INCREASING PUMP LIFE IN ABRASIVE SERVICE THROUGH STATE-OF-THE-ART SURFACE PROTECTION

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ABSTRACT

In hydrocarbon processing and oil and gas industries, many pumps are required to transport fluids containing some level of abrasive solids. If not properly designed and equipped with wear resisting materials, the pump components can be worn in a matter of months if not weeks. This paper describes the approach adopted to increase pump life when exposed to fluids containing abrasive media. Pump design issues were addressed. Surface treatments were evaluated using testing and modeling techniques. New surface coatings were developed. Service life was improved through a combination of mechanical and fluid dynamic design changes and the use of wear resistant materials.

The program lead to the development of two new thermal-spray carbide coatings. The first has an extremely high abrasion resistance. The second has a good combination of abrasion and cavitation resistance and can be deposited to a thickness in excess of 0.040 inch (1 mm). Field tests clearly showed the benefit of using these carbide coatings to substantially increase component life. It was determined that chemical vapor deposition (CVD, boriding) is a viable technique for the coating of difficult to access

areas, which can be used in conjunction with high velocity oxy flame coatings for extensive pump protection.

INTRODUCTION

Aim

The aim is to evaluate, optimize, and implement high velocity oxy flame (HVOF) and chemical vapor deposition (CVD) coating technologies, as a means of improving the service life of hydraulic machines used in abrasive service conditions.

Abrasive solids in fluids transported by many pumps in the hydrocarbon and oil and gas industries can cause substantial wear. This can be so severe that repairs are required within weeks. Hence there is considerable interest in finding techniques to inhibit the wear of components exposed to flow. Because there is a tendency to underestimate the wear potential of the media to be pumped and capital expenditure for a new plant is kept to a minimum, installed equipment must be ungradable if it is to be made serviceable at an acceptable cost.

The complex geometry of parts, such as impellers, restricts the use of line-of-sight coating processes to easily accessible surfaces. Therefore, non line-of-sight surface treatments also have to be considered for deep channels. In order to develop a route for optimum wear resistance, high velocity oxy flame (HVOF) coatings were examined for line-of-sight coating, and combined with boriding for inaccessible channels.

The solid particle erosive wear of materials is a strong function of the angle of impact. To maximize life, pump design was reexamined with the aim of matching abrasive particle trajectories to the impact angle characteristics of the wear resistant materials used, and vice versa. Design was also reviewed with the aim of accommodating the application techniques of surface treatments and the use of wear resistant materials.

HVOF deposits of carbides were examined in detail due to their high abrasion resistance, which is proven by the wide-scale use in machinery. Coating properties are a function of powder chemistry and manufacturing technique, and the deposition process. Jet Kote®, which is a second generation HVOF coating system, is an industry standard for the deposition of carbide coatings. Newly developed powders were deposited using the third generation Diamond Jet™ Hybrid HVOF system. These materials were optimized and compared with other available second generation and third generation products.

Because thermal spraying is a line-of-sight process, another surface protection process had to be found for poorly accessible parts. CVD boriding was chosen due to the hard layers formed and some field experience. Being a very high-temperature process, a range of substrates was treated to examine layer morphology and component distortion.

The surface treatments were largely characterized at the author's laboratory of tribology. Here wear tests for tribosystem simulation and metallography were conducted. Worn components were examined in order to document wear mechanisms based on which laboratory tests were chosen. The abrasion, solid particle erosion, and cavitation resistance were measured. The results were used to optimize the thermal spray coatings prior to field-testing.

Overall, the paper aims to show the route taken to introduce erosion resistant materials into pumps. This is tied into the development of the surface treatments, which is an ongoing process.

EVALUATION

Prior to the introduction of surface treatments in equipment, their suitability for service must be evaluated. In this section, the tests used to characterize wear resistant materials as well as the background on their selection is given.

Materials Investigated

Zum Gahr (1987a) investigated the abrasion resistance of many materials, but concentrated on hard phase containing cast-irons. Despite the improvement in wear resistance when compared with structural steels, obtained through the use of hard phases, these materials have never reached the abrasion resistance of the harder full hard-metals and monolithic ceramics. The high abrasion resistance of hard-metals in field applications is extensively described by Uetz (1986). Particularly the tungsten carbide based hard-metals are very resistant to scratching and tougher than ceramics, but expensive to fabricate and very heavy, due to the high density of tungsten.

Coatings have the large advantage that structural demands are carried by the substrate so that they can be optimized for surface protection. Thermal spraying soon tried to replicate hard-metal surfaces by spraying powders containing carbides, albeit with higher matrix contents than the hard-metals, using plasma guns. From the onset, these coatings were able to raise the life of components exposed to abrasive environments. As shown by Schmid and Nicoll (1990), the high temperatures of the plasma gun cause the tungsten carbide (WC) to decompose and react with the matrix, forming brittle compounds that degrade the coating. With the introduction of the high velocity flame spray systems (HVOF), the quality of the carbide coatings improved further. HVOF sprayed tungsten carbide-cobalt (WC-Co) coatings, in particular, have gained widespread acceptance as successful abrasion and erosion resistant coatings in a large number of industrial applications. The most frequently used coatings are tungsten carbide (WC) bonded with 12 percent to 17 percent by weight of cobalt (Co). The WC-Co based materials are characterized by high hardness, high wear resistance, excellent metallic and carbide phase compatibility, and compatibility with many iron and nickel based materials. In the past years, the oxygen supply pressure of the HVOF systems has been raised from approximately 100 psi to 150 psi (7 bar to 10 bar), and aerodynamic improvements made that increase spray particle velocities. Kreye (1997) documents the development and properties of these third generation systems (see NOMENCLATURE). A significant increase in spray particle velocity has taken place. This has resulted in very dense, well-bonded coatings with little WC decomposition. At the United Thermal Spray Conference in 1999, numerous authors presented papers in which the excellent wear resistance of carbide coatings deposited using the third generation devices was shown.

In Switzerland, the hydropower generation community was at the forefront of introducing wear resistant coatings for runners due to the high concentration of abrasive solids in the water. Here ceramic as well as cermet coatings were tested and optimized (Schmid, 1992). With the improvement in the quality of cermet coatings, these gradually replaced the ceramic coatings. The clear increase in runner and water supply system life has established thermal spray coatings in the industry. Simultaneously, after a brief evaluation phase (Schmid, 1989) in which plasma coated cermets were compared to second generation HVOF cermets, coatings were applied to shafts of injection water pumps.

On the North American continent, severely abrasive service conditions are experienced in oil production activities, both on the North Slope of Alaska and in Western Canada. (Typically, produced water injection with high levels of quartz sand.) Oil sands upgrade facilities, such as those operated in Northern Alberta, Canada, have continued to research and implement surface coatings as a means of improving equipment operating life. In both areas, the effective use of second generation HVOF coatings can be demonstrated. A significant increase in component life was recorded in all cases.

For the above-mentioned reasons, HVOF carbide coatings were considered for in-depth evaluation of their suitability for extensive use in pumps exposed to abrasives. It was decided, using available powder and spray component manufacturing resources, to not only rank available systems, but further develop these if found necessary. Spray deposition techniques were compared and the influence of powder chemistry, manufacturing technique, and morphology examined. Properties examined were abrasion and solid particle erosion resistance, cavitation resistance, bond strength, tendency to crack, and maximum practical coating thickness.

Coating thickness is of importance because abrasion resistant coatings can be up to a thousand times more wear resistant than the steel substrate. However, the very best cavitation resistant coatings are only about 20 times more resistant than the substrate. Hence, the coatings must be of sufficient thickness to raise the life of the component when only the cavitation wear rate is considered. This implies a thickness five to 10 times that of purely abrasion resisting coatings is required. Typically, HVOF cermet coatings are deposited to a thickness of 0.006 inch to 0.012 inch (150 μm to 300 μm). Applying the above argument, coatings need be 0.040 inch (1000 μm) thick to fulfil the joint requirement of abrasion and cavitation resistance. Ways of depositing cermets to such a thickness without cracking or spalling were examined.

Despite the successful reduction in wear using cermet thermal spray coatings, additional surface treatments had to be examined. (Thermal spray is a line-of-sight process and hence not all flow channels can be coated.) Galvanic, CVD, and diffusion processes were evaluated. The choice was strongly reduced when coating thickness and hardness were taken as selection properties.

The fairly old process of boronizing, which is reviewed in detail by Graf von Matuschka (1975), was chosen as the process to be examined in detail for the protection of difficult to access surfaces. Boronizing produces very hard surfaces, well suited for the reduction of abrasive wear, but processing temperatures are very high (1650°F to 1850°F, 900°C to 1000°C). These high temperatures can degrade the mechanical strength of the substrate and cause component deformation, which, due to the high surface hardness, cannot be corrected by machining.

Component manufacturing had to be reviewed to accommodate the process. Additionally, 13 percent chromium (Cr) steels, nickel (Ni), and titanium (Ti) based substrates were examined to investigate their properties when borided.

When two coating processes are used within the same equipment, overlapping can take place. Therefore, the possibility of overlaying borided components with HVOF coatings was also examined.

Wear Mechanism Investigation

Protective coatings are part of the tribological system found in equipment. Therefore before they can be ranked, the predominant wear mechanisms found in-service must be documented. Based on these findings, laboratory testing can be structured.

Karimi and Schmid (1992) showed that scanning electron microscopy (SEM) is required to resolve the mechanisms properly. Unfortunately, only relatively small samples of a few square centimeters can be looked at in the SEM. These are rare as they can only be cut from parts being scrapped. Schmid (1992) demonstrated that acetate replication techniques could be used with success to replicated field surfaces for later examination in the SEM. The technique is simple: acetate sheet is cut into strips of approximately 0.38 inch × 0.75 inch (1 cm × 2 cm); held at one end by a pair of tweezers, then submersed in acetone until the foil softens; placed carefully onto the surface to be replicated, avoiding the formation of bubbles; left to dry for a couple of minutes; when the edges start to lift, laid into a book where they are pressed flat over the next 24 hours; fixed to a substrate, gold sputtered, and put in the SEM for observation.

