to qualify a thermal spray coating for this service.

To evaluate the suitability of Ultracoat Hastelloy C-276 coatings, laboratory corrosion tests were conducted in simulated downhole environments. These tests included studies of possible accelerated corrosion due to galvanic effects. Results were positive, confirming that galvanic corrosion (due to the small area of coating) would not be a problem with Hastelloy C on carbon steel. Cavitation erosion tests were then conducted using the ASTM method.[10] These showed that the Ultracoat Hastelloy C coatings can both survive this severe testing, as well as demonstrate erosion rates that are similar to those of solid Hastelloy C.

These successful laboratory results led to actual tests in a producing gas well in the Gulf of Mexico. Ring samples mounted on a test spool were placed in the gas stream. The rings were carbon steel, and the coating was applied to the face and internal diameter. The coatings were machined to a smooth finish. In this well, it had been found that gas velocities above about 9.2 m/s (30 ft/s) will cause the corrosion/erosion effects in 13Cr stainless steel. Hastelloy C should be immune to these effects. An initial test exposure of a coated sample for 1 month at gas velocities of about 7.6 m/s (25 ft/s) (below the threshold) showed no problems with the coating surviving the testing. A second exposure was then conducted for a 3-month period at high velocities with the well producing at a rate of 34 million standard ft^3/day during the test. Two ring samples after testing are shown in Fig. 15. The sample on the left is a carbon steel ring with the Ultracoat Hastelloy C-276 coating. Its inside diameter is 8.9 cm (3.5 in.), which corresponds to a gas velocity of 22.9 m/s (75 ft/s). The ring sample on the right is uncoated carbon steel with an inside diameter of 11.4 cm (4.5 in.). It underwent a gas velocity of 15.3 m/s (50 ft/s). Despite the 50% higher velocity during the 3-month exposure, the Ultracoat coating and the underlying ring show no ill effects. The carbon steel sample, however, exhibits severe attack.

4. Conclusions

As demonstrated above, refinements in HVOF thermal spraying have enabled production of high-quality coatings of corrosion-resistant metallic alloys. The reduction in porosity and oxides approaches levels that are normally obtained only through controlled atmosphere chamber spraying or post-treatments. These coatings have been shown to act as true corrosion barriers and to exhibit corrosion behavior close to that of the corresponding wrought material.

These coatings can be used to address a wide range of problems in harsh environments that are beyond the capabilities of conventional coatings, both with and without sealers. Thermal spraying can offer highly cost-effective solutions to these problems because of its speed, portability, and controlled heat input to the base metal. The lack of heat buildup prevents distortion, stresses, and metallurgical change. With suitable controls of process variables and gun motion, large areas can be coated with uniform results.

Examples of several diverse applications that were successfully proven in petroleum industry operations were described. These included walls of pressure vessels and tank cars, cracked overlays, valve components, and gas well tubing, where severe corrosion or combinations of wear and corrosion were involved. Corresponding problems in other industries, such as chemical processing, pulp and paper, power generation, etc., can similarly benefit from this thermal spray technology.

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