

Ball Valves with Nanostructured Titanium Oxide Coatings for High-Pressure Acid-Leach Service: Development to Application

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ABSTRACT

Since May of 2000, Mogas Industries, in partnership with F.W. Gartner Thermal Spraying Co. and using the services of Perpetual Technologies, has invested time, energy, and resources towards developing novel ball valves for high-pressure acid-leach (HPAL) service. In addition to developing new valve designs, an aggressive coatings development effort has been undertaken to improve the protective quality of the coatings so as to enhance the performance and extend the life of valves in severe HPAL conditions. In 2001, Mogas Industries qualified and applied a nanostructured titanium oxide (n-TiO₂) coating for gold and nickel/cobalt HPAL services. The n-TiO₂ coating provided dramatically superior protection against abrasive and erosive wear, fared very well against high-pressure autoclave corrosion testing, and has performed well in HPAL service.

INTRODUCTION

The nickel/cobalt High Pressure Acid Leach (Ni/Co HPAL) process is a severe service environment with contents that are contained and flow-controlled by vessels, piping, valves, and other equipment. These components suffer significant damage due to factors such as corrosion, erosion, and abrasion and the profitability of the operation turns on their durability and dependability.

A study in 2001 estimated valve costs as 1 % - 2 % of the total plant costs; however, their influence on productivity is significantly greater. Maintenance costs for Ni/Co HPAL service are six times higher than originally anticipated, with valve maintenance representing 30 % - 40 % of the total expense.

The isolation valve of choice for this severe service has been the metal-seated, floating ball valve. This design offers advantages over other designs because of its angular rather than volumetric displacement during operation, its large, low stress, precision-lapped sealing, and its ability to continue to operate in an environment with crushed, abrasive solids. Metal-seated ball valves used in Ni/Co HPAL service incorporate a protective thermal sprayed ceramic top coat that is lap-finished to minimize wear and maximize valve sealing life.

Thermal spray technology involves the projection of molten or semi-molten particles of metals, ceramics, or their composites from powder or wire feedstock (Figure 1). Generally, any material which has a stable molten phase and can be processed into the appropriate feed specifications can be thermally sprayed. The melting is achieved chemically via oxygen-fuel combustion or electrically via an arc.

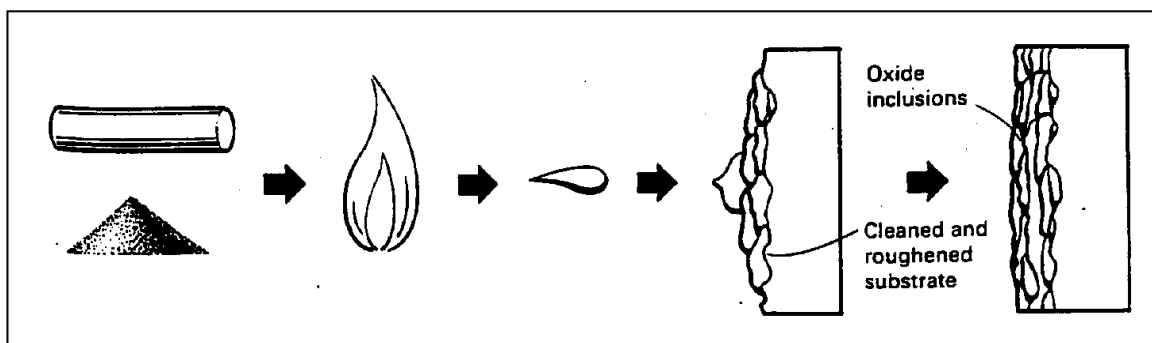


Figure 1 - Simple Schematic of the Thermal Spray Technology (1)

BACKGROUND

Valve Design

Valves for HPAL service must be designed with the severe conditions created by abrasive solids and the highly corrosive elevated temperature environment in mind.

A valve is a machine with a defined geometry including precision sealing areas, a drive system, and a pressure containing housing, all constructed of carefully selected materials as dictated by the specific function of the component. Proper sealing and operational function of a valve requires an evaluation of the function of each component.

A significant amount of design knowledge has been gained through the study and development of valves for slurry transport service, especially involving solids handling. The main difference is that the HPAL environment includes severe corrosion.

This paper focuses on coatings; however, it is important to understand that quality coatings are but a part of the requirements necessary to achieve a long functional design life. Table I lists some aspects of prime concern.

In Table I, each “Result” includes a “Control Method”, “Perceived Importance HPAL”, and a “Verification Method”. In service, true two body sliding wear will not likely exist. It is really a combination of two/three body wear controlled by the effectiveness of a scraping action and geometry. It is believed that three body (abrasive) wear is far more detrimental than pure sliding wear. Generally slurry erosion is believed to be a lesser contributor to the original seal loss; however, once a seal is worn sufficiently to develop an erosive stream, gross damage can occur rapidly.

To achieve optimum valve performance, both good design and operating procedures are required.

Coatings for Ni/Co HPAL Ball Valves

Amongst the numerous surfacing technologies, thermal spray application of single- and multi-layer coatings has been predominantly used.

Within the single-layer category, current specifications use coatings of chromia-blend and pure titania applied via plasma spray in atmosphere (APS) or vacuum (VPS) onto titanium balls and seats. Since the titanium base material is quite resistant to corrosion, the requirement for a corrosion resistant bond coat has been shown to not be critical. The chromia-blend material generally used for the Ni/Co HPAL process consists mostly of chromia with the addition of silica (5 wt%) and titania (3 wt%) to provide a bit

Table I – Issues Relating to HPAL Ball Valves

Factor	Result	Control Method	Perceived Importance	Verification
I. Solids				
Effect on mechanics	▪ pack-in increases loads and stresses	▪ geometry	****	▪ field
	▪ inability to operate ▪ over stress coating	▪ robustness of design	****	▪ model testing
Effect on wear				
Sliding 2-body	▪ loss of seal	▪ geometry/materials properties	***	▪ in-house fixture testing
Abrasive 3-body	▪ loss of seal	▪ geometry/materials properties	***	▪ ASTM G65-91
Slurry erosion	▪ loss of seal	▪ geometry/materials properties/operation	**	▪ lab testing
	▪ gross damage	▪ geometry/materials properties/operation	****	▪ field
II. Environmental				
Corrosion resistance	▪ gross corrosion causes loss of seal and mechanical integrity	▪ corrosion resistant materials	****	▪ lab testing/field
	▪ corrosion at coating bond line leads to coating & seal losses	▪ corrosion resistant materials/reduce or fill coating pores/ add dense intermediate layers	****	▪ lab testing/field
Temperature	▪ differences in CTE results in different thermal expansions of internal components, increasing loads and stopping valve operation	▪ geometry	****	▪ field
	▪ differences in CTE between coating and substrate produces bond line stresses that may result in delamination and loss of seal	▪ select compatible materials/maximize bond strength	***	▪ field/ASTM C633-79
	▪ rapid changes may cause coating cracking/delamination	▪ maximize bond strength/select high strain-fracture resistant coating	*	▪ field
Scaling	▪ silicates & particles adhere to components and promote wear and/or bridging	▪ geometry/operating practices, i.e., purging	***	▪ field
III. Operation				
Speed, Frequency, Differential Pressure	▪ effects velocities, exposure of critical seal surfaces, and heating and cooling rates	▪ operating practices/accessories/purges	***	▪ field

of toughness. The chromia-blend coating tends to provide a superior abrasion wear resistance over the titania coating; however, due to the better CTE match between the coating and the substrate, the microstructure and bond strength for the titania coating on titanium components should be theoretically superior to those of the chromia coating.

