High Velocity Air-Fuel Spraying And Its Applications in Oil and Gas Industry

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Abstract

Recent developments of High-Velocity Air-Fuel (HVAF) spraying and blasting focused on a substantial increase of spray particles velocity. The efforts further improved coating quality, allowing deposition of metallic and carbide-base coatings non-permeable to gas at thickness as low as 40-50 micron. The coatings demonstrate low dissolved oxygen content, a favorable combination of high hardness and toughness. Coupled with the enhanced technological efficiency of modern HVAF equipment, this initiated not only the acceptance of HVAF technologies in established thermal spray markets in the oil and gas industry, but also the development and successful implementation of new coating applications. The examples are wear and corrosion resistant tungsten carbide-based coatings on hydraulics rods of dock cranes, corrosion resistant Ni-Cr-Mo-type coatings on vessels of sulfur removal equipment, tungsten carbide –based coatings on restriction grid plates and slide gates of catalyst towers, high-temperature erosion resistant chromium carbide- based coatings on thermawells and valve stems, wear and cavitation resistant Co-Cr-W-C-type and carbide coatings on housing wear rings and impeller hubs of high-temperature pumps.

Introduction

Recent developments in high velocity air fuel spraying (HVAF) technology and equipment resulted in improvement of coating quality and consistency of the processes. The HVAF applications not only penetrated the traditional high velocity oxygen fuel spraying (HVOF) markets, but generated new markets where HVOF was impossible to use either due to lack of necessary properties or due to prohibiting cost. Herewith, the understanding of the modern HVAF processes by thermal spray society remains poor and little information is published about the HVAF applications success and failures. The objective of this presentation is the description of the present status of HVAF developments and its new applications in oil and gas industry.

HVAF Gun Designs

The HVAF gun uses compressed air for combustion of a gaseous fuel in a combustion chamber. Since the combustion temperature of the air-fuel mixtures is 1000 K lower than the one for oxy-fuel mixtures, but still higher than the melting temperature of many thermally sprayed alloys, it is attractive using the HVAF process for deposition of coatings susceptible to oxidation or thermal deterioration during spraying. Lower combustion temperature in the HVAF gun also allows feeding of the spray material through a large combustion chamber to gradually achieve the necessary particle temperature. Such heating is more efficient than in the nozzle or in the gaseous jet, which is a reason of high spray rates achieved in the HVAF guns. Improved heating efficiency is a driving force of lowering the cost of HVAF coatings. Herewith, lower combustion temperature in the HVAF gun means lower gas velocity in the nozzle throat. Thus, the HVAF gun requires longer nozzle to achieve similar to HVOF spray particle acceleration. Besides, due to low flame propagation velocity in the air-fuel mixtures compared to the needed gas velocity in the chamber, the HVAF gun must have means for continuous re-ignition of the air-fuel mixture.

In the first HVAF gun, AeroSpray, manufactured by Browning Thermal Spray Systems [1] and Praxair-Tafa (Indianapolis, IN, USA), a pilot oxygen-hydrogen flame was used for continuous re-ignition of the air-kerosene mixture (Fig. 1, a). The spray powder was injected in the expanded nozzle section, similar to modern high velocity oxy-kerosene guns. This was a major disadvantage, since the efficiency of the material heating in the chamber was not utilized. Evidently, the heating efficiency of such HVAF gun was inferior to the HVOF, while the benefits of lower combustion temperature for coating the quality were reported [2-4]. The SEC Gradient (Kiev, Ukraine) manufactures similar type of HVAF guns nowadays. Their major commercial applications are known for the HVAF grit blasting [5]. The equipment is used for coating deposition, too.