An example of the above techniques is given. In Figures 1 and 2, the wear surfaces of a balance drum exposed to an abrasive environment are shown. The replicas were taken on the drum surface forming the seal. Figure 1 is in the parallel gap and Figure 2 across from a labyrinth groove. Examining the figures, clear scratches formed by the impingement of abrasive particles can be seen. Visible too, by studying the form and orientation of the scratches left by the abrasive particles, are that the conditions where Figure 1 was taken are less abrasive than those for Figure 2. This displays a further use of the acetate replica; it can be used to study the flow conditions found in hydraulic equipment. The scars left by abrasive particles on steel substrates can be compared. The scratch length, depth, and width reflect the level of abrasivity, giving an idea of what measures must be taken to reduce wear to acceptable levels.

Figure 1. SEM Picture of an Acetate Replica of a Balance Piston Showing Labyrinth Sealing Surface.

Figure 2. SEM Picture of an Acetate Replica of Same Balance Piston Opposite a Channel in the Counter Face.

Interpreting the above figures, it is seen that grooves produce turbulent conditions. These, in turn, cause higher angles of impact of abrasive particles, which results in higher wear.

After studying numerous pump parts such as impellers, wearrings, balance drums, and labyrinth seals, the following mechanisms were found:

- Scratching of surfaces by abrasive particle impingement. Wear was highest at regions of high particle velocity (long scratches), or regions of turbulence (labyrinth gaps) where deformation due to high angles of impact was found (greater than 20 degrees).
- In a few instances, low levels of localized light cavitation could be detected. These are thought to arise when equipment is run outside the design point. Severe cavitation is considered a design and not a materials issue and hence not examined in this program.

Based on these findings, erosion and cavitation testing are required as a minimum to select materials.

Wear Tests

Wear tests must be able to select materials in a cost-effective manner giving the correct ranking. However, the better a test simulates in-service conditions, the more expensive it tends to be. The following tests were conducted:

- Two-body and three-body abrasion tests for quick ranking
- Multiangle erosion test to characterize the material behavior as a function of impact angle
- Magnetostrictive cavitation test for a rough ranking of the surface treatments
- Validation of results through field-testing and comparison with previous case histories

Hutchings (1992) gives a good overview of the various testing techniques used to determine the abrasion and erosion resistance of materials. A brief summary of the tests and the reason for their use is presented in APPENDIX A.

Field Test

To verify the optimization of materials using results from the tests mentioned above, a field test was conducted. A vertical axis double entry pump with Francis type first stage was used. Pumped fluid is water of glacial origin containing high levels of solids. Presently the pumps are serviced every 2500 hours to repair damage due to erosive wear. Being of older design, the pumps suffer slight inlet cavitation. The double exposure to abrasive solids and light cavitation made the pump the ideal equipment to corroborate experimental findings and developments.

Of the seven impeller blades, two were coated with a cermet of high abrasion resistance and two with a cermet optimized to be cavitation and abrasion resistant. The latter could be deposited to greater thickness without debonding or cracking. Three blades were left uncoated to serve as a reference. The impeller was run for a full season (2600 hours) and then inspected (refer to Figures 12 and 13).

OPTIMIZATION

In the HVOF deposition process, oxygen and a fuel such as propylene, hydrogen, or kerosene is burned under high pressure within a cooled combustion chamber. The combustion products are then discharged through a confined, cooled nozzle at high velocities. Depending on the combustion gas pressures, flame velocities exiting the nozzles have been determined to be of the order of ~5600 ft/s (1700 m/s), i.e., supersonic, while the maximum continuous combustion temperature, a function of the stoichiometry of the oxygen-fuel mixtures, has been measured to exceed 3500°K. Powders to be deposited are fed into the nozzle of an HVOF gun by a carrier gas, where they are heated and accelerated by the combusting gases exiting the nozzle. Although all HVOF systems use internal combustion of fuel and oxygen at high gas flowrates and pressures to produce combustion jets with high velocities, the equipment differs in design from one manufacturer to another. Consequently, the materials for HVOF spraying are often developed and optimized for spraying by specific spray systems. APPENDIX B provides an overview of some aspects of quality control for HVOF coatings.

Influence of Powder and Spray Process on Coating Performance

The main difference between the second and third generation HVOF spray systems is the velocity imparted to the spray particle. This has increased considerably. For example, data from Kreye (1997) for a WC-Co 83-17 -45 $+10$ μm material measured 1300 ft/s (400 m/s) for the second generation and 2150 ft/s (650 m/s) for the third generation devices used in this work. This higher velocity results in shorter dwell times in the flame and a higher momentum upon impact. The shorter times in the flame reduce the particle temperature, and, hence, WC decomposition and oxidation, which tend to embrittle coatings. The higher velocities increase coating density and particle bonding. The third generation coatings thus tend to be tougher, due to less WC decomposition with better bonding. This translates into improved abrasion and cavitation resistance.

The Jet Kote® and the Diamond Jet™ 2600 HVOF systems were mainly used to spray selected tungsten carbide-based coatings in this investigation. They are typical of second and third generation devices. The second generation Jet Kote® gun uses a right angle combustion system where the fuel gas and oxygen are burned in a larger diameter combustion chamber at right angles to the exit nozzle (Figure 3). The Jet Kote® system also uses a straight nozzle that also limits the exit flame velocity ratio to a maximum of Mach 1 (gas velocity: sound velocity). The third generation Diamond Jet™ Hybrid HVOF gun, on the other hand, uses a throat combustion system instead of a separate chamber for producing a high velocity flame (Figure 4). The Diamond Jet™ 2600 uses a converging-diverging nozzle and, under standard spray conditions, operates at a chamber pressure of 85 psi (6 bar). The higher combustion pressure and the converging-diverging nozzle section lead to higher gas and particle velocities as compared to the velocities attained with the Jet Kote® system.

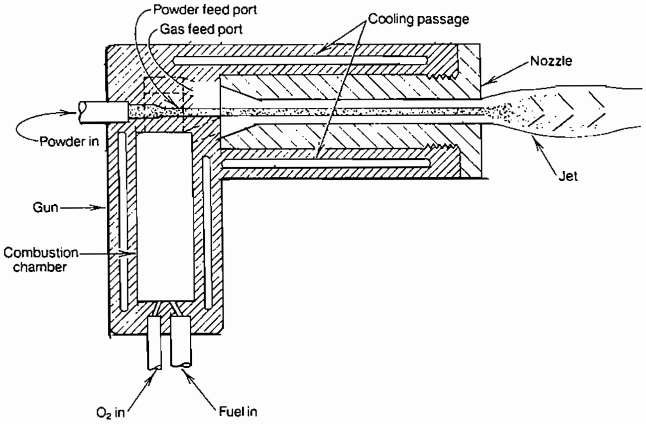

Figure 3. Schematic of Typical Second Generation HVOF Gun.

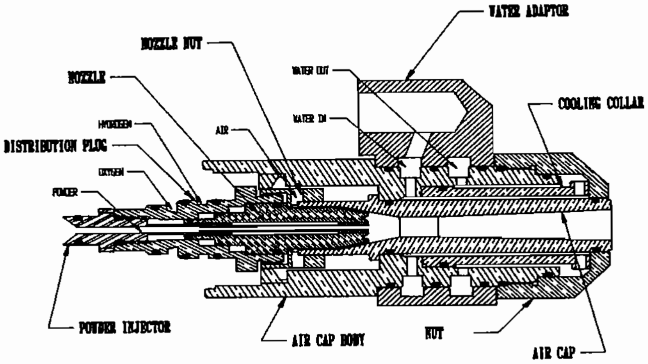

Figure 4. Schematic of Third Generation HVOF Gun.

A systematic cross comparison was made to determine the materials and spray system that would be best suited for reducing pump component wear and improving the pump service life. Spray parameter optimization was carried out using mild steel (AISI 1018 steel) coupons for depositing coatings under varying spray conditions. The coated test coupons were metallographically examined to characterize the spray conditions by measuring coating density and hardness. The conditions with the highest density and hardness were then considered as optimum for a particular material (Figure 5).

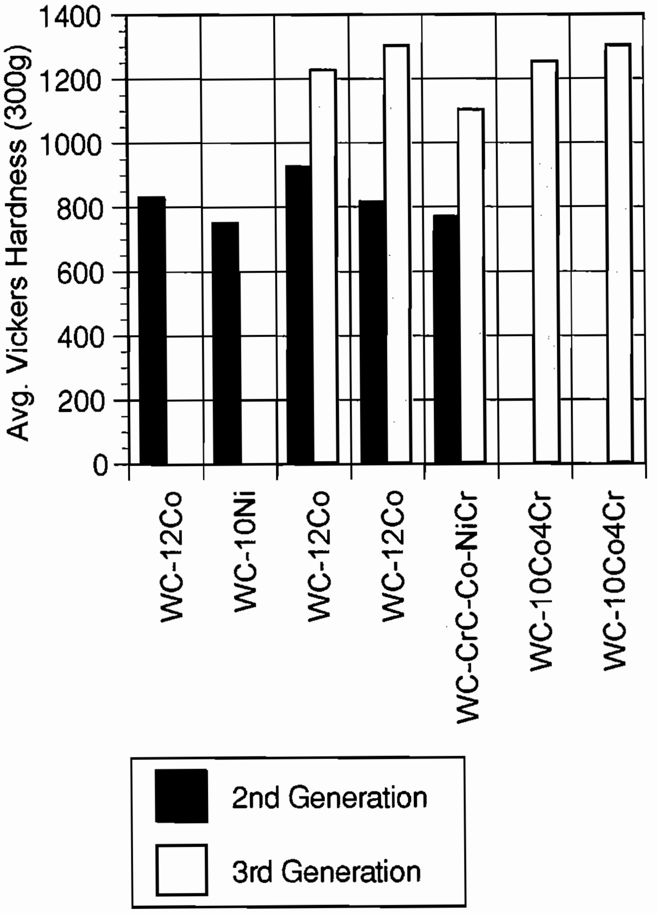

Figure 5. Comparison of the Vickers Microhardness of a Range of Second and Third Generation HVOF Sprayed WC-Based Coatings.