A dual-layer coating consisting of a ceramic top coat (e.g., chromia or titania) and a metallic bond coat (e.g., titanium and tantalum) has also been specified and approved for different Ni/Co HPAL autoclaves. Since the base material is relatively inert to the corrosive liquid, the key attribute required from the bond coat is its ability to enhance bond strength with the ceramic top coat. As mentioned by Kim et al. (2), the most notable differences in quality between coatings applied via VPS and APS were found when spraying metals. The inert, reduced pressure ambient of the VPS system allows for the application of dense, oxide-free titanium and tantalum coatings. These superior features are critical for most instances where the metallic bond coat is relied upon as a corrosion barrier (3). In HPAL field experience, however, coatings with VPS bond layer did not perform well, as discussed in the following section.

Product Field Analyses

Since May of 2000, extensive product field analyses have been carried out to better relate the compatibility of existing coatings with different HPAL environments. The goal has been to gather as much data relating to the wear and corrosion performance of coatings from actual field applications. This was the only reasonable means of making an educated decision on the direction for this development work. The following are examples of revealing data from different autoclave services.

Vacuum plasma spray (VPS) applied chromium oxide blend top coat and tantalum bond coat on titanium components: 6" Macraes (gold HPAL autoclave) seat in service for 6 months; and, 3"-900 class slurry discharge valve in Canada.

Different regions of the components were sectioned and polished to attain their cross-sectional perspective. Very similar characteristics were observed between the Macraes and Canadian autoclave components. Cross-sectional views of both the top and bond coats are presented in Figure 2 for as-sprayed samples, as well as for the two used components. The most obvious difference on the coatings exposed to HPAL conditions was in the top coat where a very porous structure remained. This differed greatly from the VPS as-sprayed structure of Figure 2-left. The top coat had undergone significant structural change due to chemical attack. Several key features within the top coat microstructure were:

- the brighter regions of the top coat were remnants of the coating with low aspect ratios, and
- the dark regions or voids were uniformly distributed throughout the coating cross-section.

The low aspect ratio remnants, the brighter regions, strongly resembled the size and shapes of the starting powder; hence, these were particles that had been only partially

molten, or not molten at all, during flight and are inherent to thermal spray coating structures (especially in ceramic coatings). It is interesting to note that the voids were fairly well distributed throughout the cross-section of the top coat. These features are evidence of the preferential attack of the lamellar splats that had experienced a stoichiometric change while in their in-flight molten phase. Takeuchi et al. (4) have shown that chromium oxide (Cr_2O_3) applied via the VPS/LPPS process forms a coating with different stoichiometries, e.g., Cr_2O_3 , CrO , Cr_3O_4 , and CrO_2 . One or more of the latter three phases may not be as corrosion resistant to the acid vapor or slurry, as compared to Cr_2O_3 .

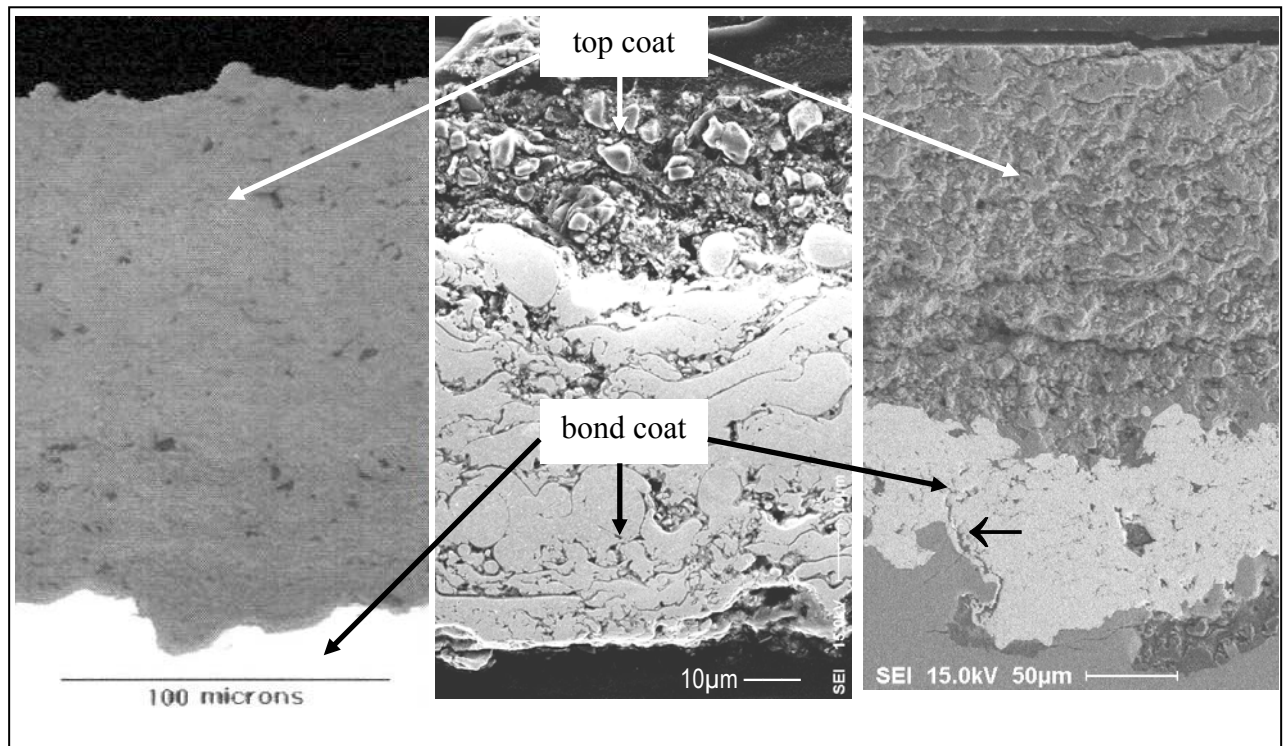


Figure 2 – Cross-sectional View of: As-sprayed VPS Chromia Blend and Tantalum Coatings (left); 2-Layer Coating Flake from Macraes Component (center); and Intact Coating Region from Canadian Autoclave Component (right)

The micrographs (Figure 2-center and right) of the tantalum bond coat layers that have been exposed to the Macraes and Canadian autoclave service, respectively, clearly show signs of etching at the splat boundaries. As-sprayed VPS-applied tantalum does not show splat boundaries since the inert, low-pressure environment inhibits oxidation (Figure 2-left). This was evidence that the splat boundaries were chemically attacked. In addition, splat boundary corrosion led to permeability of the corrosive media to the substrate, thus creating a galvanic cell between the tantalum bond coat and titanium substrate.

