Drive & Control profile

Technical Article

Advances in high velocity oxygen fuel spraying enhance long-term durability in Bosch Rexroth large hydraulic cylinder rods

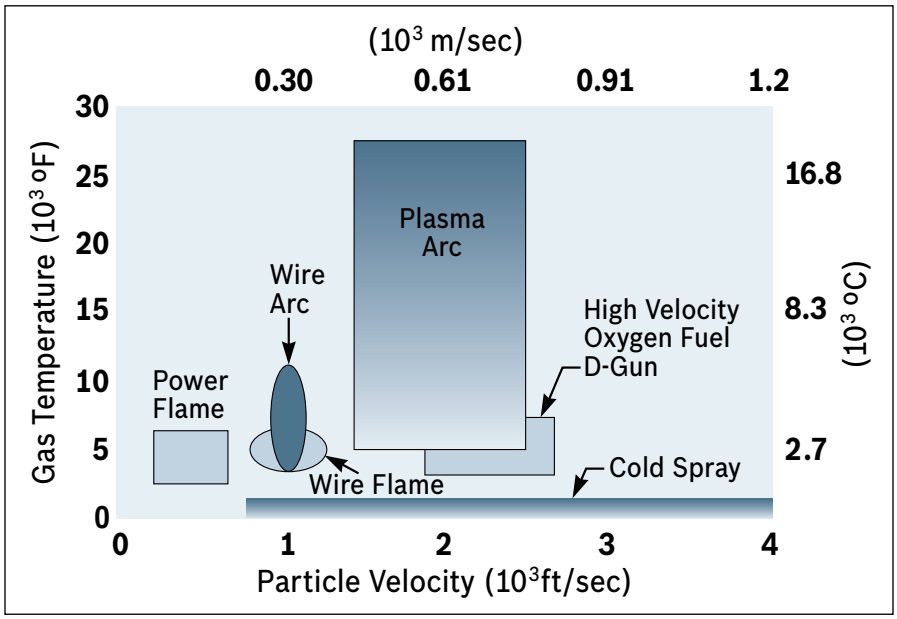

Fig. 1: HVOF is typically used when metals and metal matrix composites are applied. The metal doesn't require a very high temperature for melting, and the increased velocity promotes a higher coating density.

From miter gates to casters, from oil rigs to excavation equipment, large hydraulic cylinders (LHCs) are integral components in the functioning of large machines in mechanically demanding and corrosive environments. The design of this equipment and the materials utilized in these large-scale hydraulic systems are engineered to provide reliable performance throughout their expected lifecycle in response to environmental conditions.

On LHCs, maintaining the integrity of the cylinder rod, which is routinely exposed to environmental conditions in operation, is essential for maintaining the long-term operating life of the system. The rod surface needs an appropriate coating to

Technical Challenges

- Protect the condition and integrity of large hydraulic cylinder (LHC) rods when used in mechanically demanding and corrosive environments
- Improve the quality, durability, and performance of LHC rod coatings and coating applications processes

Advances in HVOF

- High Velocity Oxygen Flame (HVOF) process used to apply a new generation of metal and metal matrix composite rod coatings
- New grit blasting techniques improve surface preparation and coating adhesion and cohesion
- Refinements in coating powder shape and particle size distribution optimize performance of HVOF flame application
- Better control of HVOF combustion characteristics such as gas flow and pressure and thermal expansion yield more uniform coating and longer life time expectancy

provide a good, durable base for the cylinder's tribological system between the cylinder head and the piston rod.

In order to have a durable solution one needs sufficient mechanical properties and corrosion resistance. There has been an evolution in the technologies used to create and apply these cylinder rod coatings; this Technical Paper examines how High Velocity Oxygen Fuel (HVOF) spraying has developed, including advances in coating technologies, surface preparation, improvement in coating materials, and the HVOF process.