Microstructure characterization studies were conducted to compare the structure, porosity, density, oxide content, and the distribution and volume fraction of carbides in the coatings sprayed by the second and the third generation systems. The light areas in the microstructures (refer to Figures 10 and 11) indicate the metallic binding matrix, and the grey areas indicate the tungsten carbide particles. Pores or pullouts generally appear dark in the micrographs. Microhardness measurements were taken on polished coating cross-sections by indenting at a load of 300 g for 10 seconds using a Vicker's hardness tester. Ten measurements were taken and averaged. Other coating characteristics such as surface roughness and superficial hardness were also determined.

The effects of deposition process and powder composition on wear resistance were measured using the two-body and three-body (slurry) abrasion tests. In Figures 6 and 7, the results for a range of second and third generation coatings are compared. As mentioned before, the two-body abrasion results are a good indicator of the low-angle-impingement-erosion-resistance of a coating. This is what coatings are largely exposed to in pumps. Judging by these results, the expected increase in coating life is approximately six times when going from a second generation to a third generation process. In fact, when compared to the steel substrate, this can be between 600 to 2000 times when granite is the abrasive.

A further advantage of the third generation devices is that Cr can be added to the Co matrix. Because less WC decomposition takes place, the Cr is largely in solid solution in the Co and has not formed carbides. The coatings therefore are tougher, with a matrix with a high work hardening rate, and have a better corrosion resistance than pure Co or Ni matrix materials. All results clearly showed that the WC-CoCr system is best suited for the reduction of erosive wear.

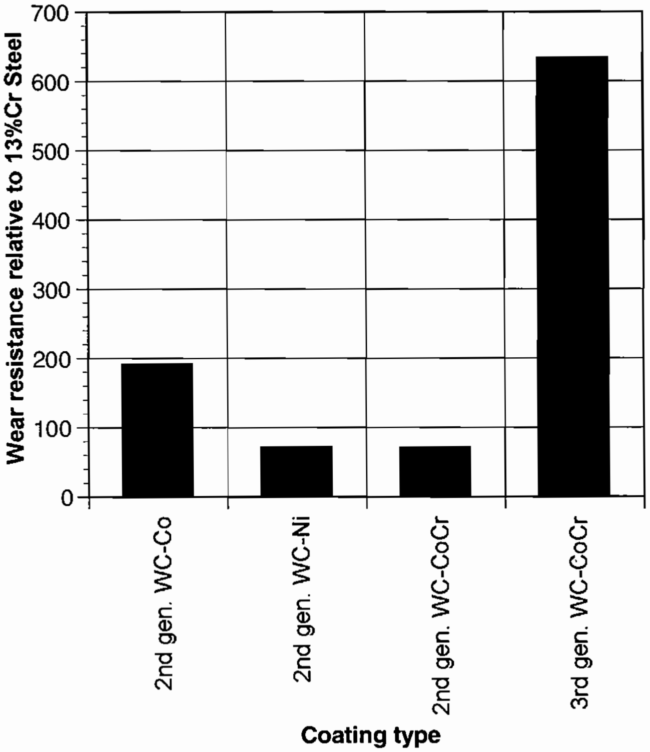

Figure 6. Graph of Wear Resistance of Coatings Relative to 13 Percent Chromium Steel.

In Figure 8, results of erosion tests conducted on third generation coatings are presented. Two powders of the same WC-CoCr composition, produced by two different manufacturing routes, were deposited using two commercial third generation HVOF guns. From the data, it is clearly evident that the powder must be matched to the process to achieve optimum performance. The biggest difference was seen with process A, which had an excellent resistance when depositing powder A, but a rather poor performance when depositing powder B. Process B, with kerosene, appeared to be less sensitive to the powder morphology, but failed to produce coatings with a wear resistance as good as process A, which used hydrogen as a fuel.

The carbide powder shape and size are a dominant factor when matching powders to a spray process. The carbide content and size strongly influence the abrasion (Figure 7) and cavitation resistance. This is demonstrated in Figure 9, which shows the cavitation-wear of two coatings of identical chemistry but different carbide size.

When very fine carbides (submicron) are used, the carbide to matrix interface is large (Figure 10). This favors the formation of eta phases, which, as mentioned earlier, tend to embrittle the coating. They however raise the matrix hardness and can increase the abrasion resistance of the coating (Figure 5). Reactions between the matrix and the WC can take place during all high-temperature steps such as powder sintering during manufacture or spraying. A careful optimization of the powder manufacturing and spray route is therefore required to optimize the coating properties.

Cavitation theory is that homogeneous materials are superior to heterogeneous materials, where interfaces are points of weakness. Therefore, if hard-phases are present, these should be as fine as possible. Yet this effect has to be weighed against the above-mentioned potential decomposition of the WCs. A powder was manufactured having carbides of about 0.00008 inch (2 μm) in diameter. Sintering was very light to reduce phase changes. When deposited, using a third generation HVOF system burning hydrogen, the coating (Figure 11) was very tough and had a cavitation resistance four times that of 13 percent Cr steel (Figure 9).

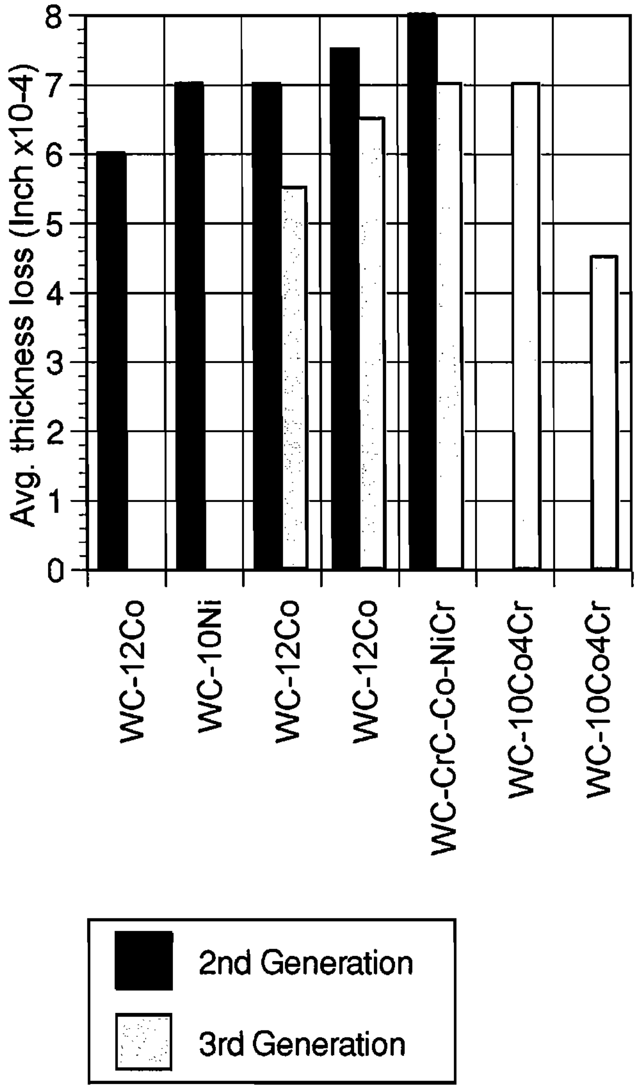

Figure 7. Comparison of the Slurry Abrasion Wear Loss of a Range of Second and Third Generation HVOF Sprayed WC-Based Coatings.

The coatings shown in Figures 10 and 11 are optimized coatings. The fine carbide material has an abrasion resistance, which has not been surpassed by any thermal spray coating tested to date. It is limited to about 0.012 inch (300 μm) in thickness in standard applications. The coarser material, shown in Figure 11, has a lesser abrasion resistance, which is compensated by a higher cavitation resistance, and the good nature to be deposited in excess of 0.040 inch (1 mm) without coating cracking or spallation. The coarser carbide containing coating is suggested for use in abrasive environments where light cavitation is present. The regions particularly exposed to cavitation must be coated to a thickness approaching 0.040 inch (1 mm) to prolong component life. The coating is also suggested for parts of complex shape where coating thickness control is difficult.

As mentioned in the wear test section, select coatings were further tested in a cavitation tunnel on an aerofoil. These tests are very close to the field component cavitation environment and, fortunately, largely confirmed the wear results from the magnetostrictive device. It was also observed that machining could reduce the cavitation resistance of the uppermost surface region of the coating. This is problematic because cavitation is also intensified by rough surfaces, therefore the onset of cavitation, even though only theoretically restricted to the upper coating layers, can instigate further wear.

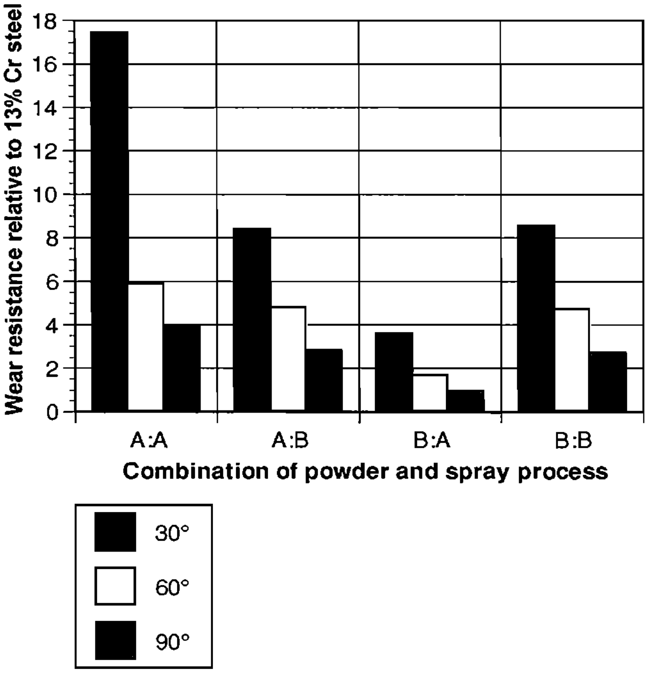

Figure 8. Graph Showing the Influence on Wear Resistance of Powder Type and Deposition Technique.