The damage resulting from the galvanic corrosion between the tantalum bond coat and titanium substrate is clearly seen in the lower portion of Figure 2-right. There were cracks and flaws formed in both the bond coat and the substrate. The cracks were caused by hydrogen embrittlement, with hydrogen forming at the cathode region (tantalum layer) of the galvanic cell. Both tantalum and titanium are susceptible to hydrogen attack. This observation was further validated by microhardness measurements where the average microhardness of the tantalum layer from the Canadian autoclave ball was measured to be 213 HV_{0.1} as compared to 163 HV_{0.1} on VPS as-sprayed tantalum coating (2). The increased hardness of the tantalum layer, after exposure, is indicative of a chemical deterioration within the region, including hydrogen embrittlement leading to the crack formation.

Atmospheric plasma spray (APS) applied chromium oxide blend top coat with APS applied titanium bond coat from 10" discharge valve ball used at Cawse Nickel for 7 months.

Flakes of chromium oxide blend top coat were removed from a 10" discharge valve ball and analyzed to view its structure and composition. The bond coat remained on the component. Figure 3 provides a cross-sectional view of the top coat and the elemental maps of key constituents in the corresponding region of the coating. The SEM micrograph of the flake shows the presence of unmelted particles and microcracks in a matrix of dense chromium oxide blend (Cr₂O₃-blend). When compared to the as-sprayed microstructure of the same coating, the flake did not show any obvious signs of degradation. Elemental mapping of the cross-section did not reveal any significant segregation within the flake. The presence of a distinct silicon-rich region was likely a result of contamination originating from the powder or the polishing media; in any case, they were too few to play any role in the coating's performance. The SiC at the surface were part of the silicates found in the scale. Based on these results, there was no evidence of corrosive attack within the APS top coat flake.

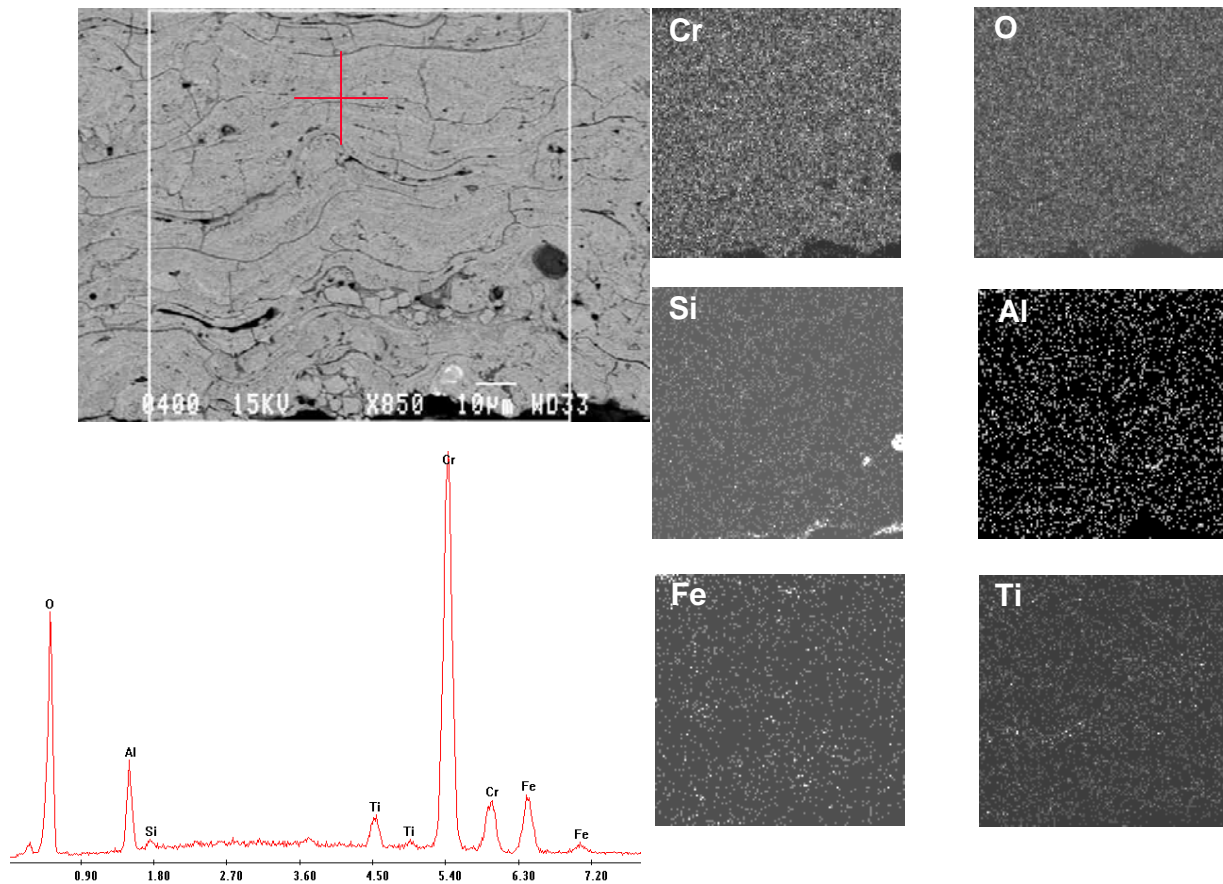


Figure 3 – SEM Cross-sectional View of the APS Top Coat (top left), Elemental Mapping of the Corresponding Region (right); and EDS Spectra of Local Regions of Coating (bottom left)

Nanostructured Thermal Spray Coatings

Between 1996 and 2001, Dr. Lawrence T. Kabacoff (Program Officer) at the United States Office of Naval Research (ONR) headed an investigation on the "Thermal Spray Processing of Nanostructured Coatings" (5). The work was based on the notion that properties of existing materials drastically change when physical features (i.e., grain size, fiber diameter, layer thickness, particle diameter) of a material are reduced to and kept below 100 nm. ONR's objective was to save the Navy money by extending the service life of machinery and other assets. A practical constraint of using existing Navy thermal spray hardware for the application of nanostructured coatings was imposed on the program. Amongst the numerous successes derived from the program, the results from a specific nanostructured coating, alumina-titania, were of relevance to our goals.