Cylinder rod operating conditions

Typically, a cylinder used in off-shore applications has high demands on corrosion resistance and reparability, while cylinders functioning in a large civil application like dams will have high demands on durability and long-term reliability. Environmental sources of corrosion vary from arctic to tropical seawater (salinity), to no more than an occasional drop of rain in dam applications.

The expected operational lifespan of LHCs varies based on their application, ranging from a few years to up to 30 years in civil applications. If the rod coating fails through damage or wear, significant impacts can occur: the cylinders seals can be quickly damaged (a matter of a few strokes, depending on the type and severity of damage). Loss of seal integrity means that required pressure buildup within the cylinder can be significantly reduced, leading to hydraulic cylinder functional failure.

Thus, developing reliably durable cylinder coatings has been a key technology challenge for LHC manufacturers; while various methods have been developed, the HVOF process provides several effective advantages.

Development of coating technologies

There are several cylinder rod coating technologies that have been or are currently in use. These include:

- Electrodeposited hard chromium (indoor use in industrial systems)
- Electrodeposited nickel-hard chromium (outdoor use in dams, canal miter gates, and other civil applications)
- Plasma sprayed ceramic (for industrial use except ocean water conditions)
- Overlay laser-welded or Plasma Transferred Arc (PTA) welding (almost exclusively in the offshore oil and gas)
- HVOF sprayed metallic/metal matrix (broadest range of industrial and offshore applications)

The HVOF sprayed metallic/metal matrix coating evolved from earlier generation plasma sprayed ceramic coatings. This evolution was driven by a desire to improve the corrosion resistance of rod coatings; particularly for applications where the LHC rod is operated in harsher environments and is kept extended outside the cylinder for longer periods of time.

Although the plasma sprayed ceramic coatings demonstrate effective rod protection, this is typically dependent on the quality of the plasma spraying process. If the plasma spraying process is not properly controlled, quality suffers, leading to early corrosion problems and excessive hydraulic fluid leakage due to damage to the sealing system.

HVOF process

HVOF spraying is a process in which a powdered substance is sprayed onto the surface of the piston rod. The particles are heated by a burning gas mixture of a fuel (e.g. hydrogen, methane) and oxygen. Subsequently, the particles are accelerated to supersonic speeds before they hit the substrate material. During this collision the partially molten particles undergo plastic deformation and rapidly solidify to form the typical 'stacked pancake' morphology. The HVOF gun (see Figure 7) is specifically designed for obtaining these high particle speeds.

HVOF: Achieving coating properties and quality

The properties of the current generation of HVOF coatings are the result of a dynamic interplay of factors that have been refined through research and development.

Coating porosity and oxidation level are two such properties. Due to the buildup mechanism of the coating, there is always a certain amount of porosity and oxidation present in the final coating. On the one hand, porosity can accelerate corrosion; however, the porosity on the surface also acts as small oil pockets, which ensures a good tribological surface.

A certain degree of oxidation adds to the hardness, flexibility, and wear resistance of the coating; however, if oxidation levels are too high, this can impede the corrosion resistance. Controlling and balancing these properties through quality processes and HVOF process refinements has been the focus of coating development efforts.

Grit blasting improves surface preparation

Any coating must have both adhesion and cohesion to achieve optimum longevity and protection. Cohesion is optimized by choice of powder and process characteristics. Adhesion, however, is achieved by a number of mechanisms, e.g. physical bonding, metallurgical bonding, and mechanical bonding. In HVOF, adhesion of the coating mostly depends on the mechanical interlocking of the coating to the surface.

Mechanical bonding is generally improved by a higher contact surface area, which can be increased by roughening the surface of the substrate. Controlled and optimized grit blasting not only increases the contact surface area; it also provides micro-hooks for mechanical interlocking of the coating particles with the rod surface.

Some manufacturers of HVOF coatings have switched from grit blasting that uses korund (i.e. aluminum oxide) particles to a special non-korund blasting grit. It was found that the sharp aluminum oxide particles have the potential to be embedded in the substrate. Subsequently, most likely due to the difference in thermal properties compared to the substrate, this can cause uneven build-up of the coating during the spraying process. This undesired build-up can potentially cause reduction of coating adhesion, excess porosity, and oxidation in the coating, significantly reducing the local mechanical properties and corrosion protection.