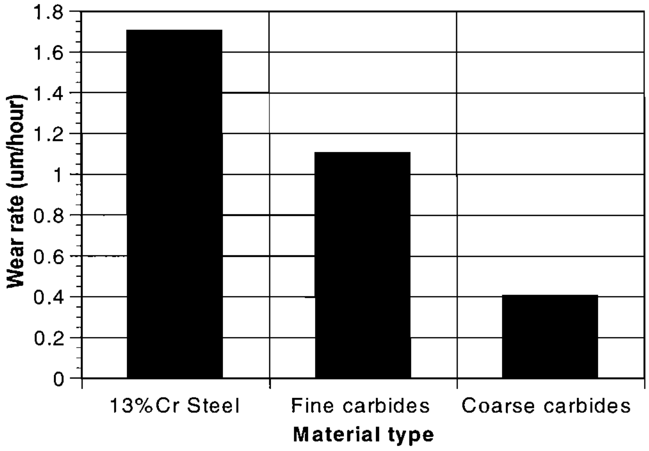

Figure 9. Cavitation Rate of Materials Tested Using the Magnetostrictive Device.

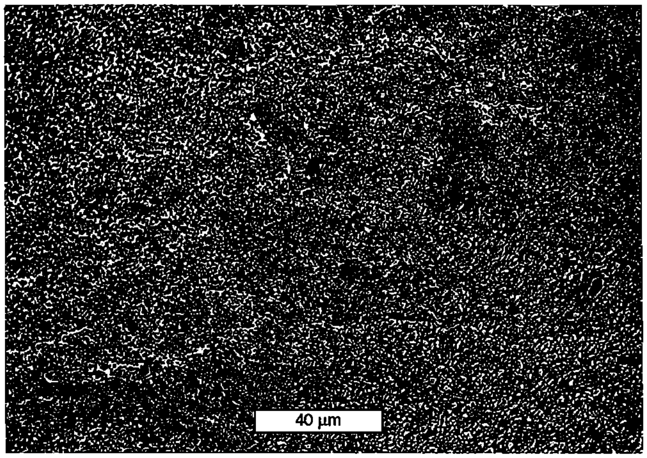

Figure 10. Cross Section Through a Third Generation HVOF Coating with a Very Fine Carbide Structure.

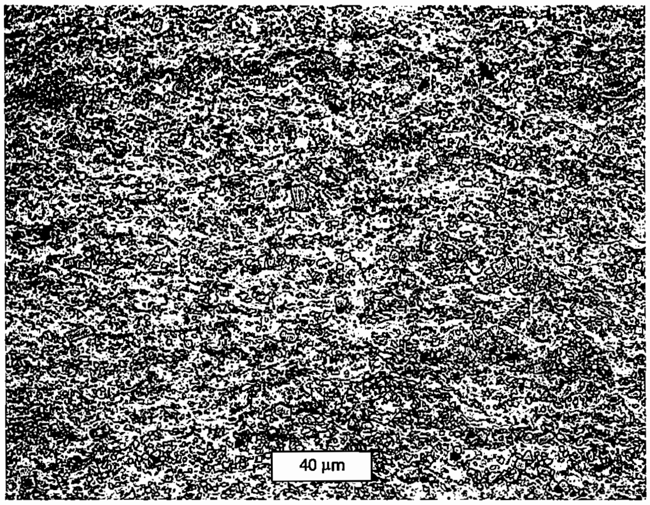

Figure 11. Cross Section Through a Third Generation HVOF Coating with a Slightly Coarser Carbide Structure.

Field Test Experience

The coatings shown in Figures 10 and 11 were applied to the pump described previously. After 2600 hours, the runners were removed, examined optically, and replicas made for SEM investigation. In Figure 12, one of the uncoated blades, used as a reference, is shown. Severe local wear has taken place and the part has suffered a general loss of material. The erosion damage is visible in the wave pattern that has formed on the surface and is an indication of the eddy flow. In strong contrast (Figure 13), the coated blades displayed no measurable wear. As was to be expected, the more abrasion resistant coating had vertical cracks at the blade route. This is a difficult to coat area where high coating stresses can build up. The more cavitation resistant variant, which can be deposited to greater thickness, did not crack. Surprisingly, the cracks did not result in increased wear around the crack face as would be expected. This is a further indicator of high coating integrity.

Figure 12. Uncoated Leading Edge of Field Tested Impeller after 2600 Hours of Operation.

The results of the field test correlated well with data obtained from the laboratory tests. Both the applied coatings significantly reduced component wear and, if applied to the entire runner, will increase the time between overhaul at least fourfold.

Figure 13. Coated Leading Edge of Field Tested Impeller after 2600 Hours of Operation.

Choice of the Boriding Process

As mentioned earlier, boriding is a very high temperature process, 1650°F to 1850°F (900°C to 1000°C). This strongly limits the materials that can be treated due to metallurgical changes upon heating and cooling. It can also result in strong deformation of the part as stresses are relieved. Being a diffusion process, the thickness of the layer formed is a function of temperature, time, and alloy composition. Generally speaking, the higher the alloy content, the thinner the layer.

To counter the effect of distortion, materials must be machined in an annealed condition and stress relieved between operations if necessary. A trial part should be manufactured and borided to gain information on the extent of deformation and instigate corrective action. Another technique is to mask areas of high tolerance and finish these after boriding.

In accordance with theory, the plain carbon steel formed the thickest layer 0.012 inch to 0.016 inch (300 µm to 400 µm), followed by the nickel based substrate 0.010 inch (250 µm). The 13 percent Cr steel had a layer of about 0.004 inch (100 µm), with occasional porosity. All the deposits were of dual phase, with a monoboride hard outer layer and a slightly softer diboride inner layer, as shown in Figure 14. The dual phase structure resulted in stresses between the layers. These were large enough in the Ni based material to result in the spallation of the upper layer. In Figure 14, the start of a horizontal crack, due to these stresses, can be seen. All the diffusion layers had a needle-like structure typical of boriding. The dual phase structure is indicative of a high boron concentration during coating, which results in relatively high diffusion rates.

A Ti based material was borided too. Only sporadic pockets of coating could be found. This suggests that the boriding was not optimized for Ti, which requires an initial stage of high vacuum and temperature to remove diffused oxygen. If not removed, the oxygen hinders the inward diffusion of boron and hence the formation of a layer.

In Figure 15, the erosion results of 13 percent Cr steel treated by two slightly differing boriding processes are compared to the treated plain carbon steel. It is observed that the carbon steel layer is more resistant at low angles of impact, but more brittle at high angles when compared to the Cr steel. The tougher nature of the Cr steel coating could be linked to its structure, which is cracked vertically (normal to the surface) and not horizontally as for the carbon steel. This effect will reduce spallation.

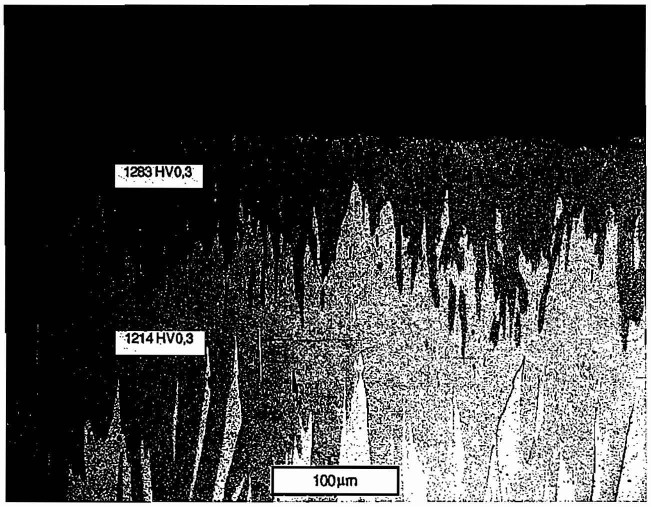

Figure 14. Cross Section Through a Borided Layer on a Plain Carbon Steel.

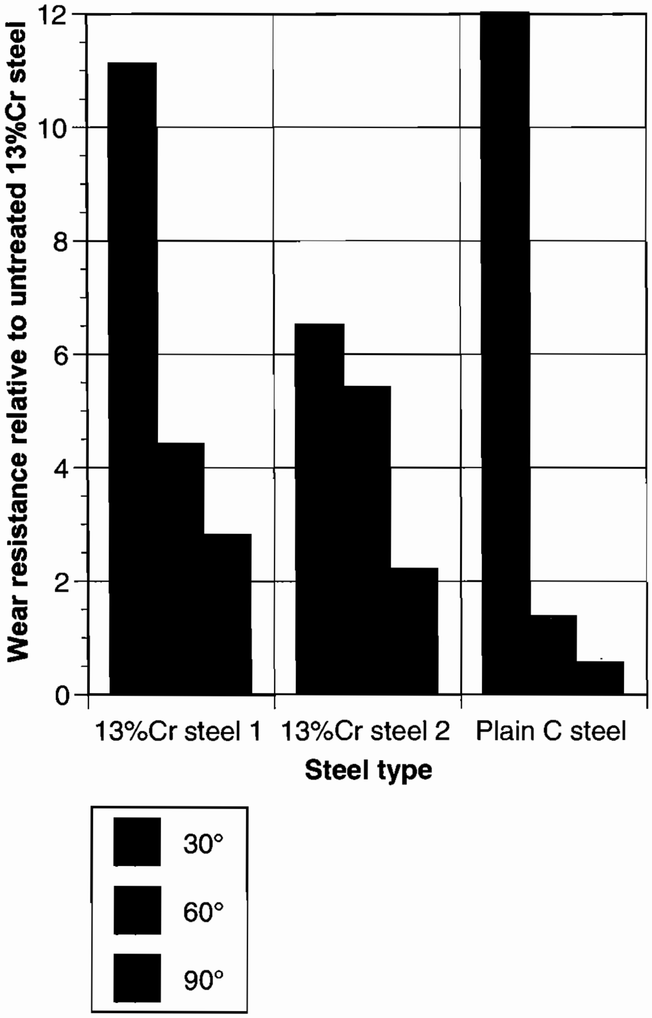

Figure 15. Graph of the Erosion Resistance of Borided Steels as a Function of the Angle of Impact Relative to Untreated 13 Percent Chromium Steel.