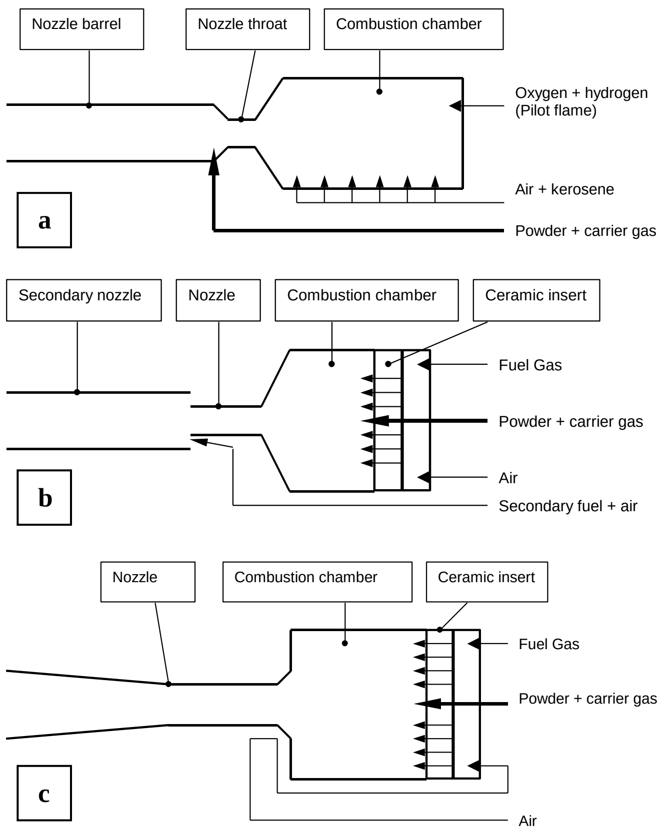

Figure 1: Principal schematics of HVAF guns: AeroSpray (a), SB9300 and M3 (b), AK-07 and AK-06 (c).

Modern commercial applications of HVAF coatings [6-9] are performed with the guns designed as presented in Fig. 1, b (UniqueCoat Technologies, Oilville, VA, USA) and Fig. 1, c (Kermetico Inc., Benicia, CA, USA). In these guns, a catalytic ceramic insert with holes is set in the entrance of the combustion chamber. A mixture of air and fuel gas flows through the ceramic holes into the chamber. After the mixture initial ignition, the ceramic heats up above the mixture auto-ignition temperature and continuously re-ignites the mixture flowing through it. Such design is often referred to as Activated Combustion HVAF. The spray powder is injected into the combustion chamber. Due to the large diameter of the chamber, the flow of gas in it is slow, providing long time for gradual heating of the spray particles under favorable conditions of a high pressure heating gas. Entering the nozzle, the spray particles are accelerated by a sonic gas flow in its throat and by a supersonic gas flow in its diverging section (if present). Thus, the heating and accelerating sections of the gun are separated, each can be modified to independently affect the spray particle velocity (nozzle length and configuration) and temperature (dimensions of combustion chamber and injector module design). The guns are air-cooled.

The SB9300 gun is equipped with a secondary cylindrical nozzle, where additional air-fuel mixture is added to increase the "virtual" length of the nozzle and the power of the gun. The M3 gun has the diverging secondary nozzle. Combined with larger gas consumption, this results in substantial increase of the spray particle velocity and improvement of the coating quality.

In the AK-07 gun design, the secondary nozzle is not used since it affects the powder stream concentration inside the nozzle, limiting the nozzle length due to its clogging problems. The entire flow of gas is directed into the chamber and then into the nozzle, maximizing energy transfer in both heating and accelerating sections. The critical nozzle diameter is increased. The large nozzle diameter minimizes the influence of the nozzle walls on the spray particle acceleration, providing even distribution of the particle velocity (the ratio of the particle stream diameter to the nozzle diameter is reduced to 0.2). It also removes the limit for the nozzle length. The supplied air cools the nozzle and the chamber first, then heated air flows into the mixing and combustion chambers. This way the total consumption of air is minimized. The use of hot air increases the combustion temperature and eliminates combustion instability problems due to presence of droplets of liquefied fuel. The injections of small amounts of hydrogen into the powder carrier gas provides additional tool for fine regulation of the spray particle temperature.