The ONR program developed a method of applying a commonly used wear-resistant coating material, alumina-titania, in nanostructured form. The new n- Al_2O_3 -

13TiO₂ coating possessed far superior properties over its microstructured commercial counterpart of the same composition. The properties included:

- enhanced bond strength (up to 2X)
- superior wear resistance (2 to 4X)
- remarkable toughness

Mogas Industries, FW Gartner Thermal Spray Co, and Perpetual Technologies' Coatings Development

In May of 2000, Mogas Industries partnered with FW Gartner Thermal Spraying Co. (FWGTS) and acquired the consulting services of Perpetual Technologies to develop a customized, nanostructured ceramic coating specifically for Au and Ni/Co HPAL ball valves. This would permit Mogas Industries to maintain control over a unique coating that outperforms all others. To effectively meet the objective, the following preliminary tasks were carried out:

1. research field performances of different coatings
2. research new and existing coatings, e.g., functionally graded structures, titanium-base cermet structures, etc.
3. carry out detailed failure analyses
4. make an educated decision on coating material(s)
5. proceed with developing a customized nanostructured coating
6. determine feasibility of post-spray processing of nanostructured coating
7. carry out laboratory testing for abrasion, erosion and corrosion resistance

Upon evaluating the results of the first three tasks, it was evident that no existing coatings/processes would adequately serve the HPAL application; hence, a decision was made to proceed with development of a nanostructured titanium dioxide (n-TiO₂) based top coat with no bond coat. The main reasons for this decision were the following:

- Based on the wide use of titanium in HPAL autoclaves, there were no questions about the inertness of titanium oxide to the harsh environment.
- Titanium oxide has a coefficient of thermal expansion similar to titanium; hence, the residual stress between the coating and substrate would be mitigated and could lead to enhanced bond strengths.
- The presence of a metallic bond coat was linked to accelerated corrosion and embrittlement.
- Stoichiometric changes occur in VPS applied ceramic coatings.

Development activities were systematically pursued and by October 1, 2001, Mogas Industries and FW Gartner had qualified and begun commercially applying the first generation, patent-pending, n-TiO₂ coatings onto HPAL ball valves. Numerous oral presentations and papers have been given and published on Mogas' progressive n-TiO₂ coatings effort (6-11). Since this group's initial introduction of n-TiO₂ coatings to the public, at least one other group has focused their effort in developing a similar coating (12). On February 26, 2003 an Australian Innovation Patent was certified to Mogas

Industries and FW Gartner for the application of n-TiO₂ coatings (13); patents for other countries were filed in 2002.

DEVELOPMENT

Coatings Development (in chronological order)

The general approach to the processing of nanostructured thermal spray ceramic coatings is illustrated in Figure 4. The main aspects of the approach included processing well bonded agglomerates of nanostructured or ultrafine particles, thermal spraying of powder to optimize coating properties, and characterization/testing of coating.

Once an adequate powder feedstock was processed, APS spray parameters were developed to optimize bond strength, microstructure, microhardness, and crack propagation characteristics. Comparisons were made between APS TiO₂ coatings derived from conventional microstructured and customized nanostructured powders.

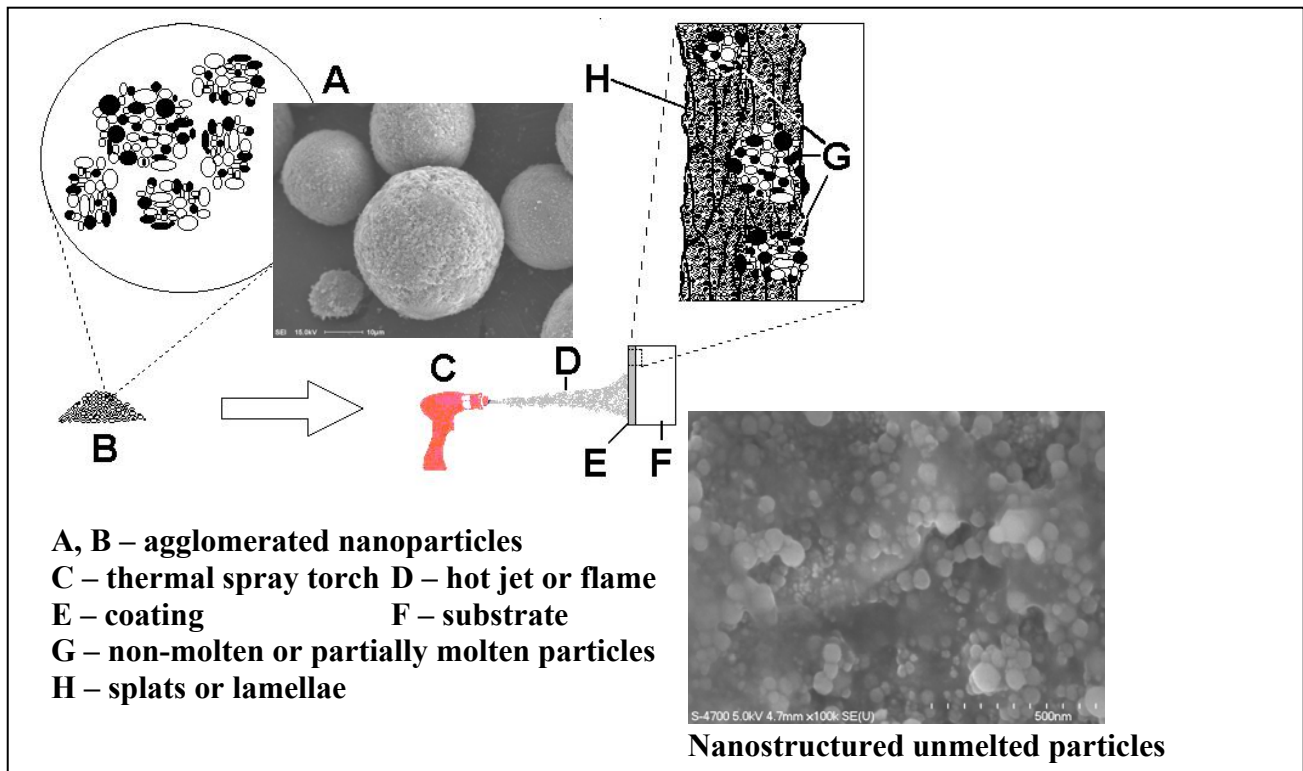


Figure 4 – Schematic of Approach to Thermal Spraying of Nanostructured Ceramic Coatings

Figure 5 provides a comparison between the two coating cross-sectional microstructures. The commercial coating (Figure 5-left) consists of lamellar structure with vertical microcracks and dense unmelted particles (outlined by dashed box) distributed throughout the coating. The different shades of gray reflect the different phases of TiO_2 in the coating.