It has been found that certain non-korund grit particles do not cause these defects, while retaining the desired surface morphology for optimal mechanical interlocking. This process also yields a rod substrate that is cleaner and better prepared to mechanically interlock with the coating, substantially improving the coating adhesion to the substrate.

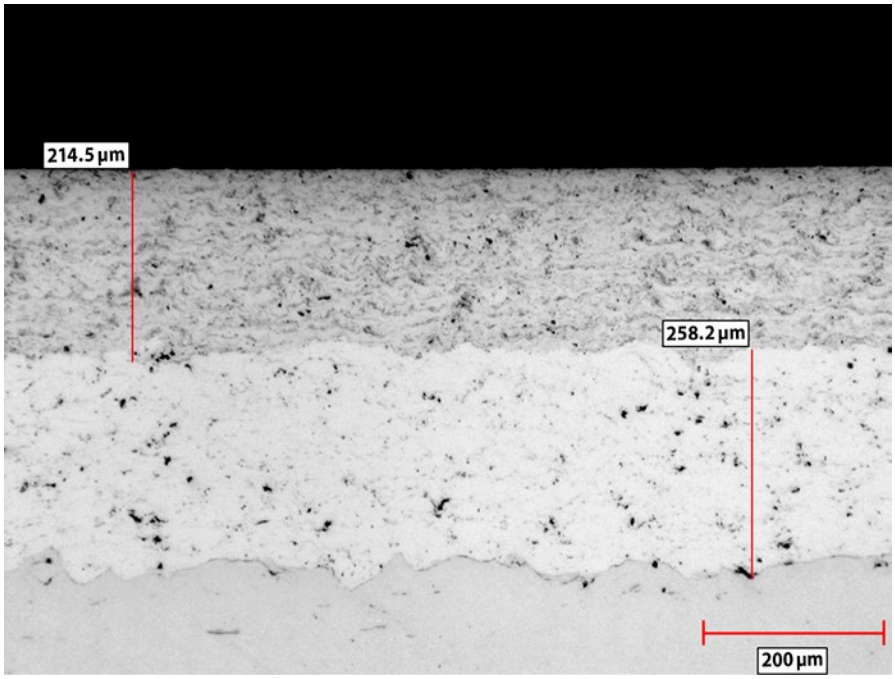

Fig. 2: Cross section of dual layer HVOF coating developed by Bosch Rexroth, depicting strong adhesion through mechanical interlocking with rod metal surface and between individual coating layers.