The coating hardness was always in excess of 1200 HV 0.3, which is 20 percent above that of quartz. The system therefore is in the low wear regime as long as gross-spallation is not a predominant mechanism. The absolute wear rates measured in the two-body abrasion and erosion tests are very good, although not quite as good as the best HVOF carbide coatings. From these results, it is apparent the boriding is a viable option for the reduction of abrasive wear.

Surfaces were grit blasted, borided, and WC-CoCr HVOF sprayed on top. The aim was to determine if thermal spray coatings would bond to the borided substrates. Examining the metallographic cross-sections, it was observed that the boride coating structure was disturbed by the rough surfaces, resulting in voids and cracking. The HVOF coatings did not bond well either. It is therefore not suggested to roughen surfaces prior to boriding or to coat them with thermal spray coatings later on. Areas to be coated by HVOF must be masked preceding boriding or the borided layer removed before spraying.

Further, as with the thermal spray coating process, optimization must take place. By adapting the boriding treatments, titanium and nickel-based substrates should be treatable on a production basis.

IMPLEMENTATION

For the implementation of wear resisting materials in hydraulic machines, the following points make up the decision process and must be followed:

- Identification of possible wear resistant materials and coatings (based on wear resistance relative to the environment, abrasive mineralogy, and size, corrosion potential, operating temperature)
- Restraints from the coating technique (component access, processing temperatures)
- Design modification of the candidate materials (material chemistry, morphology, and deposition process)
- Flow correction to avoid turbulence and high particle velocities

Design of Pump Components

The general flowpath of abrasive particles within a horizontal multistage centrifugal pump assembly is illustrated in Figure 16.

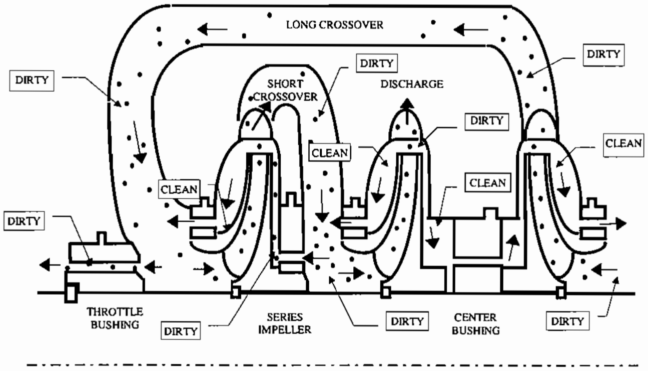

Figure 16. Pumpage Flow Diagram, Multistage Opposed Impeller Design.

In a multistage pump, abrasive particles are centrifuged outward but are returned toward the center of the pump at the crossover channels. The impeller eye wear-ring is subjected to abrasive wear, but this is less severe than wear at the impeller hub ring. Similarly, the interstage bushing at the center will be less worn than the throttle bushing.

In a horizontal between-bearings single-stage pump of double-suction design, the abrasive particles enter equally on both sides of the impeller and again are centrifuged outward (Figure 17). Aggressive particle impingement occurs at the location of the volute lip (cut-water) and on both sides of the impeller vane. This configuration has wear-ring labyrinths fitted on each side of the impeller. There are no interstage bushings to worry about. When a pump is stopped, abrasive particles settle throughout the pump, including the eye side wear-ring. When the pump is restarted, pressure acts to push the particles through the clearance gap in the wear-rings and bushings.

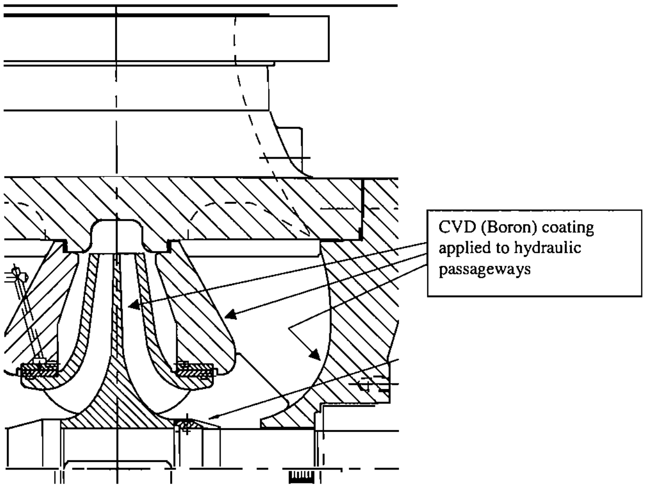

Figure 17. Between Bearings Horizontal Pump (Double-Suction)

Two-body abrasive wear takes place when a fixed hard particle or surface protuberance is pressed against a softer moving surface. Three-body abrasive wear occurs when a hard particle is introduced between two surfaces that are moving relative to each other. The two mechanisms produce the same wear mechanisms, although intensities differ, tending to be less for the three-body event.

Abrasive-type wear mechanisms also occur when a hard particle impacts a surface at a shallow angle and are defined as low angle impingement erosions. In all cases, material can be removed from the surface, creating a series of grooves. Softer materials, in particular, are easily abraded, whereas hard brittle materials may show little effect (refer to Figure A-1).

A wear mechanism change is often associated with an increase in the angle of impingement. Under high impingement angle erosion, repeated impacts cause fatigue failure and pitting of the surface. Erosive wear is accelerated in regions of turbulent flow and at corners and other discontinuities. Resistance to erosive wear depends upon the ability of the material to absorb the impact energy. Hard brittle materials will exhibit impact damage, whereas tough elastic materials are more resistant to erosive wear.

Methods and materials for the prevention of corrosion and adhesive wear are well known and regularly applied in the design of centrifugal pumps. However, pump components of these materials are subject to rapid abrasive and erosive wear when they are applied in services containing high levels of hard abrasive particles. This is commonly encountered in services such as produced water injection and oil sands upgrading processes.

A combination of protective HVOF thermal spray and CVD diffusion coatings has proven to successfully extend the working life of pump components exposed to such abrasive wear mechanisms. The application of HVOF coatings is limited to surfaces within line-of-sight of the gun. Wear parts such as bushings, sleeves, and shafts can be readily accessed and thereby readily protected with an HVOF coating. Accessible areas of the casing and impeller can also be coated. However there are obvious access constraints. CVD (boronize) coatings have been used to protect casings and impellers in otherwise inaccessible areas.

Components Subject to the HVOF Coating Process

HVOF coatings containing tungsten carbide are a proven means of extending the life of pump components when abrasive particles are present in the pumpage. They have been the preferred coatings for wear parts in moderate abrasive conditions, and have been successfully used in combination with solid tungsten carbide wear parts in severely abrasive service.

As previously indicated, the HVOF application process allows only areas that are visible to the thermal spray nozzle to be coated. That notwithstanding, coatings have been successfully applied to a wide range of pump and hydraulic turbine components including:

- Wear-rings
- Balance pistons
- Bushings and sleeves
- Impeller vanes and shrouds
- Impeller thrust rings
- Volutes and diffusers
- Covers and sideplates
- Exposed areas of shafts

Refer to Figures 18, 19, 20, 21, and 22 for examples.

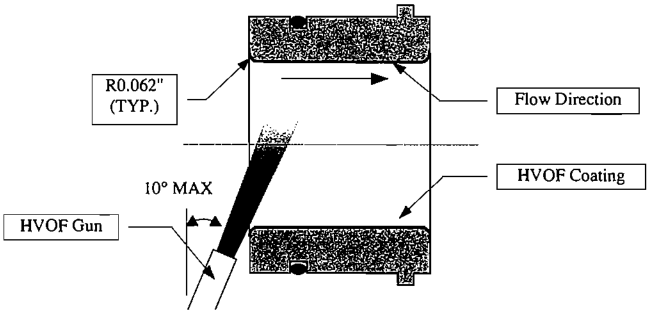

Figure 18. HVOF Coating of Bushing Component.

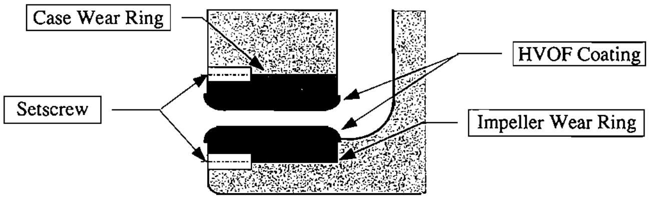

Figure 19. HVOF Coating of Replaceable Wear-Rings.

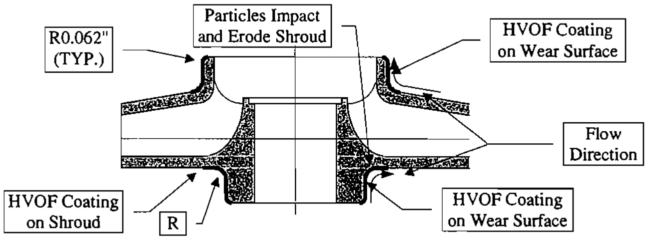

Figure 20. HVOF Coating of Integral Impeller Wear-Rings.

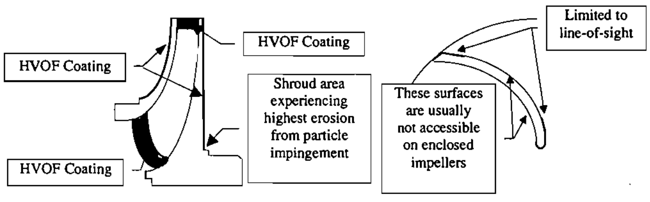

Figure 21. HVOF Coating of Impeller Component.

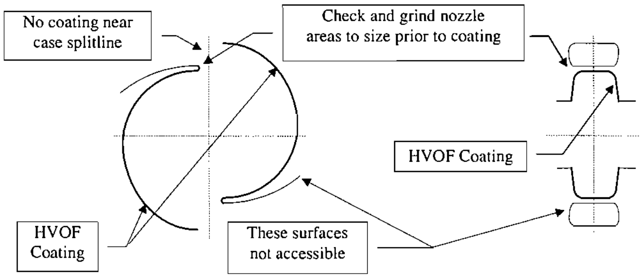

Figure 22. HVOF Coating of Volute Profiles.