Modern AK-07 gun is equipped with 3 chambers and 5 nozzles of different configurations and lengths. In the de Laval type nozzle the spray particle velocity reaches 1200-1300 m/s. The variety of the gun setups and a wide range of spray parameters (the gun operates within 160-240 kW window) allow to efficiently deposit very different materials – metal-ceramics, high-temperature alloys, copper, aluminum with a variety of the powder particle sizes. Usual spray rates are 15-30 kg/hr. The AK-06 is a smaller HVAF gun. It operates at 100-140 kW power. The gun is specifically designed for hand-held applications. Herewith, it has technological advantages for spraying small and temperature-sensitive parts, achieving better coating quality. Even smaller guns (50-80 kW) are available today, designed for hand-held spraying and grit blasting, as well as for internal diameters spraying.

The AK-HVAF guns are efficiently used for grit blasting with alumina. Since the same gun is used for spraying and blasting, no additional setup is needed for the surface preparation. Compared to conventional grit blasting, the HVAF grit blasting is 10-fold faster and consumes 50-fold less grit. Since HVAF spraying usually requires a spray part surface preheating with the gun before coating deposition, both preheating and HVAF grit blasting are combined in one operation, resulting in substantial cost and time saving.

Experimental Procedures

The AcuKote HVAF system and AK-07 gun (Kermetico, Benicia, CA, USA) was used for developing the coating application hardware and processes, using chamber # 2 and #3, nozzles #3 (cylindrical) and #5L (de Laval type). Propane was used as a fuel gas. The gas velocity and de Laval nozzle configurations were calculated using mathematical model based on the combined Euler-Lagrange method [10]. The spray particle velocity and temperature were measured with Acuraspray G-3 (Tecnar, St. Bruno, QC, Canada). The hardware and spray process optimization was performed measuring the gas permeability of 40-50 micrometers thick coatings, deposited onto porous AISI 316SS discs (25 mm diameter, 3 mm thick, pore size 2 micron), using GPT-02 tester (Kermetico, Benicia, CA, USA) with maximal nitrogen pressure drop 210 MPa. The gas permeability method is described elsewhere [11]. For structural investigations the coatings were applied onto 75x25x6 mm AISI 1018 steel coupons. Coating structure was analyzed with optical metallography. Image analysis of 10 frames was used to estimate coating porosity at magnification x400. Coating microhardness was measured per ASTM 384 at 300 g load. Coating deposit efficiency was measured when spraying onto 100 mm diameter and 200 mm long AISI 1018 steel samples, using 0.5 g accuracy scales for weighing the samples and 2 g accuracy scales for measuring the powder flow rate through the powder feeder. The WC-10%Co-4%Cr powder, particle size 5-30 micrometers (Amperit 558.059, H.C. Starck; referred below as WC-10Co-4Cr) and the Cr_3C_2-25%(Ni-20%Cr) powder, particle size 10-38 micrometers (Amperit 584.072, H.C. Starck; referred below as Cr_3C_2-25NiCr) were used for coatings deposition.

Development of Improved Coating Technology

The objective of this investigation was an improvement of coating density and hardness by modifying the AK-07 gun hardware and spray parameters in order to generate higher spray particles velocity without affecting their temperature. This was achieved by developing new nozzles, maximizing the combustion chamber pressure and increasing the length of the combustion chamber compensating the lost of the particle dwell time in the chamber at higher gas flow rates.

Calculated sound velocity in the products of air-propane combustion in the AK-07 gun was 857 m/s (cold air) and 866 m/s (hot air) under assumption that the combustion temperature increases by 20K for each 100K increase of the inlet air temperature. Thus, regardless the pressure in the chamber, the gas velocity in the cylindrical nozzle is limited by about 860 m/s. However, at the exit of the correctly expanded de Laval nozzle the gas velocity increases noticeably with the chamber pressure (Fig. 2). Such nozzles were designed and the gun was modified to maximize the combustion chamber pressure.

Measured spray particles velocity and temperature for the WC-Co-Cr powder were 820-870 m/s and 1850-1900ºC correspondingly when sprayed with the original chamber #2 and cylindrical nozzle # 3 (absolute chamber pressure 0.45 MPa, spray rate 10 kg/hr). The use of the de Laval nozzle #5L with longer chamber #3 resulted in substantial increase of the spray particles velocity, reaching 1250-1300 m/s with the chamber pressure increase (Fig. 3, a). Particle temperature was slightly dropping with the chamber pressure increase (Fig. 3, b), but was not changed substantially compared to the original setup.