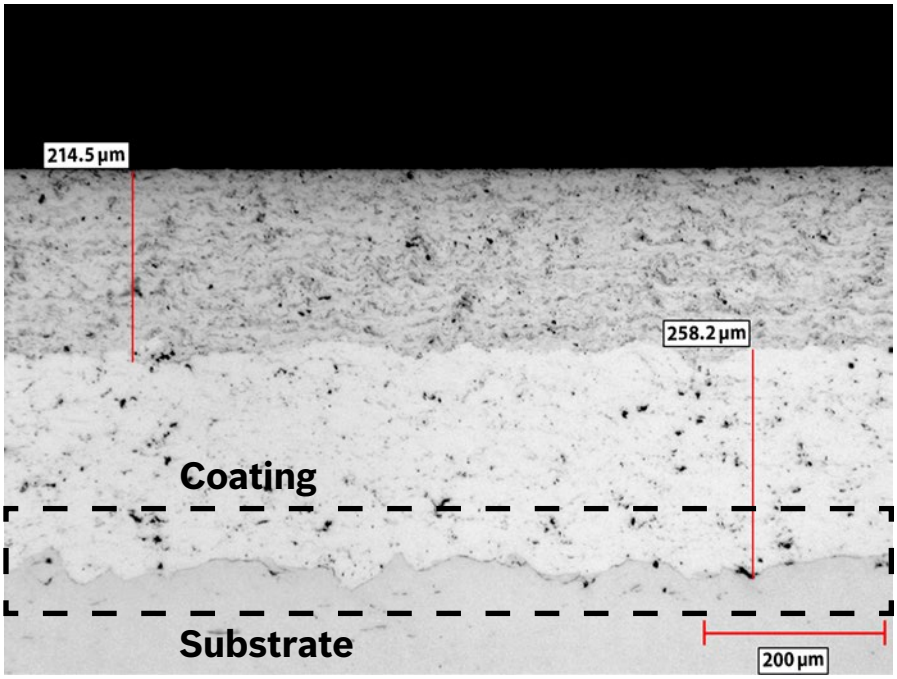

Fig. 3: Cutaway view of finished HVOF coating layers and mechanical interlocking with rod surface.

Fig. 4: Grit inclusion and effect on coating integrity.

HVOF coating materials
HVOF coating materials have also undergone evolution, focused on three related properties: the chemical composition of the powder, the size (distribution) of the powder particles, and the production method of the powder.

Chemical composition: The chemical composition of the rod coating is critical to achieving the desired combination of mechanical properties and corrosion resistance. The latter is typically determined through the Pitting Resistance Equivalent Number (PREN), a measurement of the pitting corrosion resistance of nickel containing stainless steels. A material with a PREN value of greater than 32 is considered to be sea water resistant. For example, the Rexroth Enduroq 2000 HVOF rod coating has a PREN value ranging from 60-70, which is comparable to Hastelloy and Inconel alloys.

Because the HVOF process uses high velocity oxygen flame (which obviously can affect the ultimate properties of the coating), it is necessary to take this process into account and compensate for differences in behavior of the metallic constituents in the flame and during coating formation on the substrate. More precisely controlling material properties, such as differences in sublimation, melting range, thermal expansion, and shrinkage due to solidification, makes it possible to optimize the composition of coating materials to the HVOF process.

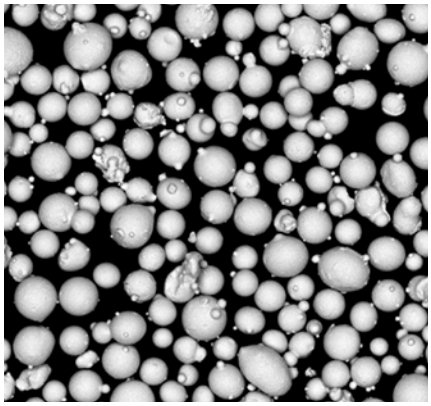

Fig. 5: Scanning electron microscope image of proprietary HVOF powder demonstrates highly uniform size and shape of particles.

For example: Certain HVOF coating processes yield a relatively hard coating, which means that stress in the coating due to thermal expansion or solidification shrinkage could cause detrimental coating cracks. One way to reduce these effects is to develop powders with constituents that lower the melting range of the alloy.

Powder shape: To control various properties of the powders used in HVOF powders, some producers have developed processes that yield a spherical powder with a minimal amount of oxides. The spherical shape of the powder gives the best possible flow characteristics in the feeding system, which in turn provides the HVOF gun with a continuous and constant flow of powder to achieve consistent coating quality. Additionally, the oxidation levels in the coating are minimized with spherical shaped powder.

Particle size: The powder particle size is also very important. If particles are too small, it has been determined that they can become overheated in the flame; too large particles will not melt sufficiently to achieve a homogenous coating and can cause excessive porosity. Overheating of the powder particles can cause the coating to be highly oxidized and porous, thus effectively reducing its corrosion resistance. When the powder doesn't melt enough the resulting coating lacks cohesion and adhesion.