Components Subject to the CVD (Boronize) Process

Use of the boronizing process fits best with carbon steel and chrome steel components in areas that are inaccessible to line-of-sight coatings. As previously illustrated (refer to Figure 17), this process is most commonly applied to the internal hydraulic passageways of impellers and casings.

Powder-pack boronizing is a high-temperature chemical-vapor-deposition (CVD) process whereby boron atoms diffuse into the base metal of the component to form metallurgical alloys at the surface. These alloys are an integral part of the base metal and are of very high hardness. The base material influences the structure and properties of the hardened case. Steels with a silicon content greater than 0.8 percent are generally unsuitable for this process. The successful application of this process relies upon the quality of the base material and careful structuring of the manufacturing process. The component is placed in a suitable container and embedded in the boronizing agent. It is then placed in a furnace supplied with a protective gas and subjected to a time/temperature cycle appropriate to the desired thickness of the hardened surface. A major advantage of this process is that surfaces that are normally inaccessible can be hardened.

The vendor must mask surfaces that do not require hardening, or surfaces that are to be machined after coating. Worn or damaged coated surfaces can be weld repaired and recoated. Most boride coatings start to oxidize at temperatures exceeding 950°F (500°C).

- *Carbon and low alloy steels*—Cast or wrought carbon steels can be coated. The type of coating used is boride with a 1850°F (1010°C) diffusion process temperature. Heating time is generally 16 to 24 hours, followed by a slow cool down. This results in a total case depth of 0.008 inch (200 µm) minimum with a surface growth of 0.0015 inch to 0.002 inch (38 µm to 50 µm). Post coating heat treatment is not required.

- *Martensitic chrome steels (AISI 400 series)*—Steels of this classification can also be coated. In this case, the type of coating used is boron silicide with a 1800°F (980°C) diffusion process temperature: Heating time again is generally 16 to 24 hours, followed by an oven cool to 1300°F, ± 10°F (705°C, ± 6°C), holding for two hours, followed by a still-air slow cool down. This results in a total case depth of 0.004 inch (100 µm) minimum with a surface growth of 0.0007 inch to 0.001 inch (18 µm to 25 µm).

- *Austenitic stainless steels (AISI 300 series)*—It is not recommendable to use this coating process on austenitic stainless steels, although all the alloys can be coated. The thickness of the coating will be less than that obtainable with the martensitic chrome steels. The processing temperatures will sensitize the base material, making it susceptible to intergranular corrosion.

- *Austenitic-ferritic steels (duplex, super duplex)*—It is not recommendable to use this coating process on austenitic-ferritic chrome steels. The processing temperature will cause sigma phase formation, leading to a marked embrittlement of the ferrite phase.

- *Nickel, cobalt, and tungsten alloys*—Most nickel and cobalt base alloys can be coated, including weld overlay deposits of hard facing materials. As solid components, materials such as Stellite® or various grades of tungsten carbide can be coated.

- *Titanium*—A special process is available for titanium alloys. Since even small amounts of oxygen are deleterious to the process, the component has to be degassed under vacuum to remove any oxygen dissolved in the material. The type of coating is titanium boride. This process is still somewhat experimental.

CASE HISTORIES

Two examples of background case histories are provided. In both cases, the pumps in question were operated until they could no longer fulfil the design operating conditions in terms of flow and head. Subsequent disassembly at each service interval revealed extensive damage to wear parts, impeller (vanes and shrouds), and casing (in areas of high turbulence).

The step-by-step upgrade process identifies the learning experiences gathered along the way.

Case History A

• Location:	Mildred Lake, Alberta, Canada
• Service:	Slurry recycle pump Bitumen, 2 to 10 percent coke by weight
• Temperature:	705°F to 750°F maximum (374°C to 400°C maximum)
• Viscosity:	3.37 cp
• Sp Gr:	0.96
• Pump size:	8×10×18 CDA
• Speed:	3000 rpm, turbine drive
• Rated head:	750 ft (230 m)
• Rated flow:	1600 gpm (360 m^3/hr)

- Driver is a steam turbine 563 hp (420 kW)
- Original materials of construction

• Volute case:	ASTM A487 CA6NM with TMT coating
• End covers:	ASTM A487 CA6NM with TMT coating
• Wear-rings:	CA6NM with welded Stellite® overlay
• Impeller:	ASTM A351 CD4MCu

The pumps were sold and installed in 1984, in Ft. McMurray. The originally supplied design had removable sideplates and conventional wear-ring design on the impeller and casing (Figure 23). The pump service life with this design was 270 days.

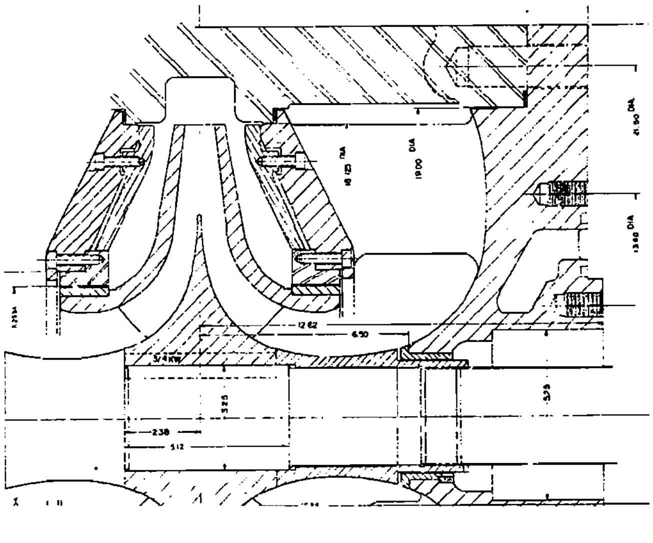

Figure 23. Case History A Original Pump Configuration.

Upgrade #1

The pumps were sent to the pump OEM facility in the mid 80s for repair. The sideplates were then coated with a LW-IN 30 tungsten carbide. Case wear-rings and impeller wear-rings were also coated with the same tungsten carbide. Shaft sleeves were 12 to 17 percent Cr with Stellite® C1. The initial mode of failure was usually in the wearing areas, this being the impeller wear-rings and the case wear-rings. It seems that the sharp shoulders were an impingement area for this abrasive service. The impeller was also washed in the shroud area close to the impeller wear-ring and on the discharge vanes. The pump service life with this design was 270 days.

Upgrade #2

The pumps were reengineered, noting all areas of the particle impingement. (HVOF second generation spray processes were used in refurbishment.) Sideplates were made integral to the end cover, as the sideplates were eroding at the fitted edge on top of the end cover to case fit. Jet Kote® 112 was applied 0.012 inch (0.3 mm) thick. Case wear-rings were also made integral to the sideplate to remove the impingement area. The integral design also had the largest radius possible to remove the 90 degree area. Jet Kote® 112 (0.012 inch (0.3 mm) thick) was applied to the sideplates.

Impeller wear-rings were upgraded to the integral design with the largest possible radius from the impeller shroud to the wear-ring landing area, making sure not to remove a lot of the wear-ring surface area. Volute case was not modified but left as the bare CA6NM casing with Jet Kote® 112 (0.012 (0.3 mm) thick), six inches (150 mm) up the volute lips. All sleeves and retaining sleeves were coated with Jet Kote® 112 (0.012 inch (0.3 mm) thick).

The mode of failure was at the integral wear-ring clearances. These had opened and eroded away at their location on the impeller and the sideplate. The impeller discharge vanes had holed through as well as the impeller shrouds. The service life for this design was 540 days.

Upgrade #3

HVOF second generation thermal spray processes and CVD boronizing treatments were used in combination to refurbish the pump to its current design configuration (Figure 24). These further steps included integral design on the wear-rings, impeller, and sideplate. The upgraded sideplate and impeller coatings were applied (0.020 inch (0.5 mm) thick), all retaining sleeves were also sprayed with Jet Kote® 6189 (0.010 inch (0.25 mm) thick). The impeller was upgraded with CVD and then coated with Jet Kote® 6189 (0.020 inch (0.5 mm) thick) on the discharge vanes and shroud areas. The shaft was upgraded to a tighter interference fit and the keyways had a larger radius in the corners since the customer had experienced some loosening of impellers and shaft breakage.

The mode of failure of this configuration was found to be at the integral wear-ring clearances that opened and eroded away at their location on the impeller and the sideplate. The impeller discharge vanes had holed through as well as the impeller shrouds. The method of failure was almost identical to that previously experienced, but proved to provide the longest run of all pumps at about 1156 days.

A future consideration for this pump would be to apply third generation coatings as a means of further improvement.

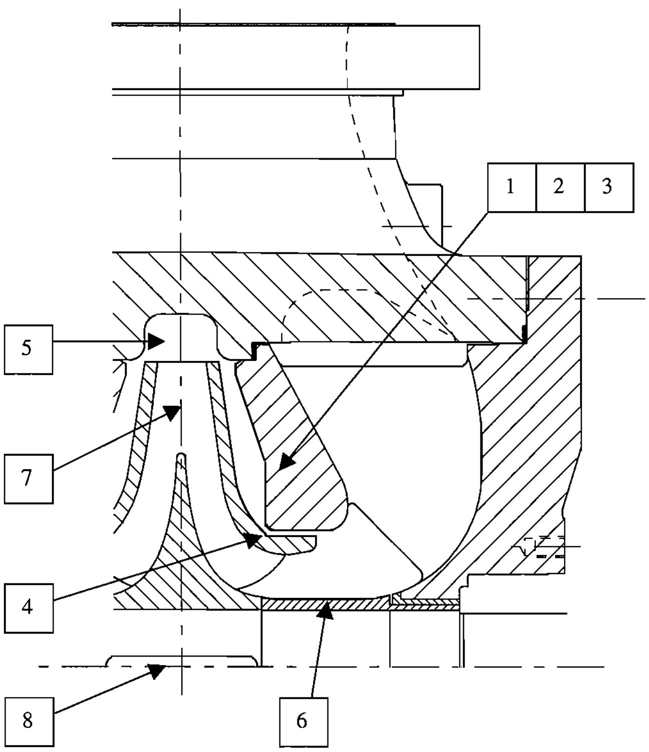

Figure 24. Case History A Current Pump Configuration.