The microstructure of the APS-applied nanostructured TiO_2 coating (Figure 5-right) had characteristics similar to the APS commercial coating. However, notable differences were found in the nanostructured coating, including the presence of finer microcracks and a uniform distribution of unmelted particles/agglomerates with fine pores (outlined by dashed box).

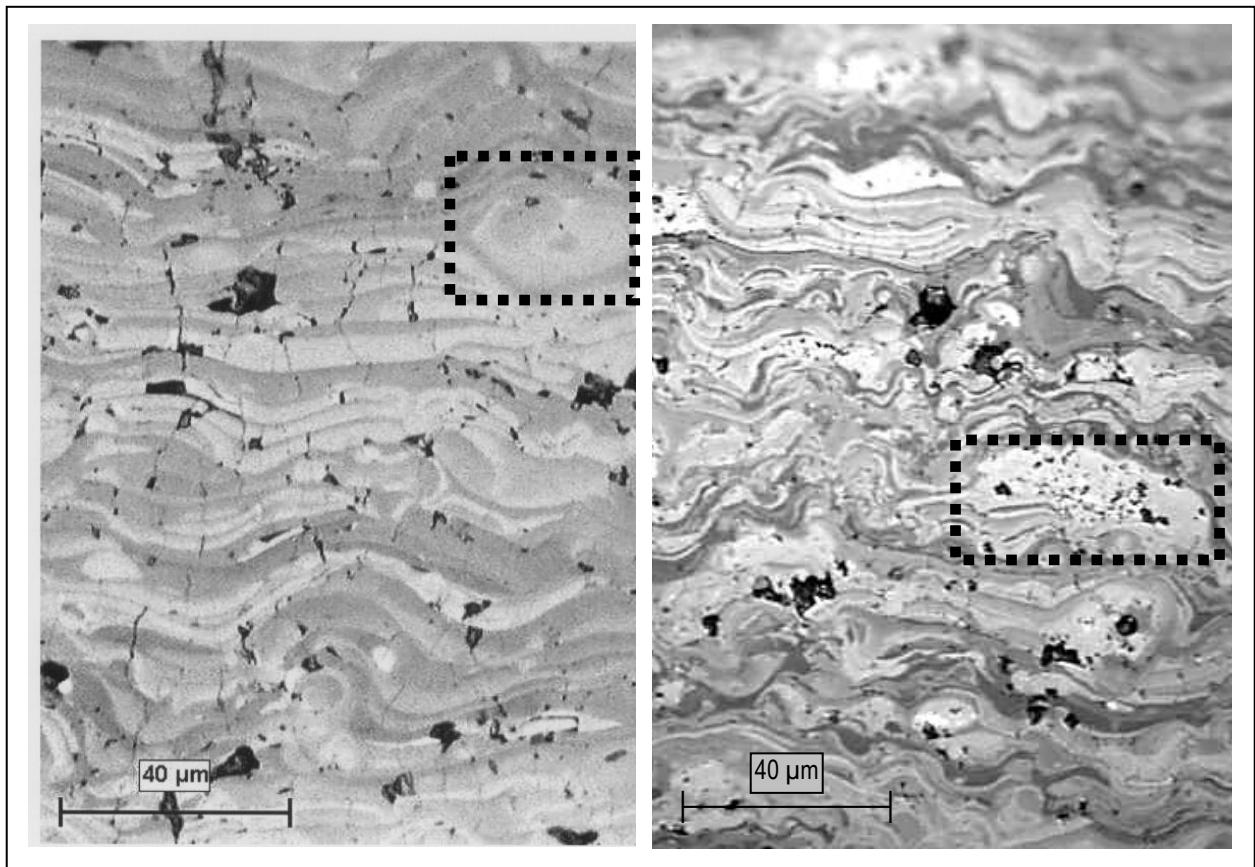


Figure 5 – Cross-sectional View of APS TiO_2 Coatings: Conventional (left) and Nanostructured (bottom)

A very interesting feature was noted when viewing the crack patterns formed by micro-indentations. Figure 6 provides views of the indentation (at 500 g load) regions for both APS coatings. It was apparent that the commercial coating had higher degrees of crack density, width, and length, as compared to the nanostructured coating. A closer look at the region around the cracks in the APS-applied nanostructured coating (Figure 7) reveals interesting associations between the presence of nano-porous unmelted or

partially-melted particles and crack propagation. These porous particles seem to deflect the crack and/or blunt the crack tip, thus hindering its propagation, unlike the dense unmelted particles found in the commercial coating (arrow in Figure 6-left).

Once the association between coating toughness and porous unmelted particles were realized, the focus shifted from developing and applying novel nanostructured titanium dioxide coating using a conventional thermal spray process (APS) to selecting and developing a deposition process to further increase the presence of the porous unmelted particles.

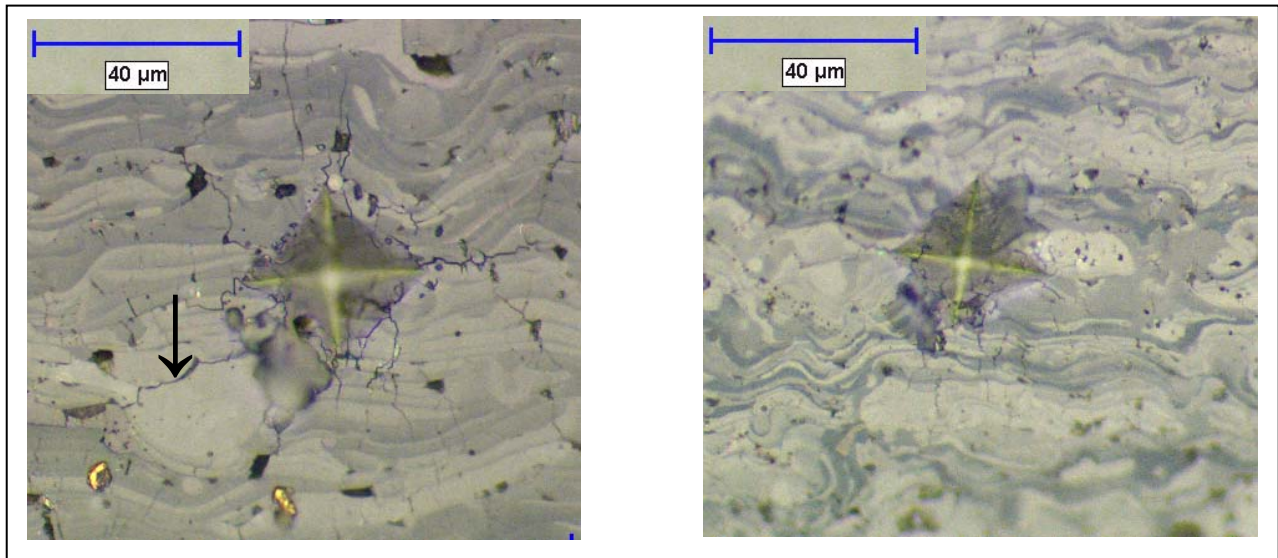


Figure 6 – Micro-indentation Crack Pattern on Commercial (left) and Nanostructured (right) APS-applied TiO₂ Coatings