Most commercially available powders have a particle size distribution,

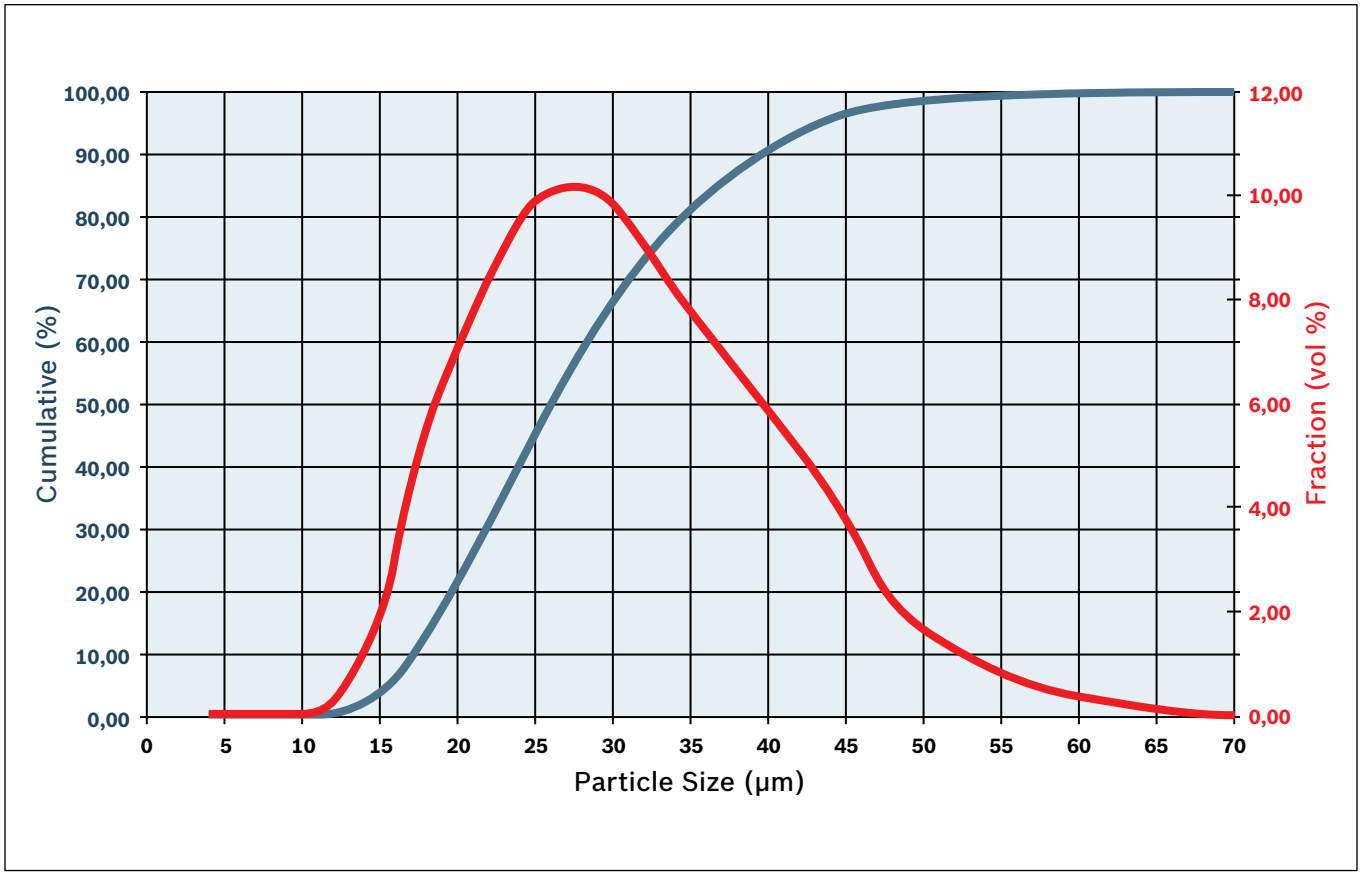

Fig. 6: Chart depicts typical powder diameter distribution for better control of coating characteristics prior to HVOF spraying.

defined by a lower and an upper limit; measuring this distribution to ensure that it remains within process limits is a necessary step to ensuring HVOF coating integrity.