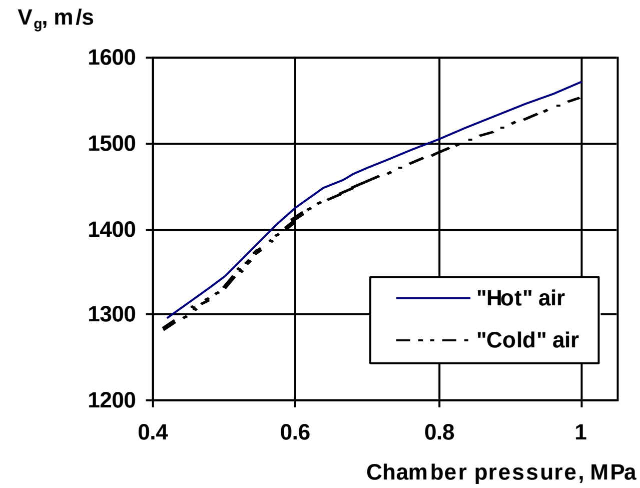

Figure 2: Results of calculations of the influence of absolute combustion chamber pressure on the gas velocity V_g at the exit of the de Laval nozzle

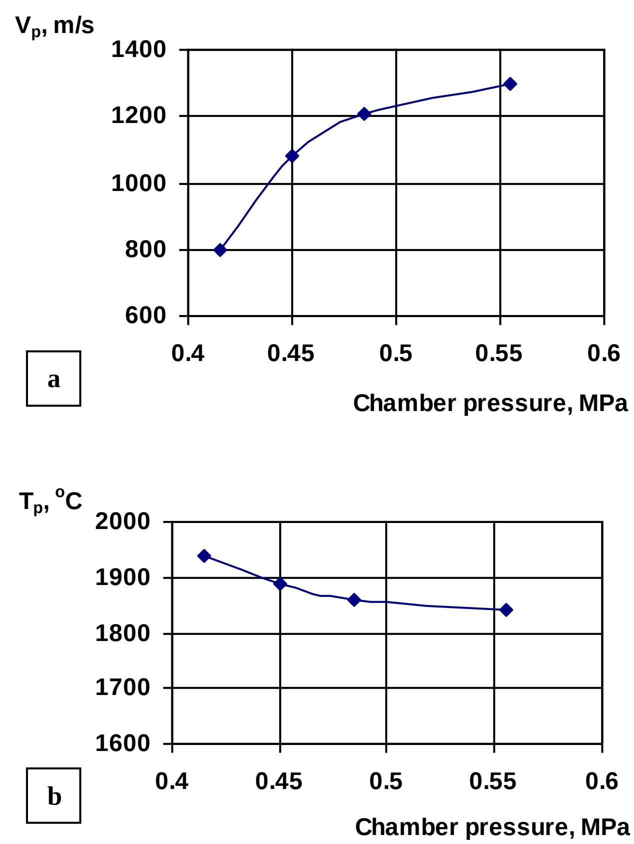

Figure 3: Influence of combustion chamber pressure in the AK-07 HVAF gun (nozzle #5L) on the WC-10Co-4Cr particle velocity V_p (a) and temperature T_p (b).

Table 1: Influence of nozzle setup and combustion chamber pressure in the AK-07 HVAF gun on the WC-10C-4Cr coatings characteristics (data for spraying with chamber #3)

Nozzle	3	5L			5L*
Combustion chamber pressure, MPa	0.45	0.49	0.52	0.56	0.56
Gas permeability, nm^2	180	1.4	0.0	0.0	0.0
Porosity, %	0.8	<0.5	<0.5	<0.5	<0.5
Microhardness, HV_{300} St. deviation, HV_{300}	1130 106	1336 70	1339 105	1345 56	1450 52
Deposit efficiency, %	60	52	48	43	43