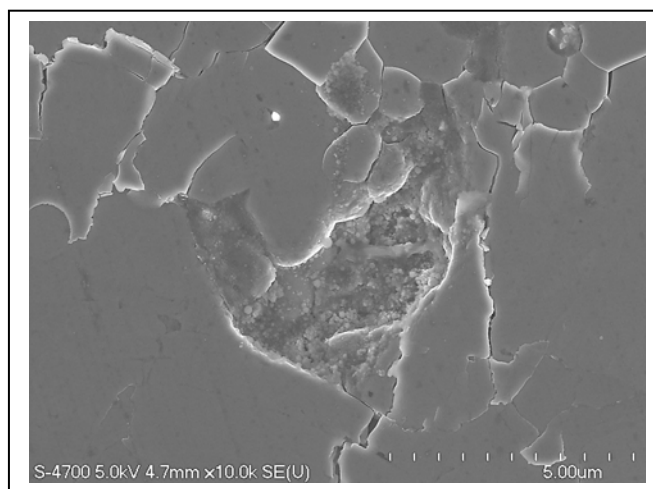


Figure 7 – Field Emission-SEM Micrograph of Cracks around Porous Nanostructured Unmelted Particles

The technical objective was to further increase the toughness of the coatings without compromising their hardness or strength. The difficult task would be in introducing more of these porous unmelted particles without compromising on the mechanical integrity of the coating. Figure 8 provides a cross-sectional view and crack pattern of the n-TiO₂ coating deposited by a proprietary process.

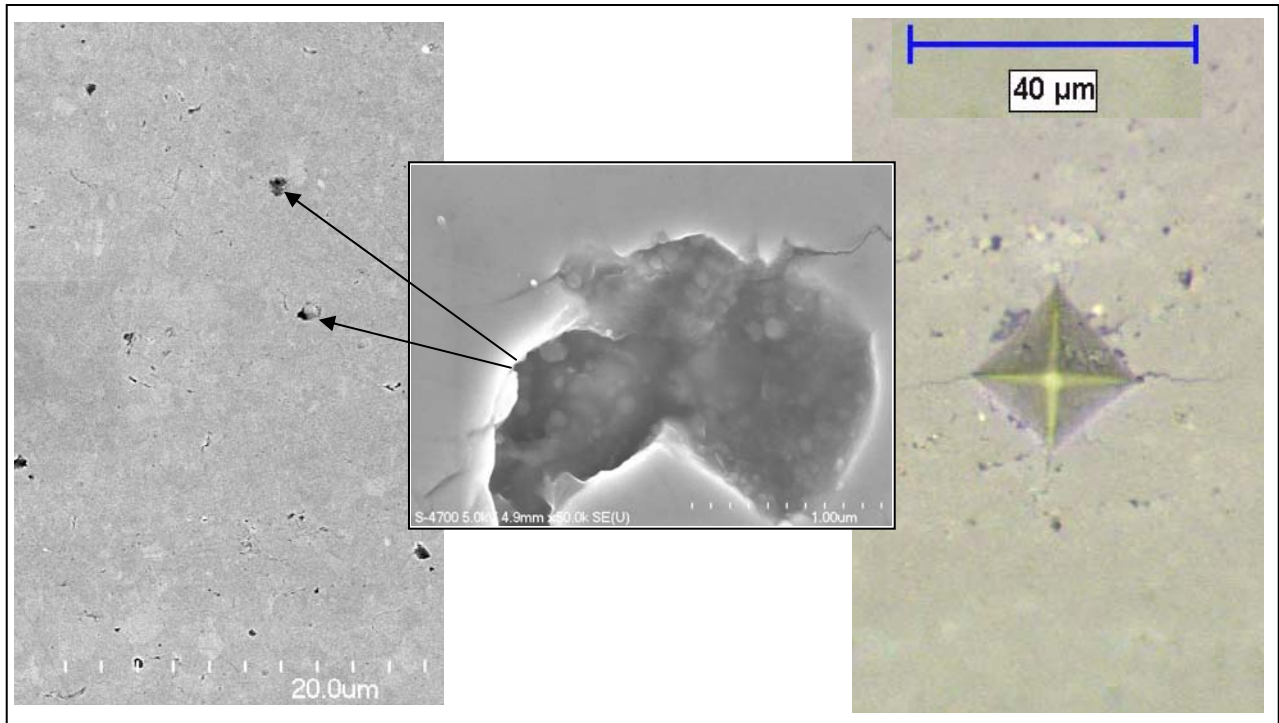


Figure 8 - Cross-sectional View of n-TiO₂ Coating Deposited using a Proprietary Process: FE-SEM of Coating (left) and Porous Particles (center); Micro-indentation Crack Pattern (right)

At first glance, it is obvious that this structure differs greatly from previous coatings. The structure is denser (< 1% porosity) and uniform (non-lamellar and single phase), with no signs of microcracks at these magnifications. The high magnification view of the dark spots within the structure (Figure 8-center) reveals the presence of the familiar porous unmelted particles, distributed uniformly throughout the coating. The crack pattern around the Vickers indent (Figure 8-right) shows very low degrees of crack density, width, and length, as compared to the APS coatings. This apparent increase in toughness was in addition to a notable increase in average microhardness.

The ASTM G65 (procedure E), dry sand rubber wheel abrasion test results for the coatings are presented in Figure 9. It is well understood that abrasive wear resistance is a reflection of strength/hardness and toughness. As we move from left to right in Figure 9, the coating gets not only harder, but also tougher. It is the dramatic enhancement in toughness that provides such a drastic increase in abrasive wear resistance. Unlike

conventional materials/coatings, where increase in hardness is often accompanied by a decrease in toughness, these nanostructured coatings seem to defy this trend.