Case History B

- Location: Prudhoe Bay, North Slope, Alaska
- Service: Produced water injection pumps; seawater and quartz sand
- Temperature: 160°F to 180°F (70°C to 80°C)
- Sp Gr: 0.97 at 180 F (80°C)
- Pump size: HP cp 175-275-5s/33
- Speed: 6328 rpm
- Total differential head: 6487 ft (2000 m)
- Flow: 3300 gpm (750 m^3/hr)
- Driver: Sulzer gas turbine type S-3
- Original materials of construction:
  - Wear-rings: CF3M with Stellite® 6 and 12 overlay
  - Balance piston/sleeve: CF3M with Stellite® 6 and 12 overlay
  - Impellers: 316L
  - Casings/diffusers: 316L

The pumps were started in late 1984 and were run intermittently at low flowrates (Valantas and Bolleter, 1988). As water rates increased to what would be normal in the spring and summer of 1986, the pump run times dropped to 700 hours. After reviewing the design, it was determined that abrasives were causing the problems. A subsequent study revealed that the majority of the abrasive matter was sand ranging from fines up to 1/16 inch (1.5 mm) in diameter. The sand was from the oil reservoir.

Upgrade #1

The first upgrade involved a design change in order to improve the rotordynamic performance characteristics. Swirl brakes were installed on the balance piston assembly. The pump service life with this design remained at 700 hours.

Upgrade #2

(HVOF second generation spray processes were then introduced in regurbishment.) The balance piston assembly was Jet-Koted™and swirl brakes were added. The pump service life with this design improved, but only marginally, to 881 hours.

Upgrade #3

- HVOF Jet-Kote™ balance piston assembly and swirl brakes
- HVOF Jet-Kote™ wear-rings
- Pump service life, 8700 hr estimated average

(The opportunity for Upgrade #3 was prompted by issues other than wear. Pumps in this configuration achieved a maximum of two year's operation.)

Upgrade #4

It was clear that the service conditions were so severe that further significant increases in service life would demand the integration of solid tungsten carbide components into the design. (The means of achieving this task may form the basis for a future technical paper. In the meantime, a brief synopsis of the change is given.)

Significant material and design changes throughout the entire pump were implemented, targeting a 43,500 hour run. The plan included combating abrasive/erosive wear while also adding rotor stability features. It was understood that with increasing wear at the labyrinths, the rotor would eventually become unstable.

The current configuration is:

- Lomakin bearing
- Fluid pivot radial bearings
- HVOF coating of shaft at exposed locations between impellers
- HVOF coating of diffuser and casing surfaces
- Solid tungsten carbide wear parts with amorphous diamond-like coat (including the eye wear-rings)
- Titanium impellers (cavitation resistance and rotordynamic considerations with the solid tungsten carbide components)
- Polygon shaft impeller and balance piston fits (part of the solid tungsten carbide retention method)
- Improved suction impeller hydraulics

The pump was started in July 1997 and is currently still running with no sign of increased vibration or degradation (~ 20,000 hr).

CONCLUSIONS AND RECOMMENDATIONS

There is an increasing demand for hydraulic machinery such as centrifugal pumps and hydraulic turbines to withstand abrasive service environments. In the instance of centrifugal pumps, this demand is particularly prevalent in Western Canada and the North Slope in Alaska.

To support the need for improved service life and reliability, advancements in pump design and material technologies are continually investigated and applied as refurbishment and retrofit exercises. Field experience has demonstrated that abrasive wear performance of pump components can be greatly improved by the use of a combination of HVOF and CVD coatings. It can be demonstrated that techniques are now available to significantly increase effective pump life and performance. It is suggested that these are used in manufacture of original equipment and not only, as is often the case, as a maintenance operation.

Field experiences with HVOF coatings are based on the use of second generation coating technologies. It can be shown that third generation (Diamond Jet™ Hybrid) HVOF systems produce WC-based coatings with superior microstructures and properties than the second generation HVOF systems. Thermal spray WC-based powders can be modified to either increase the abrasion or cavitation resistance, depending on the severity of the wear mechanisms in the pump. WC-coating systems exist that have a very low tendency to crack, thereby lending themselves to the coating of complex components where ideal angles of spray particle impingement seldom exist. These can be suitable for the deposition of coatings up to a thickness of 1 mm. The Diamond Jet™ Hybrid process is found to be a suitable process for producing WC-based coatings with dense microstructures and high wear resistance. Third generation HVOF coatings are therefore to be considered as the next step toward improving machine operating life for these environments.

It was determined that CVD (boriding) is a viable technique for the coating of difficult to access areas, which can be used in conjunction with HVOF coatings for extensive pump protection. It is well known that the substrate alloy composition affects boride layer growth and hardness. New was the large difference in layer toughness. A substrate delivering both toughness and hardness was found.

CVD (boronizing) coatings can be used in order to protect areas that are inaccessible to thermal spray application processes. However, the affect of the CVD application process on corrosion resistance and mechanical properties of the base material must be fully considered.

In severely abrasive applications, it is found necessary to supplement these processes further with the use of solid ceramic materials for wear components.

NOMENCLATURE

CVD = Chemical vapor deposition

Cermet = Ceramic particles bound by a metal matrix such as cemented carbides (also called hard metals) where refractory carbides are bound in Co or Ni matrices.

eta (η) phase = In the WC-Co system, mixed carbide phases can form, particularly when carbon is reduced beyond the stoichiometric level. These tend to be brittle but hard. The most common of these brittle phases are the eta (η) phases with the composition Co_xW_yC, where x and y can be 3:3, 6:6, or 2:6. In the presence of Cr, similar but more complex mixed carbides form.

HVOF = High velocity oxy-fuel flame spraying

HVOF generation = The generation to which a flame-spray device belongs. Defined by the velocity imparted to the powder particle and the degree of sophistication. In Kreye (1997), a detailed listing is given of velocities for WC powders as a function of the spray gun. Typically, for the WC-Co 83-17, $-45 + 10$ μm powder these are:

- First generation: 1300 to 1500 ft/s (400 to 450 m/s), first HVOF systems such as Jet Kote®, parallel barrel
- Second generation: 1300 to 1500 ft/s (400 to 450 m/s), improved HVOF systems, easier to use, parallel barrel, oxygen pressure of 45 to 75 psig (3 to 5 bar gauge), examples are standard Diamond Jet™ and Jet Kote® II
- Third generation: 1950 to 2150 ft/s (590 to 660 m/s), constricting-districting barrel, oxygen pressures of 85 to 150 psig (6 to 10 bar gauge), latest generation such as Diamond Jet™ Hybrid 2600 and 2700 series

APPENDIX A

Following are descriptions of the testing techniques used to determine the abrasion, erosion, and cavitation resistance of materials.

Two-Body Abrasion Test

The two-body abrasion test is ideal for the quick ranking of the abrasion resistance of materials, because very little material is required and the test can be easily and quickly done. Experience has shown that when the abrasive paper used has been chosen correctly, a very good impression is gained of the wear due to solid particle impact at low angles (below 15 degrees). In this test, the specimen is moved over the surface of an abrasive paper using a well-defined pressure. For the test results reported here, pressures of 14.5 psi, 72.5 psi, and 145 psi (10, 50, and 100 N/cm^2) were used. To obtain reproducible results, the specimen must always traverse fresh abrasive.

As mentioned above, the abrasive paper used is critical to achieving the correct ranking. This is related to the ability of the abrasive to scratch the surface. In Figure A-1, this is schematically shown. When an abrasive can clearly scratch a surface, it is at least 20 percent harder, and the wear rate will be high. Should the wear surfaces be 20 percent harder than the abrasive, the wear rate will probably be low.

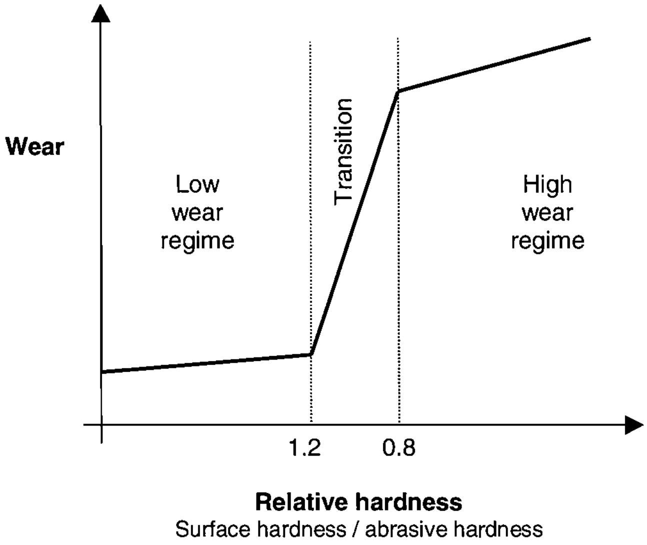

Figure A-1. Schematic of Relative Wear as a Function of Surface Hardness to Abrasive Hardness Ratio.

Three-Body Abrasion Test (Slurry Abrasion Test)

The slurry abrasion wear test involves sliding coated cylindrical buttons against a cast-iron plate in aluminum oxide slurry under a fixed load and for a specified length of time, as shown in Figure A-2. At the end of the test, the coating wear is determined as thickness or weight loss. An average of three runs is taken to improve accuracy. To minimize variations, the surfaces of all coated specimens and the cast-iron plates are ground with diamond or silicon carbide wheels to a constant average surface roughness. The abrasive wear resistance of all the coatings was measured in a slurry of aluminum oxide and water.