*Modified injector module to increase particle temperature

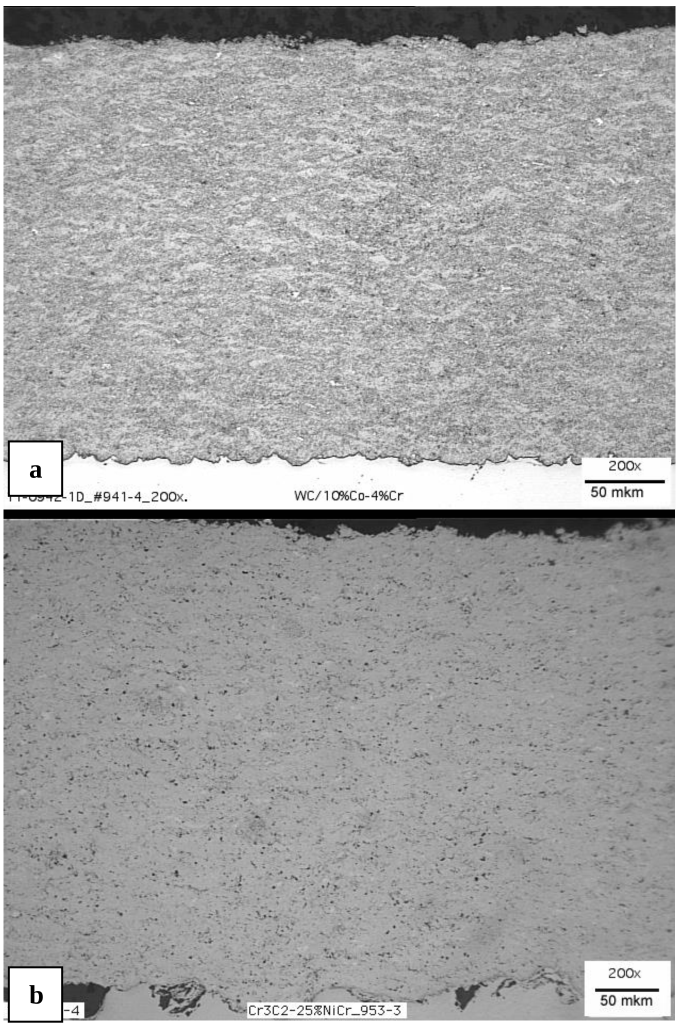

Figure 4: Micrographs of WC-10Co-4Cr (a) and Cr_3C_2-25NiCr coatings (x200, etched)

The WC-Co-Cr coatings properties are presented in Table 1. The coatings hardness and density were noticeably improved when using nozzle #5L, but the deposit efficiency decreased. The coatings density improved with the chamber pressure increase. The higher chamber pressure negatively affected the deposit efficiency. The use of modified injector module for higher heating of the spray particles substantially increased the coating hardness, but did not improve the deposit efficiency. The later indicates that the drop of the deposit efficiency with the increase of the chamber pressure is related to the higher erosion at higher spray particle velocity rather than to the influence of the lower particle temperature. Typical micrograph of developed WC-10Co-4Cr coating is presented in Fig. 4, a.

Similar improvements were achieved with the developed hardware for the Cr_3C_2-25NiCr coatings. The coatings properties are presented in Table 2 and a typical micrograph – in Fig.4, b.

Table 2: Influence of nozzle setup and combustion chamber pressure in the AK-07 HVAF gun on the Cr_3C_2-25NiCr coatings characteristics (data for spraying with chamber #3)

Nozzle	3	5L
Combustion chamber pressure, MPa	0.45	0.56
Gas permeability, nm^2	87	0.0
Porosity, %	0.9	<0.5
Microhardness, HV_{300} St. deviation, HV_{300}	860 75	1085 51
Deposit efficiency, %	56	45

New Coating Applications in Oil and Gas Industry

Good technological and cost efficiency of the HVAF processes and improved coating quality generate growing interest of the coating markets, including oil and gas industry. Kermetico Inc. routinely applies HVAF coatings in traditional HVOF applications on the valve gates, valve balls and stems, pump shafts, sleeves, packing nuts and cartridges, compressor rods and turbine shafts. Herewith, new applications are developed and successfully implemented at Chevron Richmond Refinery (Richmond, CA), Tesoro Golden Eagle Refinery (Martinez, CA), Valero Refinery (Benicia, CA) and ConocoPhillips Rodeo Refinery (Rodeo, CA). Some of them are presented below.