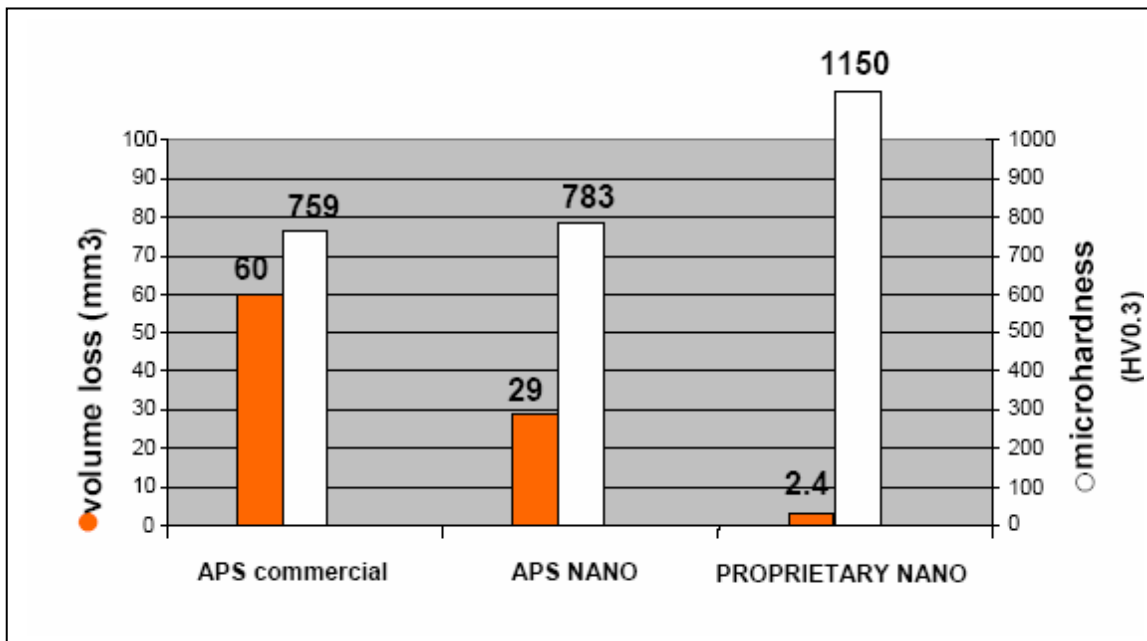


Figure 9 - Abrasive Wear Volume Loss and Microhardness

The other wear property with direct relevance to the HPAL environment is slurry erosion. The following test procedures were used to evaluate the coatings:

- a minimum of 3 tests were carried out on each coating with the scar volume loss measured using laser profilometry
- alumina erosive particle Number 100 (150 microns) was mixed with neutral pH deionised water to form a slurry concentration of 0.66 wt%
- continuous slurry jet had a constant flow rate of 1 l/min and a constant velocity of 20 m/s
- the spray nozzle had a 1 mm inside diameter and 5 cm long barrel, placed 7.6 cm from the test-piece which provided a straight cylindrical shape jet
- impingement angles were 30° and 90°
- exposure durations were 5 min for 90° and 20 min for 30°

The results from the slurry erosion test (Figure 10) showed improved resistance for the n-TiO₂ coating, in the same order as per the abrasion resistance. A unique feature was observed which substantiates the hypothesis derived from the abrasion test results of enhancing the toughness without compromising on the hardness. Thus, unlike conventional materials/coatings, the n-TiO₂ showed improved erosion resistance at both low and high angle slurry impingements.

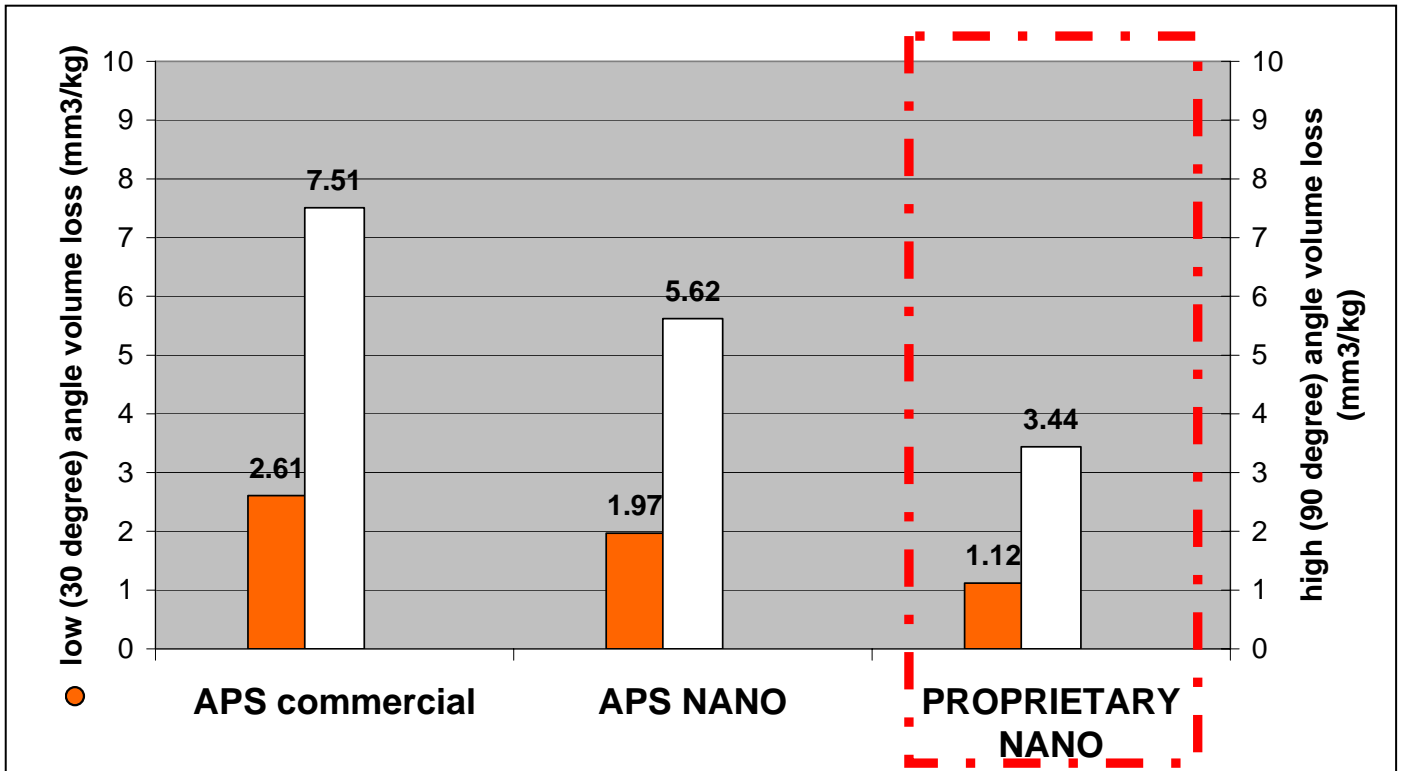


Figure 10 – Slurry Erosion Volume Loss at Low and High Impingement Angles

Due to the severe environment of the Ni/Co autoclaves, accurate performance can only be determined with confidence in the actual autoclave environment. The next best option was to carry out corrosion tests in environments approaching those of the actual autoclaves. Test coupons were sprayed by FW Gartner and corrosion tested by Bacon Donaldson Consultants in British Columbia, Canada. Figure 11 provides photographs of the n-TiO₂ coating on Ti Gr12 test samples before (left) and after (right) exposure to 270 °C sulphuric acid solution, at pH 0.09.