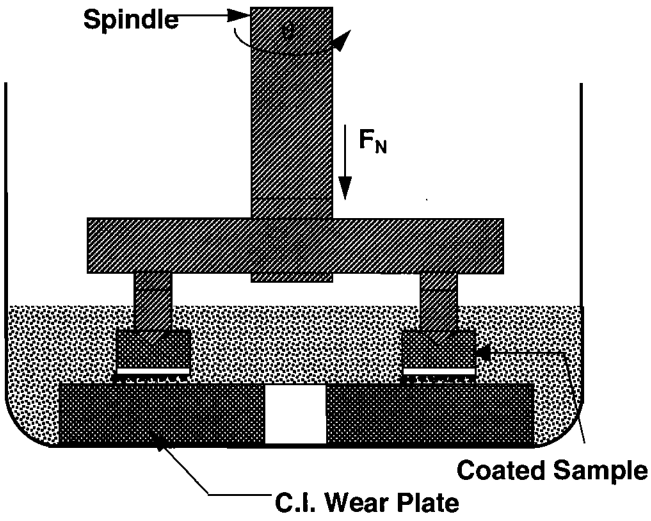

Figure A-2. Schematic of Slurry Abrasion Tester.

Erosion Test

The wear mechanism investigation showed that components washed by turbulent flow were exposed to high angles of impact by the erodent. In Figure A-3, a generalized view of the wear of materials as a function of angle of impact is given. Here it is seen that no material performs well at all impingement angles, and, that generally, an increase in wear is seen with a rise in angle of impact. This is to be expected considering the velocity vector of the erodent normal to the surface.

Based on these observations, an erosive test should evaluate a range of angles. In this way, the wear of the surface treatment can be characterized. A test rig has been used to test at a wide range of angles.

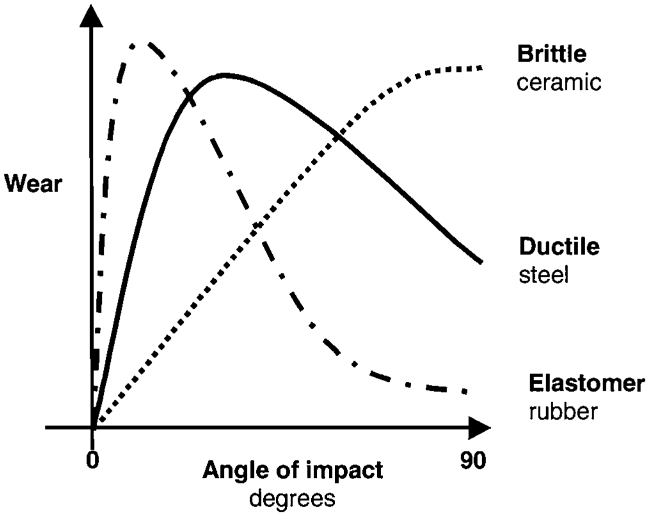

Figure A-3. Generalized Overview of the Erosive Wear Resistance of Materials as a Function of the Angle of Impact.

In the new test, shown in Figure A-4, the abrasive is introduced at the center of a rotating tube and accelerated as it passes down the tube. The erodent strikes specimen plates positioned on the wall of the containing vessel. Because the abrasive particles leave the tube at a constant angle—independent of tube velocity in the testing domain—the angle of impact is given by the angle of the specimen relative to the tangent of the circle described by the tube. The rig has been equipped to test four materials concurrently, at a minimum of four angles at the same time. Standard angle settings are 15, 30, 60, and 90 degrees. The velocity is controlled by the speed of rotation of the tube and can be set between 160 to 790 ft/s (50 to 240 m/s). To avoid dust, control particle velocity, and particle impact-angle, the test chamber is evacuated. A further advantage is that the erodent found in the field can be used. For the test results presented, glacial moraine, of granite mineralogy, was used. The maximum particle size was 0.005 inch (117 μm) with an average of 0.0018 inch (45 μm).

Cavitation Testing

After long periods of exposure to cavitation, all materials will eventually wear. Therefore hydraulic equipment must be designed in such a manner that no cavitation takes place or bubble-fields collapse in the fluid well away from surfaces. Even when this approach is adopted, cavitation can still occur under unfavorable operating

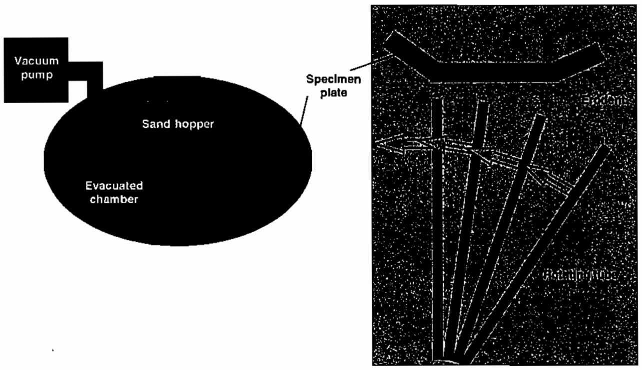

Figure A-4. Schematic of Erosion Tester.

conditions. During such, coatings applied to prevent erosion due to abrasive particles must not be severely worn. Many of the ceramic coatings applied by plasma spraying are very resistant to low-angle impingement by solids, yet are readily worn by cavitation. Therefore it is important to test the cavitation resistance of materials developed to resist solid particle erosion to ensure that they have an adequate cavitation erosion resistance to survive short periods of cavitation.

The magnetostrictive or piezoelectric cavitation testers operated according to ASTM G32-92 are a very convenient means of ranking materials. The results presented here are from such a device. The exact conditions were:

- Temperature: 77°F ± 3.5°F (25°C ± 2°C)
- Frequency: 25 Hz
- Distance between specimen and swinger: 0.040 inch (1 mm)
- Amplitude: 0.0016 inch (40 μm)

As with all tribological tests, the aim is to achieve a measurable result within a short period of time. However, the acceleration of wear may not change the predominant wear mechanism, otherwise an incorrect ranking can be the result. The acceleration of wear as a function of the cavitation testing device is well described in table form by Durrer (1986). This is done for homogeneous materials, and only wear rates and not mechanisms are examined. The cavitation bubble form and their collapse, however, are very well studied. Due to this uncertainty, materials, selected using the ASTM G32-92 device, were run in a flow channel in which cavitation similar to that found in pumps was simulated.

APPENDIX B

Aspects of HVOF Coating Quality Control

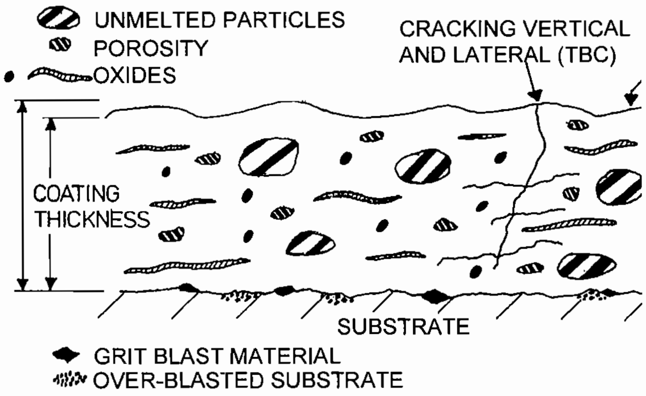

Figure B-1. Possible Defects in HVOF Coatings.

Typical contents of a coating specification will include controls for all aspects of preparation, application, and finishing.

- Part preparation
    - Visual inspection (contamination, machining, deburring, surface finish)

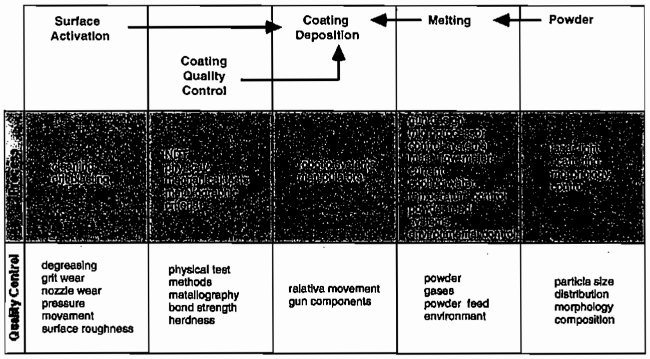

Figure B-2. A Schematic Overview of the Operations Required for the Deposition of a Coating, Presented Together with the Influencing Parameters That Must Be Controlled.

- Part preparation (continued)
    - Dimensional control (of premachined areas—angles, depth)
    - Surface finish of prepared surface
    - Cleaning and handling (degreasing, gloves)
    - Masking prior to surface application
    - Part handling (dust removal, gloves, time limits)
- Spray powder
    - Powder specification
    - Blending (mix ratio, time)
    - Drying (158°F to 176°F (70°C to 80°C), five hours)
    - Storage
- Coating
    - Spray parameters
    - Equipment for parts handling (control specimens, cleaning)
    - Cooling (when, where, how—angle, gas, pressure)
    - Coating thickness (oversize for grinding?)
    - Part marking
    - Control sample (tests, storage)
- Coating control
    - Metallography (preparation according to specification)
    - Coating microstructure, hardness (porosity, phase distribution, crack debonding, hardness measurement type, procedure, tolerable scatter)
    - Other tests (test type, sample frequency)
- Machining
    - Grinding material
    - Grinding parameters (wheel speed, part rotation, feed rate, cooling)
    - Superfinish (as above)
- Surface finish (measurement method, surface preparation, dimensional control)
- Repair (coating removal method, surface preparation, dimensional control)
- List of suppliers (powder, coating application, machining)

The integrity of finished coatings can be determined by several levels of inspection.

- Level 1
    - Optical image: Color of coating
    - Thickness: Measure with micrometer
    - Roughness: Measure (Ra, Rz)
- Level 2
    - Adhesion: Bend test with samples (bend over 90 degrees shall not peel)
    - Hardness: Measure of macrohardness
- Level 3
    - Microstructure: Microhardness, porosity, unmolten particles, cracks, oxides, interface contamination
- Level 4
    - Adhesion: Bond strength tests with three samples
- Level 5
    - Corrosion/abrasion testing: Salt spray tests, two-body, three-body abrasion tests

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