<u>Restriction Grid and Sliding Gate of Catalyst Tower</u>

The surface of a restriction grid (upper slide plate with orifice) of a catalyst tower is subjected to severe erosion by the catalyst, abrasive wear and corrosion within the range of temperatures from ambient to 315ºC. The guiding surfaces of sliding gates, spacer bars as well as slide stems undertake an abrasive wear attack. The surface area of the restriction grid plate is typically 1.5 x 1.2 m with other parts matching those dimensions. All are made of alloyed carbon steel. For a time the Colmonoy 88 type coating with thickness of 1.0 mm (fused on the stem, as-sprayed on the other parts) was specified for those surfaces protection. However, the coating lasted only 2.5 years on plates and gates, while requested performance of 5 years was needed. Kermetico Inc. applied the WC-10Co-4Cr HVAF coating to requested 0.50 mm thickness for the 2 towers sets (Fig. 5). The plates and gates were removed form service exactly in 5 years, coating still intact on all parts. Currently this coating is listed in the customer specifications.

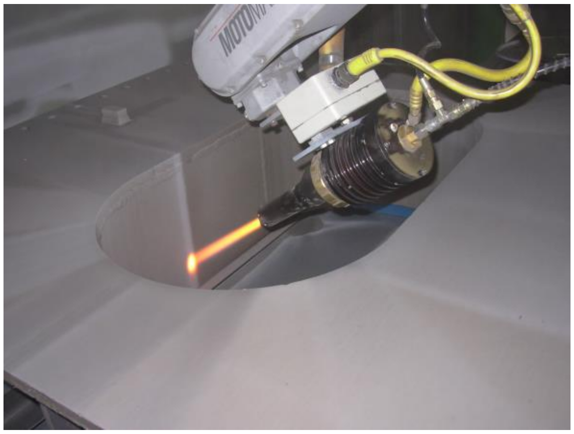

Figure 5: Application of the WC-10Co-4Cr coating with the AK-07 HVAF gun onto restriction grid with orifice (upper slide plate of the catalyst tower)

<u>Hydraulic Rods of Dock Cranes</u>

The hydraulics rods of dock cranes operate under conditions of abrasive wear and seawater corrosion. The rods diameter varies from 30 to 70 mm and length - from 0.7 m to 2.5 m. They are typically made of AISI 1040 series steels, heat treated and hard-chrome plated (0.15-0.20 mm coating thickness). Besides abrasive wear, the hard chrome coating experiences sever pitting attack, which requires the rod replacement within 0.5-year service. Several attempts to use the WC-10C-4Cr HVOF coatings failed for the same reason – pitting corrosion. Kermetico Inc. started the work with repairing the old rods: stripping old chrome coatings, grinding to remove major spots of corrosion wear, DOT-welding deep pits, applying WC-10Co-4Cr HVAF coating, grinding/superfinishing rods to size. Some rods required spraying of as much as 0.8 mm thick coatings. After 1-year service and confirmation of the coating performance, the application of the HVAF coatings (Fig. 6) became the standard procedure for all hydraulic rods in this service. After 2-years service, the initially applied WC-10Co-4Cr HVAF coatings are still working on the repaired hydraulic rods and no failures for the later coated rods are reported.