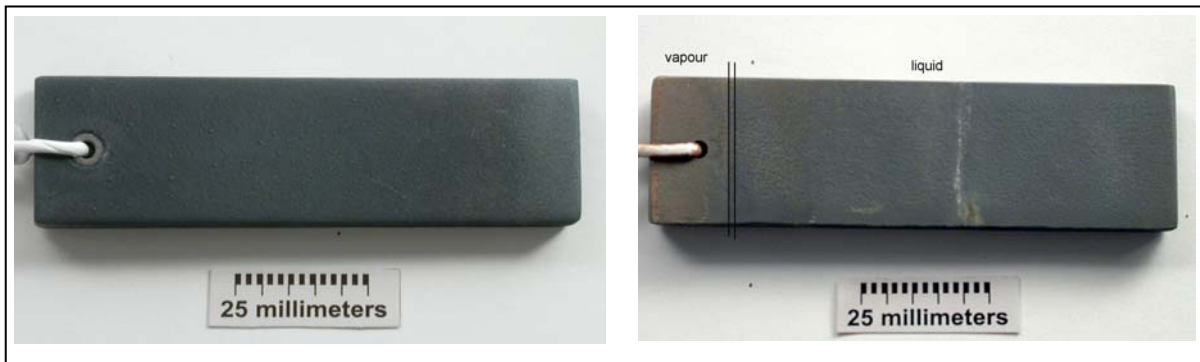


Figure 11 – Photographs of n-TiO₂ Coating on Ti Gr12 Coupons Before (left) and After (right) Exposure to 270 °C Sulphuric Acid Solution, at pH 0.09

Although the corrosion test conditions were not severe enough to inflict any noticeable macroscopic coating degradation, changes in the bond strengths were evident and may be indicative of the degree of chemical attack within the coating and/or substrate. Details on the test conditions and bond strengths for coatings sprayed by both FW Gartner and another thermal spray provider are provided in Table II.

Table II – Corrosion Test Conditions and their Effects on Bond Strengths

Sample Coating/Substrate	Condition	Bond Strength (psi)	
		As-Sprayed	After Exposure
n-TiO ₂ /Ti Gr12	270 °C @ pH 0.09	5100	6600
TiO ₂ /Ti Gr12	270 °C @ pH 0.09	5820	3960
n-TiO ₂ /SAF 2507	190 °C @ pH 2.0	2790	3120
n-TiO ₂ (+)/SAF 2507	190 °C @ pH 2.0	6660	7320
TiO ₂ (Au)/SAF 2507	190 °C @ pH 2.0	7320	1800
Cr ₂ O ₃ (Ta)/A20	50 °C in H ₂ SO ₄	2760	1800
Cr ₂ O ₃ /A20	50 °C in H ₂ SO ₄	2042	1350
Cr ₂ O ₃ (+)/A20	50 °C in H ₂ SO ₄	1260	2160
Cr ₂ O ₃ (Au)/A20	50 °C in H ₂ SO ₄	1200	1050

Please note:

- xxxx(+) were coatings with the enhanced processing
- xxxx(Au) were coatings with gold bond coat; all coatings in this category were sprayed by a thermal spray provider other than FW Gartner
- xxxx(Ta) were coatings with tantalum bond coat

Although the bond strength data after corrosion testing were derived from a single sampling per coating type, values that show changes greater than the typical data scatter of below 15 % are likely indicative of real changes. As expected, the as-sprayed bond strengths were generally related to the degree of mismatch in coefficient of thermal expansion between the top coat and substrate materials. In most cases, greater CTE mismatches resulted in lower bond strength. The increase in bond strength found in some samples exposed to the relatively elevated temperatures is likely due to the stress relief effect within the coating. The characterization work on the samples is still being carried out and will be presented in future reports; however, any significant decrease in bond strengths is likely attributable to corrosive attack at the metallic substrate surface.

Bond Strength

A critical component to the performance and longevity of any coating is its bond strength with the underlying substrate. This program has invested considerable effort into enhancing this critical feature and is implementing a process enhancement to further increase bond strength, hardness, and density of our n-TiO₂ coating. By implementing the process enhancement, a substantial increase in bond strength has been attained in our present production n-TiO₂-2004 coatings (11,832 psi bond strength), as compared to the

previous production n-TiO₂-2002 coating (4,960 psi bond strength). The other positive attributes of the process enhancement included a reduction of at least 35 % in porosity and an increase of 7 % or more in microhardness.

FIELD RESULT

Due to numerous variables in the service conditions that each valve endures, most performance comparisons between valves are made in an indirect manner with, in some cases, uncertain critical assumptions. In 2003, Lihir installed two 10" ID Ti Gr5 Mogas ball valves (with n-TiO₂ and Cr₂O₃-blend coatings) into the same service exposures and conditions for the same duration. Figure 12 provides photographs of the ball surface upon inspection after 10 months service.



Figure 12 – Photographs of the Ball Surfaces with Cr₂O₃-blend Coating (left) and with n-TiO₂ Coating (right) after Same Service Exposure and Conditions

It was clearly evident that the n-TiO₂ coating was in a far superior state when compared to the non-nanostructured Cr₂O₃-blend coating. The surface of Cr₂O₃-blend coated ball had large regions without coating. In contrast, the n-TiO₂ coated ball had a few isolated regions without coating.

CONCLUSIONS

Customized nanostructured TiO₂-base coatings have been developed, qualified, and applied onto ball valves for HPAL autoclaves. The novel corrosion resistant coatings possess enhanced toughness and increased hardness; these features contribute to their superior abrasive and erosive wear resistance over the conventional coating of the same material. By developing the n-TiO₂ coating, a new coating with abrasive wear resistance matching that of the chromia-blend coating is now available. A field result that provided direct comparisons between Mogas 10" ID ball valves with n-TiO₂ coating and with Cr₂O₃-blend coating, placed in the same service for the same period of time, showed clear evidence of the superior performance of the n-TiO₂ coating. This well-adhered titanium dioxide coating eliminates concerns over possible corrosion and bond strength issues associated with the chromia-blend coating. All parties involved in this effort will continue their ongoing work to further develop superior coatings and valve designs for HPAL ball valve application.

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