A fully mathematical description of a powder is not possible, but a particle size distribution curve, such as the one presented here, provides an effective method for measuring and controlling this HVOF process variable.

Improvements in HVOF coating have been achieved by significantly lowering the amount of finer particles and slightly increasing the amount of courser particles allowed in the powder mixture. This improves several coating powder characteristics: a lowered amount of oxidized particles in the layer, reduced tensile stress in the coating, and reduced consumption of consumables like air caps.

HVOF process control

While it is crucial to exert precise control over both surface preparation and coating chemical composition, it has been found that control of the HVOF flame is the key factor in optimizing coating formation and, ultimately, coating durability. The flame determines the speed, temperature, direction, and to some extent the chemical composition of the particles that form the coating.

The combustion parameters, i.e. the absolute and relative fuel and oxygen gas flows, determine the temperature and stoichiometry of the flame, which—together with the flame speed—determines the temperature and oxidation level of the powder at the point of collision with the substrate. The flame speed is determined by a complex interaction of combustion parameters, including:

- Gas flows and pressures
- Chemical reaction parameters
- Thermal expansion
- The geometry of the burn chamber and air cap.

Certain HVOF coating manufacturers have developed several improvements in this process. It has been found that the flame has to be optimized to ensure the particles have the optimum speed and temperature combination to create a dense, low oxide containing coating with excellent cohesion and adhesion to the substrate surface.

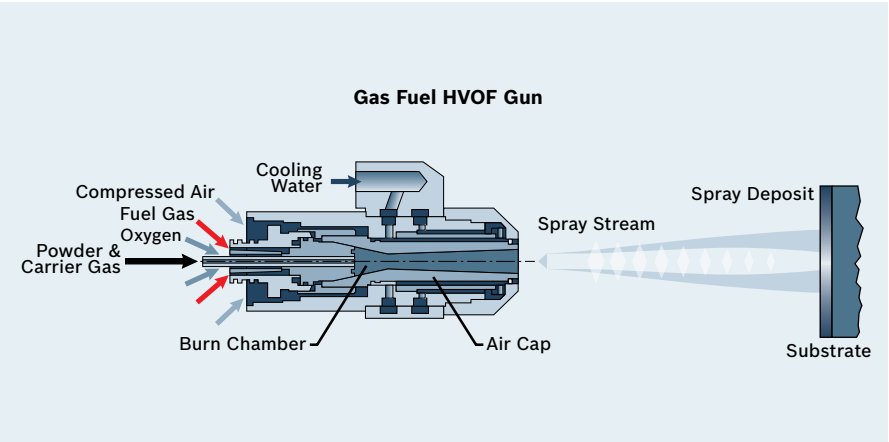

Fig. 7: HVOF is one of several thermal spraying coating technologies; these differ in material supply (powder vs. wire), heat source (electric vs. flame), flame temperature, and flame speed. This gun was specifically designed for HVOF spraying.

An important factor controlling this process is the HVOF spraying distance, i.e. the distance from the gun exit to the substrate surface. It is important this distance is well chosen in combination with the other flame parameters and powder characteristics. Combined with the design of the spraying gun, controlling these factors has been shown to enhance the overall performance of the HVOF process.

Conclusion

The growth of many offshore industrial activities—such as offshore oil and natural gas exploration and wind energy production—with demanding operational environments continues to drive development in coating technologies to protect the critical equipment such as LHC rods that these operations require.

The HVOF spraying process has evolved to enable the production of consistently high quality coatings that extend the performance and operational life of the LHC rods. By combining improvements in rod surface preparation, coating powder materials and composition, and more precise control of HVOF combustion characteristics, both coating flexibility and corrosion resistance have been improved by these developments, enabling a broader and more durable use of LHC systems in offshore saline water environments. HVOF coatings have also been shown to be effective alternatives for conditions where electrolytically applied hard chromium or nickel-chrome cylinder rod coatings are under-qualified.

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