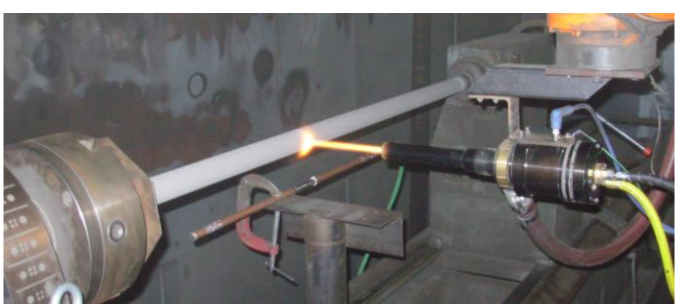

Figure 6: Application of the WC-10Co-4Cr coating with the AK-07 HVAF gun onto hydraulic rod of sea dock crane

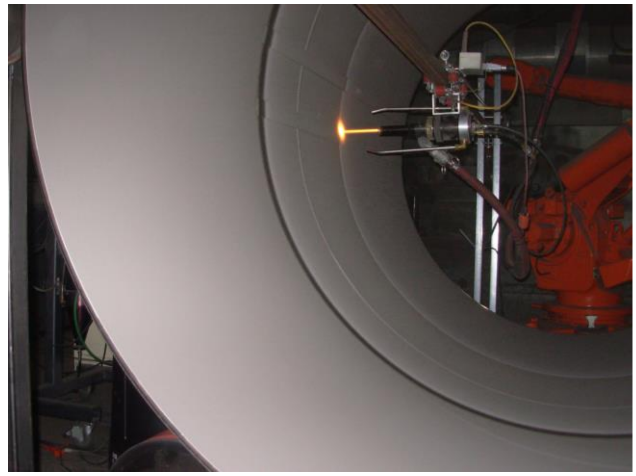

Figure 7: Robotic application of the Hastelloy C- type HVAF coating onto inner surface of the outlet channel of the sulfur condenser with the AK-07 gun (a) and hand-held application with the AK-06 gun over the welds after installation of the de-mister structure (b)

<u>Sulfur Condenser Vessel</u>

Refinery sulfur recovery plant has multiple vessels and ducts exposed to corrosion due to the presence of sulfur containing fumes and moisture in altering temperature conditions. Categorized as pressure vessels, the towers, condensers and channels are usually made of mild carbon steel. The sulfur condenser outlet channel suffers extensive pitting due to dew point corrosion caused by condensation of sulfuric acid on the "cold spots" where the metal surface temperature drops below 120ºC. After successful testing in boiling concentrated sulfuric acid, the Hastelloy C- type HVAF coating of 0.7 mm thickness was specified to apply on the complete inner surface of the outlet channel (1.8 m diameter, 2.4 m long), welded to it gas outlet (0.76 m diameter, 0.3 m long) as well as on the channel cover (1.8 m diameter). The inner surface of the channel was grit blasted with the AK-07 gun and the coating robotically applied safe the masked areas for welding of the de-mister frame and plates (Fig. 7, a). Following the welding of the de-mister support structure, the welds were hand-held sprayed with the AK-06 gun (Fig 7, b). After installation of the channel at the plant, the hole was flame-cut in the bottom through the coating and the liquid sulfur outlet welded to it. Finally, the coating was applied over the cut area and inside the liquid sulfur outlet with hand-held AK-06 gun on-site. After one-year operation, the coating on the channel and cover is intact and remains in service.

Other Recently Developed Applications

In high-temperature pumps, the impeller hubs and housing wear rings are subjected to erosion and cavitation attack. The Stellite- type plasma transferred arc weld overlays are commonly specified in these areas. The HVAF Stellite 6- type coatings are successfully used for repairs over the overlays. The HVAF-sprayed WC-10Co-4Cr coating on the impeller hubs coupled with the Stellite-6 type coating on the housing wear ring outperform weld overlays, specifically in the pumps with tight tolerances of the gap between the impeller and the housing. Besides, these HVAF coatings are 4-fold less costly then weld overlays. The HVAF sprayed Cr_3C_2-25NiCr coating extends lifetime of the thermawells protecting the thermocouples of the catalyst tower. This coating outperforms Stellite-type weld overlays on the high-temperature valve stems. The Fe-5Ni-28Cr-6Mo-2C HVAF coating (hardness 53-55 HRC) is effective solution for corrosion and wear problems on the valve stems and seats, pump impellers and stainless steel shafts.

Conclusions

The designs of modern HVAF guns are described. The guns demonstrate improved efficiency due to favorable heating conditions of the spray material inside the combustion chamber. The spray particle heating and acceleration are performed in separate areas of the gun – the chamber and the nozzle, what simplifies the gun setup development and adjustment to wide range of coating deposition requirements. New HVAF gun setups are developed, which accelerates the spray particles up to 1200-1300 m/s. This results in improvement of coatings quality. The cemented carbide coatings are non-permeable to gas at thickness as low as 40-50 micrometers. The WC-10Co-4Cr coating hardness is increased to 1300-1500 HV_{300} and Cr_3C_2-25NiCr coating hardness – to 1000-1100 HV_{300}. The traditional and new coating markets in the oil and gas industry accepted the HVAF coatings on many critical components. The new coating applications include the plates and gates of the catalyst towers, hydraulic rods of dock cranes, sulfur condenser vessels of sulfur recovery plant, high-temperature pump impeller hubs and housings, valve stems and seats.

Acknowledgement

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References

1. J. Browning, Abrasive Blast and Flame Spray System with Particle Entry into Accelerating Stream at Quiescent Zone thereof, US Patent 4604306, August 5, 1986
2. L. Jacobs, M.M. Hyland and M. De Bonte, Comparative Study of WC-cermet Coatings Sprayed via the HVOF and the HVAF Process, *J. Therm. Spray Technol*., 1998, **7**(2), p 213-218
3. L. Jacobs, M.M. Hyland and M. De Bonte, Study of the Influence of Microstructural Properties on the Sliding-Wear Behavior of HVOF and HVAF Sprayed WC-Cermet Coatings, *J. Therm. Spray Technol*., 1999, **8**(1), p 125-132
4. S. Matthews, M. Hyland and B. James, Microhardness Variation in Relation to Carbide Development in Heat Treated Cr_3C_2-NiCr Thermal Spray Coatings, *Acta Materialia*, 2003, **51**(14), p 4267-4277
5. Y. Evdokimenko et al., High Velocity Flame Spray Jet Apparatus for Thermoabrasive Cutting or Cleaning or for the Application of Protective Coating, US Patent 5607342, March 4, 1997
6. A. Verstak and V. Baranovski, AC-HVAF Sprayed Tungsten Carbide: Properties and Applications, *Thermal Spray 2006: Building on 100 Years of Success*, B.R Marple, M.M. Hyland, Y.-C. Lan, R.S. Lima and J. Voger, Ed., May 15-18, 2006 (Seattle, WA), ASM International, 2006, paper 11827
7. A. Verstak and V. Baranovski, Deposition of Carbides by Activated Combustion HVAF Spraying, *Thermal Spray Solutions: Advances in Technology and Application*, May 10-14, 2004 (Osaka, Japan), DVS- German Welding Society, 2004, p 551-555
8. A. Verstak and V. Baranovski, Activated Combustion HVAF Coatings for Protection Against Wear and High Temperature Corrosion, *Thermal Spray 2003: Advancing the Science and Applying the Technology*, B.R. Marple and C. Moreau, Ed., May 5-8, 2003, V.1 (Orlando, Florida), ASM International, 2003, paper 559
9. A. Verstak and V. Baranovski, Dynamic Air Deposited Coatings for Power and Black Liquor Recovery Boilers, *Corrosion NACExpo99*, 54th NACE Annual Conference, April 25-30, 1999 (San Antonio, TX), NACE International, paper 74
10. A. Voronetski, S. Suchkov, L. Filimonov, V. Belashchenko, Modeling and Optimization of HVOF Processes, *Thermal Spray 2006: Building on 100 Years of Success*, B.R Marple, M.M. Hyland, Y.-C. Lan, R.S. Lima and J. Voger, Ed., May 15-18, 2006 (Seattle, WA), ASM International, 2006, p 317-322
11. A. Verstak, V. Baranovski and M. Calkins, Critical Factors for Coatings Performance in Kraft Pulping Digesters, *Corrosion NACExpo99*, 54th NACE Annual Conference, April 25-30, 1999 (San Antonio, TX), NACE International, paper 286